

Evaluation of Staged Under Frequency Load Shedding Strategy for Generator Trip Events at Arun Substation Using DIgSILENT Powerfactory

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ABSTRAK

Stabilitas frekuensi merupakan indikator utama keandalan sistem tenaga listrik karena gangguan seperti kehilangan pembangkitan dapat menyebabkan penurunan frekuensi cepat dan berpotensi menimbulkan blackout. Penelitian ini mengevaluasi efektivitas skema pelepasan beban menggunakan Under Frequency Relay (UFR) di Gardu Induk Arun melalui simulasi dinamis DIgSILENT PowerFactory. Skenario yang diuji adalah kehilangan pembangkitan secara tiba-tiba dengan perbandingan kondisi tanpa dan dengan UFR. Hasil menunjukkan bahwa tanpa UFR, kehilangan daya 48,421 MW menyebabkan frekuensi turun di bawah 42 Hz dalam kurang dari 16 detik dan berujung pada kegagalan sistem. Dengan UFR dua tahap (27,6 MW pada 49,5 Hz dan 28,4 MW pada 49,2 Hz), penurunan frekuensi dapat dihentikan dan sistem kembali stabil pada 50,12 Hz dalam sekitar 3 detik. Dengan demikian, UFR efektif menjaga stabilitas sistem.

Kata kunci: *Under Frequency Relay, Pelepasan Beban, Stabilitas Frekuensi, DIgSILENT PowerFactory, Gardu Induk*

ABSTRACT

Frequency stability is a key indicator of power system reliability, as disturbances such as generation loss can cause rapid frequency decline and potentially lead to a blackout. This study evaluates the effectiveness of a load shedding scheme using an Under Frequency Relay (UFR) at the Arun Substation through dynamic simulation in DIgSILENT PowerFactory. The scenario involves a sudden loss of generation, comparing conditions without and with UFR. Results show that without UFR, a 48.421 MW power loss causes the frequency to drop below 42 Hz in less than 16 seconds, leading to system failure. With a two-stage UFR scheme (27.6 MW at 49.5 Hz and 28.4 MW at 49.2 Hz), the frequency decline is arrested and the system stabilizes at 50.12 Hz within about 3 seconds. Thus, the UFR scheme is effective in maintaining system stability.

Keywords: *Under Frequency Relay, Load Shedding, Frequency Stability, DIgSILENT PowerFactory, Substation*

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1. INTRODUCTION

Frequency stability is a critical aspect of power system reliability, as any deviation from the nominal value may disrupt the balance between generation and demand. A frequency decline typically occurs due to sudden generator outages, imbalance between load and supply, or severe short-circuit disturbances (**Abdurrohim et al., 2024**). If not addressed promptly, such disturbances may escalate into cascading failures that can eventually cause a total blackout, resulting in significant economic and social losses (**Chandra & Pradhan, 2021**). Therefore, the implementation of effective control and protection schemes is essential to maintain system stability under abnormal conditions (**Hatziargyriou et al., 2021**).

One widely adopted protection strategy is the automatic load shedding scheme using an Under Frequency Relay (UFR) (**Hong & Nguyen, 2020**). This device continuously monitors the system frequency and disconnects selected loads in stages whenever the frequency drops below a predefined threshold. According to ANSI/IEEE C37.106-2003, the under-frequency threshold is typically set at 49.5 Hz or lower in a 50 Hz system (**Jaya et al., 2023**). The staged shedding approach ensures that only the necessary amount of load is disconnected, thereby restoring the generation–demand balance without excessively reducing service to consumers (**Meunasah, 2024**).

The application of UFR presents several notable advantages. It provides an automatic and fast response to under-frequency events, reducing reliance on operator intervention (**Rafsanjani & Diantari, 2019**). It also allows staged and selective load shedding, which minimizes unnecessary disconnection and prioritizes critical loads (**Sartika et al., 2019**), (**Sitorus et al., 2022**). Furthermore, UFR can prevent further system collapse by acting within milliseconds of a disturbance. Nevertheless, UFR also has inherent limitations. Improper relay settings may result in excessive load disconnection, thereby causing unnecessary service interruptions (**Rafsanjani & Diantari, 2019**). Regular testing and calibration are required to ensure its reliability. Additionally, UFR may react to minor transient frequency dips if the time delay is not properly configured, potentially leading to false tripping (**Siyanda Mnguni, 2020**).

