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Using Solar Photovoltaic Systems, Battery Energy Storage Systems, and Underfrequency Load-Shedding to Improve the Frequency Stability of Power Systems

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ABSTRACT

Electrical power systems operate at 50 Hz. However, generation loss, a sudden increase in loads, or faults in the system cause disturbances and deviations that destabilize the frequency of electrical power systems. Therefore, there is a need to study and improve the frequency stability of electrical power systems during disturbances. The present study examines improving the frequency stability of electrical power system, using a solar photovoltaic (PV) system, a battery energy storage system (BESS), and underfrequency load-shedding (UFLS) to estimate and control the frequency. The proposed method was tested on a standard Institute of Electrical and Electronics Engineers' (IEEE®) 9-bus system that was simulated in MATLAB® Simulink. The simulation results indicate that the used method significantly stabilizes the frequency of electrical power system.

***Keywords**:*

Frequency Stability, Energy Sources, PV, PFC, IR, UFLS, BESS.

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1. INTRODUCTION

The main factors causing instability as well as methods of improving stability have been identified by categorizing the types of stability:

(I) frequency stability, (II) voltage stability, and (III) rotor angle stability [1].

Frequency stability significantly affects the stability of power systems and can occur as either short- or long-term phenomena. Short-term frequency instability involves the formation of a tripping generation part. This occurs due to the insufficient loading of low-frequency oscillations, which causes the frequency to drop quickly, resulting in a power outage within seconds. Meanwhile, the more complex frequency instabilities occur due to the speed controls at steam stations. Boiler protection and reactors, however, are long-term phenomena that can last for tens of seconds to several minutes [2].

Renewable energies have affected the economic performance of conventional electricity producers as they decrease electricity prices and reliance on conventional methods of electricity generation, such as coal and gas. This is because renewable energies generally have lower operating costs. Furthermore, less demand, prices, and usage has led to lower profits in conventional electricity generation. Renewable energy generators have also improved the frequency stability of power systems as their dynamic response speed and time is faster than that of conventional generators [3].

Multiple studies have examined the long-term stability, protection, operation, and controls of power systems. There are two categories of power system stability analyses: (I) steady state stability or "dynamic stability", which is a function of the operating state only and (II) transient stability that relates to both power system operations and disturbances. Power systems encounter a variety of disturbances. Small disturbances occur due to load changes while large disturbances occur due to faults; such as transmission line trips and falls. The power system stability depends on both the initial operating state and the strong of the disturbance. The behavior and emergency severity situations in electrical starter systems differ for each operating condition.

The severity for an emergency depends on the type, location, and time of the malfunction. Power systems are typically altered so that the steady-state process post-disturbance is different from that the process pre-disturbance. For example, if an electrical power system initially runs as a bulk steady state operation, when a momentary disturbance happens, the network formation of the power system changes. So, when the system is stabilized, the new stable operating state will be different from the previous state. The severity and likelihood of disturbances vary between power systems. To never lose synchronization, power systems must be designed to overcome different types of emergencies. Different emergencies cause changes in system conditions or load demand for different reasons, which, in turn, causes a gradual and uncontrollable decrease in system frequency and voltage. Due to the instability of power systems, their dynamic changes and stability strongly depend on the disturbances magnitude and time that may occur [2] [4].

The present study uses the main frequency operating limits of the European distribution system [5]. Fig. 1 depicts the primary frequency determinants and operating limits of the European distribution system [6].

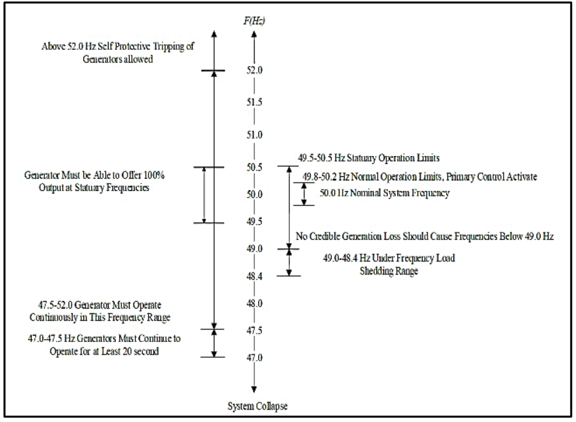

Fig. 1 Main frequency determinants and operating limits of the European distribution system.