In contrast, conventional manual load shedding methods are considerably less effective. They rely heavily on operator judgment, which introduces delays in execution and increases the probability of error, particularly during large-scale disturbances. Manual methods also lack systematic prioritization of loads, making them less efficient in protecting critical facilities such as hospitals, control centers, and government institutions (**Abdurrohim et al., 2024**). As a result, systems that rely solely on manual interventions are more vulnerable to widespread blackouts (**Jaya et al., 2023**).

Although numerous studies have investigated Under Frequency Load Shedding (UFLS) schemes, most research focuses on generalized system models and does not fully consider site-specific operational characteristics, relay coordination, and actual load distribution. In particular, limited studies have addressed the implementation and performance evaluation of staged UFLS schemes using real operational data at the Arun Substation under large generation loss scenarios. This gap highlights the need for a comprehensive investigation that integrates realistic system modeling with dynamic simulation to ensure reliable UFLS performance in practical applications.

This research contributes novelty by presenting a realistic evaluation of a staged UFLS scheme based on actual operational data from the Arun Substation and detailed dynamic

simulation using DIgSILENT PowerFactory. The study not only demonstrates the effectiveness of UFR in preventing system collapse due to large generation loss but also provides quantitative evidence of its impact on frequency recovery time and stability performance. Moreover, it offers a practical reference for determining optimal relay settings, including frequency thresholds, time delays, and staged load shedding capacity, in accordance with ANSI/IEEE C37.106-2003.

Therefore, the specific objectives of this research are to analyze the frequency response following generator outage conditions, to compare system performance with and without the implementation of UFR-based load shedding, and to determine optimal relay parameter settings capable of maintaining frequency stability and preventing blackout events. By addressing these objectives, this study aims to bridge the gap between theoretical UFLS design and real-world implementation, supporting the development of more reliable and resilient power systems.

1.1 Electric Power System

The electric power system is an interconnected network that delivers electrical energy from generation sources to end-users. Conceptually, a system is a unified structure composed of multiple inter-connected components working together to facilitate the flow of energy, materials, or information toward a common objective (**Hasibuan et al., 2022**). Accordingly, a power system comprises generation units, transmission lines, substations, and distribution networks, all operating in coordination to meet consumer electricity demands (**Kurniawan et al., 2023**). Generation units convert primary energy sources such as hydro, coal, geothermal, or petroleum into electrical energy through turbines driving generators. Transmission lines transport bulk electrical power from generating plants to load-center substations or between substations. Substations regulate power flow and adjust voltage levels through switchgear and transformers positioned between transmission networks and distribution systems (**Idriana et al., 2021**). Distribution networks deliver electrical power from load-center substations directly to consumers (**Imran et al., 2019**).

1.2 Under Frequency Load Shedding

Under Frequency Load Shedding (UFLS) is a protective scheme that automatically disconnects selected loads when system frequency falls below a set threshold due to an imbalance between generation and demand (**Hong & Nguyen, 2020**). By shedding load in one or more stages, UFLS helps restore the generation-load balance, halt further frequency decline, and prevent system collapse. Effective UFLS design requires proper setting of trigger frequencies, time delays, and load amounts, in accordance with standards such as ANSI/IEEE C37.106-2003, to ensure reliable operation with minimal impact on consumers.

Frequency stability refers to the ability of a power system to maintain a steady operating frequency following a disturbance. In an interconnected network, generation must continuously match load demand; a generation deficit causes frequency to drop, while excess generation causes it to rise (**Hatziargyriou et al., 2021**). Large frequency declines often result from the sudden loss of a major generating unit or severe short-circuit faults. Minor deviations can be corrected automatically through governor control, but significant overload conditions may require load shedding to restore frequency (**Dicky, 2018**). The rate of frequency decline is influenced by generator capacity, generator response, load demand, and the system inertia constant. The frequency decrease rate can be expressed as Equation (1), which relates the imbalance between load demand and generation supply to the system inertia and nominal frequency. This relationship indicates that a larger power deficit or lower inertia constant results in a faster frequency decline following a disturbance.

$$\frac{df}{dt} = \left(\frac{P_A}{2GH} \right) f_0 \quad (1)$$

where $\frac{df}{dt}$ is frequency decrease rate (Hz/s), P_A is difference between load demand and generator supply (MW), H is Inertia Constant (MJ/MVA), G is rating MVA generator (MVA), and f_0 is nominal frequency (Hz).

1.3 Under Frequency Relay

This relay protects the system when frequency drops below the allowable limit. In addition to monitoring frequency changes, it initiates partial load shedding in response to frequency decline and serves as the primary device for implementing the load shedding scheme (**Bekhradian et al., 2023**). The dynamic response of the Under Frequency Relay (UFR) is characterized by its pickup and tripping intervals. As expressed in Equation (2), the pickup time depends on the frequency deviation and the rate of change of frequency, indicating that a faster frequency decline results in a shorter relay activation time. Meanwhile, Equation (3) defines the total tripping time as the sum of pickup time, circuit breaker operating time, and relay processing delay, which determines the overall response speed of the load shedding mechanism (**Rajagukguk et al., 2024**).

$$t_{pick-up} = \frac{f_0 - f_1}{\frac{df}{dt}} \quad (2)$$

$$t_{trip} = t_{pick-up} + t_{cb} + t_{relay} \quad (3)$$

where df/dt is frequency decrease rate (Hz/s), $t_{pick-up}$ is time from the moment before frequency drops until the relay operates (s), t_{trip} is time from the moment before frequency drops until the circuit breaker fully operates (s), t_{cb} is circuit breaker opening time (s), t_{relay} is frequency relay operation time (s), f_1 is load shedding reference frequency (Hz), and f_0 is nominal frequency (Hz).

The estimated frequency at the moment of load shedding activation can be calculated using Equation (4). This equation relates the nominal frequency, the rate of frequency decline, and the total relay tripping time to determine the frequency level at which load shedding is executed. The formulation indicates that a higher rate of frequency decrease or a longer tripping time results in a lower load shedding frequency, highlighting the importance of fast relay operation in preventing excessive frequency deviation.

$$f_{loadshedding} = f_0 - \left(\frac{df}{dt} \right) t_{trip} \quad (4)$$

where $f_{loadshedding}$ is frequency at load shedding (Hz), t_{trip} is time from the moment before frequency drops until the circuit breaker fully operates (s), and f_0 is nominal frequency (Hz). The frequency relay setting based on formula, as shown in the following Table 1.

Table 1. Relay Setting for Simulation

Parameter	Value
df/dt	3.43 Hz/s
$t_{pick-up}$	0.145 s
t_{cb}	0.05 s
t_{relay}	0.06 s
t_{trip}	0.255 s
$f_{loadshedding}$	49.2 Hz

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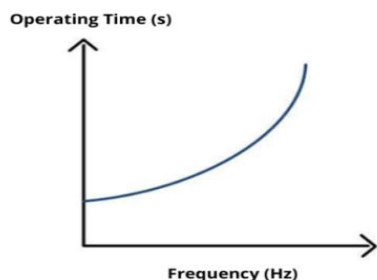


Figure 1. Characteristic Curve of UFR

The frequency relay operates based on its characteristic curve, as shown in the following Figure 1. This curve illustrates the relationship between the frequency deviation and the relay operating time, where a greater frequency drop results in a faster relay response. Conversely, when the system frequency is closer to the nominal value, the relay requires a longer delay time before triggering the load shedding process.

2. METHOD

2.1 Method of Simulation

In conducting this research, a systematic approach was applied to ensure that each stage of the study was carried out in a structured and coherent manner. The research process was divided into several sequential steps, starting from literature review and problem identification to data collection, system modeling, simulation, and analysis. These stages were designed to maintain the logical flow of the research and to ensure that the simulation results accurately reflect the real operating conditions of the Arun Substation. The overall methodology is illustrated in the research flowchart, as shown in Figure 2. This diagram illustrates the step-by-step process, starting from literature review to the final conclusion stage.