2. LITERATURE REVIEW

Ning, Jiang, and Zhu [7] (2010) investigated the ability of an underfrequency load-shedding (UFLS) scheme to prevent frequency drops from occurring in a rate-of-change-in-frequency (RoCoF)-based multi-machine power system due to imbalances between loads and generation. Simulations were performed in a five-node multi-machine model. A multi-region five-node simulation was also conducted to confirm that the transmission lines would not be overloaded. The study found that multi-machine and multi-zone models can provide stability and increase power frequency quality. Therefore, the proposed UFLS scheme was successful.

For their part, Ghafouri, Milimonfared, and Gharehpetian (2015) [8] developed three frequency control systems for power systems by coordinating the controls of distributed power sources and conventional power stations. The first system was a centralized control system, the second was a decentralized control system, and the third was a multi-agent control system which was simulated in two systems: 1) an IEEE® 34-bus distribution test system of electromagnetic transients including direct current (EMTDC) in the power systems computer aided design (PSCAD) program and 2) a single-line diagram power system of (IEEE®) 9-bus model in PSCAD. The multi-agent control system was the best for tracking drooping. The proposed control system was also tested in an IEEE® 9-bus power system in PSCAD. The simulation results revealed that the proposed system effectively improved the stability of power systems.

Furthermore**,** Qazi, Flynn, and Rather [9] (2016) examined the effect of changing the load response of an electric vehicle on frequency stability. The study suggested a control strategy based on the available electric vehicle reserve variables and system requirements. This included a real-time hybrid control of the electric vehicle volume based on responsiveness and a decentralized adaptive control to change the response of the electric vehicle in real time. A 1-bus power system was simulated in DIgSILENT. The proposed control mechanisms were found to be robust and successfully ensured frequency stability, with little effect on response speed and frequency.

In addition, Delavari, Kamwa, and Brunelle [10] (2018) presented Simscape™ power system standards for education and research on power network dynamics and control. A new unit of frequency measurement was proposed to measure the frequency of a power system model operating in phasor mode. Changes were also made to the test systems. The frequency of the system, such as the entry and exit of the load, was measured after these changes were implemented and a three-phase fault occurred. Controlling the load and using a multi-band power system stabilizer improved the frequency stability. Three systems were tested in the simulation: 1) Kundur's two-area system, 2) the Western North American power grid, and 3) Western System Coordinating Council 3-machine 9-bus.

Azhar et al. [11] (2020) examined the control scheme design of a (BESS) to keep the frequency at constant value, and (PV) system. The study examined the impact of implementing a BESS on frequency stability performance due to interference from the intermittent renewable energy sources generated by controlling the BESS with a virtual inertial controller as an inertial response unit and a droop control as the primary frequency response unit. PowerFactory® was used to conduct the tests on a standard IEEE® 9-bus system. The use of a BESS as a frequency support unit was found to increase the frequency stability of the power system. Furthermore, future studies could improve the control gain to regulate frequencies in a system.

Mditshwa et al. [12] (2022) examined the frequency conservation capability of a power system equipped with distributed energy resources, such as a BESS and a solar PV system. The BESS was controlled, using a primary frequency control (PFC) based on the droop and a virtual inertia response (VIR). The results indicated that renewable energy sources could sufficiently maintain system frequency.

3. MEASURING OF FREQUENCY

The phase technique, where the voltages of a sequence and their angles are calculated then converted from degree to radian, was used to estimate and measure the frequency (Figure 2). It was then fed into a closed loop, derived, and combined with the reference angle then divided by (1/2π) to obtain the frequency (fig. 3) [13].

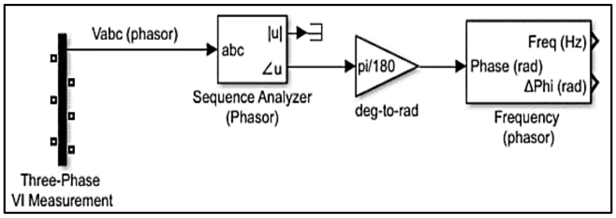

Fig. 2 Frequency measurement using node phase voltages.