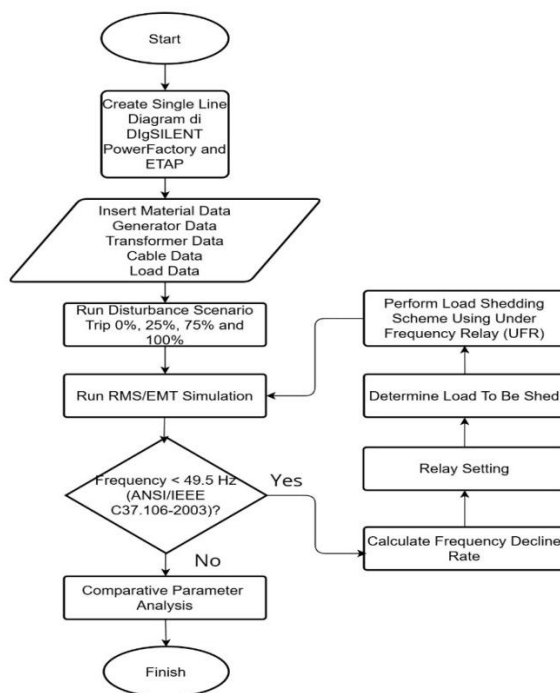


Figure 2. Flowchart of Simulation

The research process began with a literature review on Under Frequency Relay (UFR), load shedding strategies, and frequency stability standards. This step aimed to establish a strong theoretical foundation and identify the gap between existing research and practical implementation at Arun Substation. Following this, a problem identification stage was performed, focusing on the issue of frequency instability caused by sudden loss of generation.

Next, technical data collection was carried out, which included detailed generator parameters (rated capacity, operating output, voltage, power factor, and inertia constant), transformer specifications (voltage levels, MVA ratings, and impedance), transmission line data (length, impedance, and MVAR values), and distribution feeder loads during peak demand conditions. These data were essential for accurate representation of the actual substation network.

The system modeling stage was performed using DIgSILENT PowerFactory by creating a single line diagram of the Arun Substation that replicated the actual configuration. All relevant parameters were then input into the model, including busbar voltages, generator dynamic models, transformer ratings, cable specifications, load characteristics, and protection device settings.

The simulation scenarios were designed to represent both normal and disturbance conditions. Three main scenarios were tested:

1. normal operation without any disturbances,
2. sudden loss of generation without UFR installed, and
3. sudden loss of generation with UFR load shedding applied.

Dynamic simulations were conducted using RMS/EMT analysis mode in DIgSILENT PowerFactory to capture the frequency response over time. The disturbance event was modeled as a sudden disconnection of multiple generation units equivalent to a 48.421 MW loss. Frequency recovery performance, recovery time, and total load shed were recorded for analysis.

Finally, data analysis involved comparing the frequency profile and system stability between scenarios with and without UFR. The results were interpreted to evaluate the effectiveness of the UFR scheme in preventing system collapse and maintaining supply to priority consumers.

2.2 Initial Data and Simulation Model

The research data utilized in this study were obtained from PT PLN (Persero) Arun Substation, covering operational and technical parameters essential for accurate system modeling. The dataset includes the single line diagram, generator capacities, transformer specifications, feeder load profiles, and transmission load measurements recorded during peak operating conditions. These data were collected through direct field measurements and coordination with substation operational records, ensuring that the information used in this study reflects the actual conditions of the network with a high level of reliability and accuracy.

In addition to these primary datasets, supporting parameters such as generator inertia constants, circuit breaker operating times, and protection relay characteristics were also considered. Incorporating these details into the model enhances the fidelity of the simulation, allowing the replication of not only steady-state behavior but also the dynamic response of the system under disturbances. Such a comprehensive dataset is crucial for achieving realistic simulations and ensuring that the test scenarios represent plausible operating conditions faced by the substation.

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The acquired dataset serves as the foundation for constructing the simulation model in DIgSILENT PowerFactory, enabling the replication of the substation's actual performance under various disturbance scenarios. By integrating authentic field data, the simulation outcomes are expected to provide a realistic assessment of the performance and effectiveness of the Under Frequency Load Shedding (UFLS) scheme in maintaining frequency stability, in line with ANSI/IEEE C37.106-2003 guidelines. Furthermore, the use of real system parameters strengthens the credibility of the findings and provides practical insights for utility operators to optimize relay settings, enhance system resilience, and minimize the risk of widespread blackouts.

Figure 3 illustrates the single line diagram (SLD) of the configuration of the Arun Substation part simulated in this study. It is depicting the interconnection between generation units, transformers, transmission lines, and distribution feeders. In addition to the actual single line diagram of the Arun Substation, a simulation-based single line diagram was created in DIgSILENT PowerFactory to model and analyze the system performance. This diagram replicates the real substation configuration but is adapted into the simulation environment, ensuring that generator units, transformers, buses, feeders, and protection devices are accurately represented.

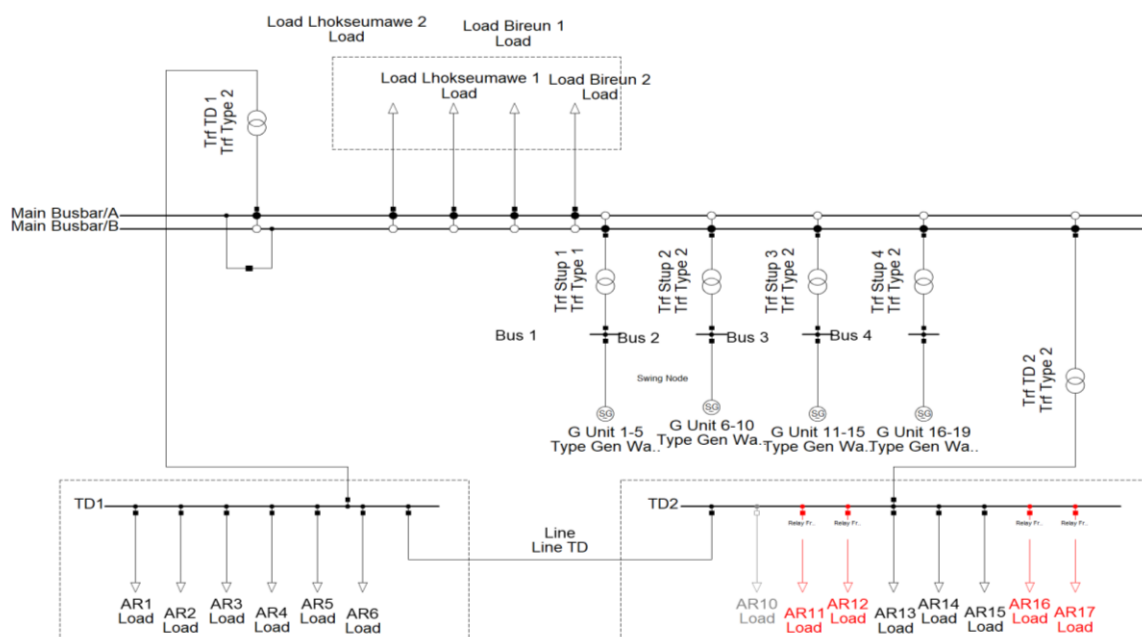


Figure 3. Simulation Model

As shown in Figure 3, the simulation model integrates technical parameters such as generator ratings, transformer capacities, transmission line impedances, and feeder load profiles. The Under Frequency Relay (UFR) scheme is embedded at strategic points in the system to enable staged automatic load shedding. By constructing this single line diagram in PowerFactory, it becomes possible to reproduce the system's dynamic response under different disturbance scenarios, such as sudden generator outages, and to evaluate the effectiveness of the UFR settings in maintaining frequency stability.

The generator rating data provide essential information regarding the operational capacity and performance limits of each generating unit within the Arun Substation network. Accurate generator rating data ensure that the simulation reflects real operating conditions, enabling precise evaluation of the Under Frequency Load Shedding (UFLS) scheme's effectiveness

under various disturbance scenarios. The detailed generator specifications used in this study are presented in Table 2.

Table 2. Generator Rating Data

Generators	S Gen (MVA)	P Gen (MW)	Voltage (kV)
Unit 1-5	60	48.421	11
Unit 6-10	60	48.421	11
Unit 11-15	60	48.421	11
Unit 15-19	60	38.736	11

Feeder load data provide information on the distribution of electrical load across different feeders connected to the substation. This dataset, measured during peak operating hours, is crucial for defining the load distribution and assessing the system's response to disturbances. The feeder load profile serves as an input for determining the optimal Under Frequency Load Shedding (UFLS) settings. The complete feeder load data are presented in Table 3.