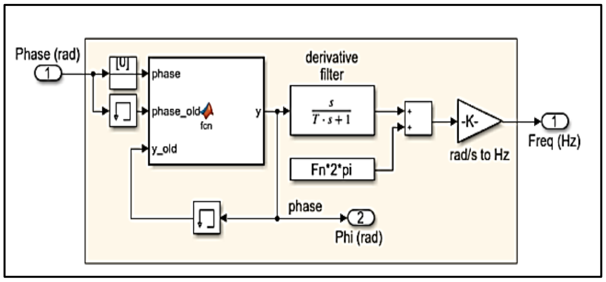

Fig. 3 Measuring frequency and phase changes.

4. FREQUENCY IMPROVEMENT

The present study uses two methods to improve frequency stability; a BESS and UFLS.

4.1 Battery Energy Storage System (BESS)

BESS was used to compensate the loss of power after measuring the frequency and then controlling it for the stabilization purpose. Two methods were utilized to measure and control the frequency: (I) PFC and (II) VIR (fig. 4) [11].

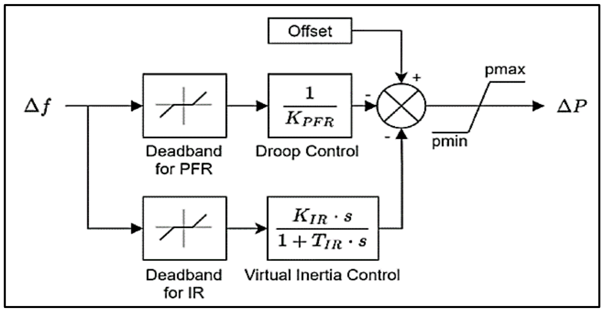

Fig. 4 Methods of frequency control for a BESS.

4.2 Underfrequency Load-Shedding (UFLS)

This method used a relay to trip loads when the frequency dropped below 49.5 Hz. The relay tripped after 0.2 second. Fig. 5 depicts the trip relay [14].

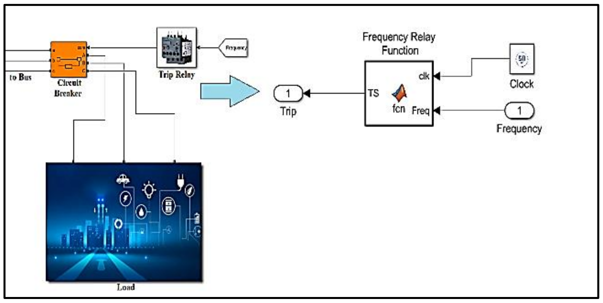

Fig. 5 Trip relay.

5. IEEE 9-Bus System Model

The electrical power system basically consists of nine busses, three electrical machines, three loads, transmission lines, and three transformers. It also contains power system stabilizers (PSS), an excitation system, a steam turbine, and a governor (fig. 6). The values and data of the standard power system were within the parameters of 50 Hz as shown in Table (1) [15].

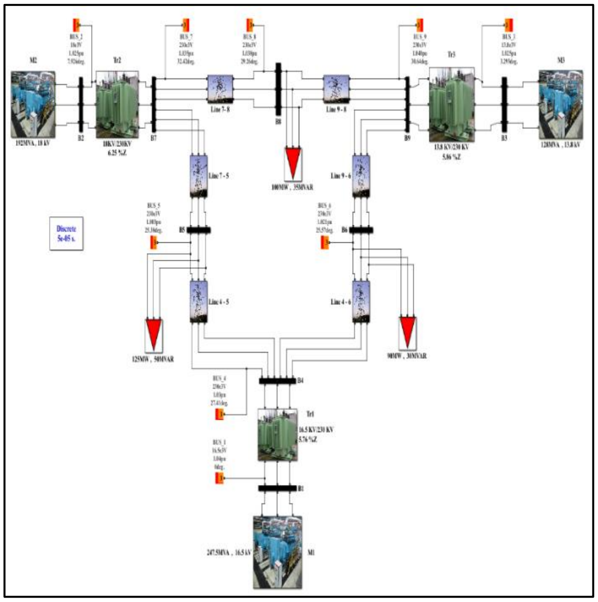

Fig. 6 An IEEE® 9-bus standard power system.

Table (1) provides the parameters of the components of an IEEE® 9-bus [15]:

Table (1) Parameters of the IEEE® 9-bus model.		
Machines	**S.M-1**	**247.5 MVA**
	S.M-2	**192 MVA**
	S.M-3	**128 MVA**
Transformers	**Trans.-1**	**Prim 16.50 to Sec. 230.0 KV**
	Trans.-2	**Prim 18.00 to Sec. 230.0 KV**
	Trans.-3	**Prim 13.80 to Sec. 230.0 KV**
Loads	**L_1**	**125.0 MW and 50.0 MVAR**
	L_2	**90.0 MW and 30.0 MVAR**
	L_3	**100.0 MW and 35.0 MVAR**

6. SIMULATION RESULTS AND DISCUSSION

The results of the present study were plotted according to the European distribution system (fig. 7).

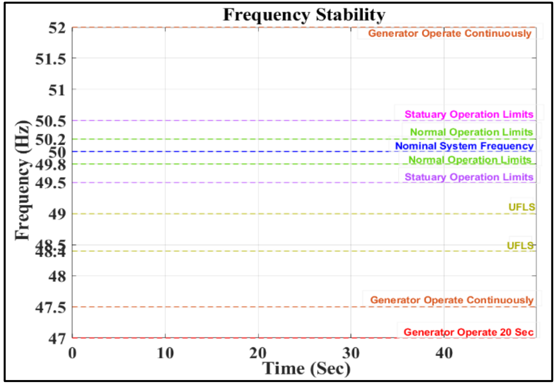

Fig. 7 European distribution system limits in MATLAB®.

The simulations were conducted in three cases:

6.1 Steady State

The results were obtained by operating a standard power system in a steady state. Therefore, the frequency was constant and in a normal state (fig. 8).

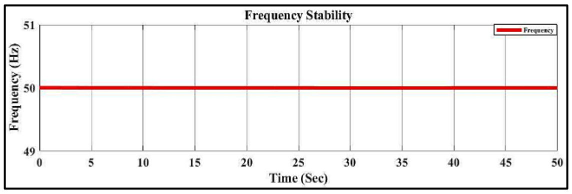

Fig. 8 System frequency in a steady state.

6.2 Battery Energy Storage System (BESS)

The electrical power system was equipped with a 25 MW PV system and a 50 MW-capacity

BESS at bus 5. The simulation was conducted in 50 seconds, where a sudden load increase occurs at bus 5. The load increased to 50 MW (total load increased by 15.87%), causing the frequency to decrease by 49.7183 Hz in 9.0606 seconds when a BESS was not used. When BESS was used with PFC and VIR controls, the frequency increased and stabilized at 49.967 Hz (99.934% of 50 Hz) in 16.7781 seconds and remained stable at 22 seconds (fig. 9).

After the 22-second mark, the BESS finished discharging and started charging, which made it behave like a load. The charging state of the BESS was 11.2% and its discharge limit was between 8 - 11%. When it began discharging, it decreased from 11.2% to 11%. The BESS started charging at 5 MW (fig. 10 and 11). As seen in Figure 10, the power of the BESS was negative; -5 MW; which means that it was charging. This affects the frequency and decreases it to 49.9284 Hz in 24.189 seconds, stabilizing it at 49.9554 Hz (99.9108% of 50 Hz) in 48.9824 seconds (fig. 9). This stability was due to the high speed at which the generators were able to compensate for the charging state of the BESS (fig. 12).

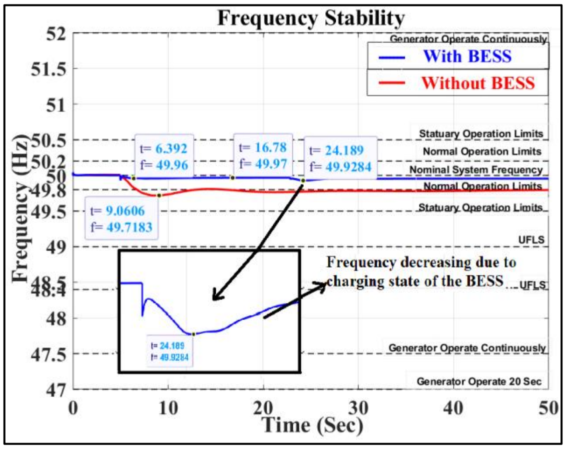

Fig. 9 The frequency stability of a power system with and without a BESS and the charging and discharging states of a BESS.

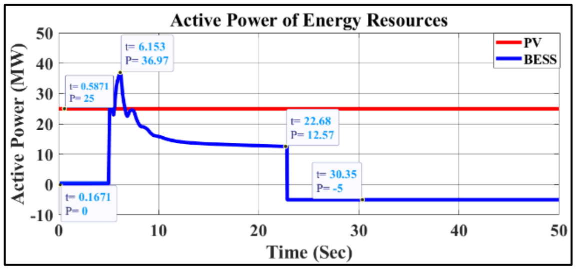

Fig. 10 A PV system and a BESS during charging and discharging states.

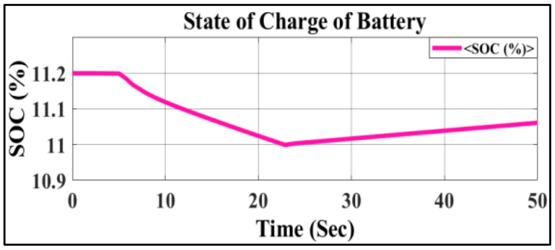

Fig. 11 The charging and discharging states of a BESS.

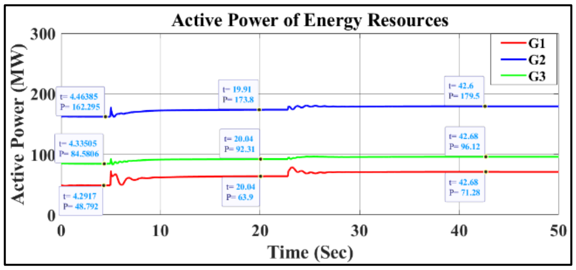

Fig. 12 The capacity of each generator of a BESS during charging and discharging states.

6.3 Underfrequency Load-Shedding (UFLS)

The simulation was conducted for 100 seconds, where a generation loss of 163 MW (51.74% from total load) occurs at the 5-second mark. This caused the frequency to decrease to 49.2416 Hz in 29.8269 seconds, thereby causing the loads to continuously trip, as it attempts to return the frequency to its normal state.

The loads were tripped in three stages. In the first stage, a 10 MW-load (3.17% from total load) was tripped at 12.23 seconds at a frequency of 49.5 Hz. However, the frequency continued to decrease to 49.4 Hz at the 18.5-second mark. This triggered the second tripping stage. In the second stage, a 30 MW-load (9.52% from total load) was tripped at the 18.5-second mark at a frequency of 49.4 Hz. This caused the frequency to increase and settle at 49.42 Hz by the 42.21 second. This triggered the third tripping stage, where a 90 MW-load (28.57% from total load) was tripped. The frequency began to increase until it settled at a normal frequency limit of 49.82 Hz at 59.91 seconds (Fig. 13). As seen in Fig. 14, the tripping duration of the first stage was 0.1868 seconds, the second was 0.1708 seconds, and the third was 29.98 seconds.

Table (2) depicts the frequency stability and tripping durations of the three stages.

Table (2) Frequency stability and tripping durations of the three stages.

Relay	Tripping Load MW	Tripping Time sec	Frequency Stability Hz	Time Stability Sec
First Relay	10 (3.17% from total load)	0.1868	49.4 (98.80% of 50 Hz)	18.67
Second Relay	30 (9.52% from total load)	0.1708	49.42 (98.84% of 50 Hz)	42.21
Third Relay	90 (28.57% from total load)	29.98	49.82 (99.64% of 50 Hz)	59.91

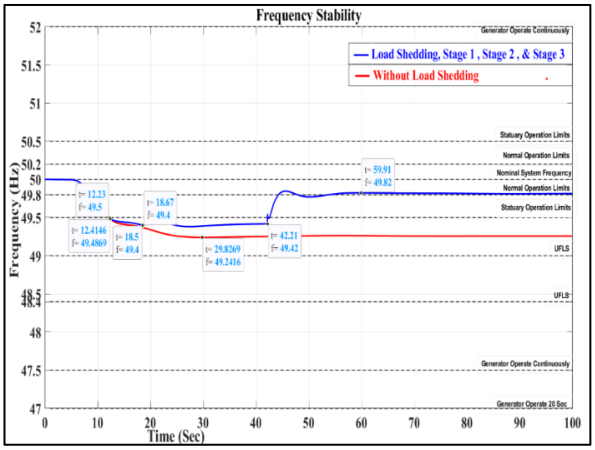

Fig. 13 The frequency stability of the power system when the loads were tripping in the three stages.

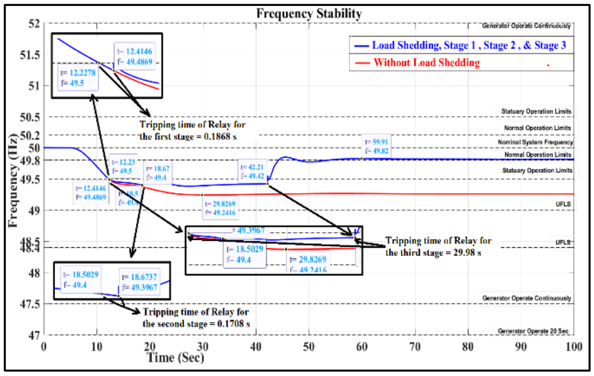

Fig. 14 The tripping time of each stage.

7. CONCLUSION

Frequency stability monitoring and control are integral in power systems, as they keep the frequency within a standard range and prevent frequency instability due to faults and load increases. The present study used MATLAB® to simulate and analyze a standard IEEE® 9-bus power system, where its frequency was measured in the steady state. A solar PV system and a BESS were used and connected to the proposed system. The frequency was found to decrease when the load increased suddenly. Therefore, the frequency improved when a BESS control was used to compensate for power increases as the loads absorbed increased. The results indicate that a improve effectively and keeps nearly constant the frequency of the power systems, i.e. increasing the margin of the frequency stability. The BESS was also found to decrease the frequency in the event of generator power loss. Furthermore, UFLS was found to improve frequency stability. So, the proposed method must also be used, in case of load increasing or generation loss, to more effectively improving the frequency stability.

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استخدام أنظمة الطاقة الشمسية الكهروضوئية، أنظمة تخزين طاقة البطاريات، وفصل الأحمال للتردد المنخفض لتحسين استقرارية التردد لمنظومات القدرة الكهربائية

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الملخص

تعمل منظومات القدرة الكهربائية عند تردد 50 هرتز. ومع ذلك، يتسبب فقدان التوليد، أو الزيادة المفاجئة في الأحمال، أو حدوث أعطال في المنظومة الى حدوث اضطرابات وانحرافات تزعزع استقرارية منظومات القدرة الكهربائية. لذلك، هناك حاجة لدراسة وتحسين استقرارية التردد لمنظومات القدرة الكهربائية أثناء الاضطرابات. درس هذا البحث تحسين ثبات التردد لمنظومة القدرة الكهربائية باستخدام نظام الطاقة الشمسية الكهروضوئية (PV)، ونظام تخزين طاقة البطارية (BESS)، وفصل الحمل للتردد المنخفض (UFLS) لتخمين التردد والتحكم فيه. تم اختبار الطريقة المقترحة على منظومة تتكون من 9 عقد قياسية (IEEE 9 - Bus®) والذي تمت محاكاته باستخدام برنامج MATLAB® Simulink. تشير نتائج المحاكاة إلى أن الطريقة المقترحة تعمل بشكل كبير على تحسين استقرارية تردد منظومة القدرة الكهربائية.

الكلمات الدالة:
استقرارية التردد؛ مصادر طاقة؛ PV؛ PFC؛ IR؛ UFLS؛ BESS.