Table 3. Feeder Load

Feeder	Group	Load R (kVA)	Load S (kVA)	Load T (kVA)	Total
AR1	TD1	733.59	714.78	695.97	2,144.34
AR2	TD1	3,348.18	3,329.37	3,310.56	9,988.11
AR3	TD1	470.25	451.44	470.25	1,391.94
AR4	TD1	2,144.34	2,163.15	2,144.34	6,451.83
AR5	TD1	643.302	658.35	695.97	1,997.622
AR6	TD1	677.16	658.35	658.35	1,993.86
AR11	TD2	1,151.59	1,151.59	1,151.59	3,454.77
AR12	TD2	2,680.425	2,720.135	2,680.425	8,080.99
AR13	TD2	2,978.25	2,998.105	2,978.25	8,954.61
AR14	TD2	6,504.9	6,504.9	6,504.9	19,514.8
AR15	TD2	1,886.225	1,866.37	1,886.225	5,638.82
AR16	TD2	6,416.7	6,416.7	6,416.7	18,440.1
AR17	TD2	5,928.26	5,928.26	5,928.26	17,784.78
Total					106,646.472

Transmission load data represent the amount of power transferred from the substation to the transmission network during peak conditions. This dataset is vital for understanding the substation's role in supplying regional demand and for evaluating the stability margin during generation loss events. Accurate transmission load data allow for realistic simulation of system performance under stress conditions. The transmission load values utilized in this study are provided in Table 4.

Table 4. Transmission Load

Line	MW	MVAR
PHT 150 kV LHOKSEUMAWE 1	27.6	6.5
PHT 150 kV LHOKSEUMAWE 2	28.4	6.9
PHT 150 kV BIREUN 1	9.7	-1.6
PHT 150 kV BIREUN 2	9.4	-1.5
Total	75.1	10.3

3. RESULT AND DISCUSSION

3.1 Test Results Under Normal Conditions

The simulation results under normal system conditions show that generation and load are balanced, with a total active power of 184 MW. This power consists of 181.1 MW used to meet load consumption and approximately 1.2 MW lost as system losses, as presented in Table 5.

Table 5. System Condition During Normal Operation

No	Description	Power Supply (MW)	Power Consumption (MW)	Total Power (MW)
1	Power Generation Supply	184		184
2	Transmission Load		75.1	183.5
3	Distribution Load		106.6	
4	System Losses		1.8	
System Condition				Balanced

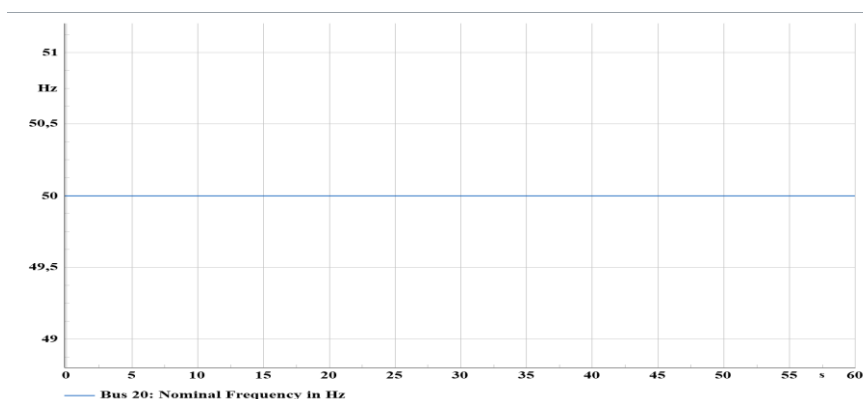


Figure 4. Frequency Condition During Normal Operation

Based on the simulation results under normal system conditions shown in Figure 4, it can be observed that the generated power is balanced with the power supplied to the load, resulting in a system frequency stable at 50 Hz.

3.2 Test Results of Generator Unit 1, 2, 3, 4, and 5 Tripping Before the Installation of UFR

The simulation results during the trip of PLTMG Arun Units 1–5 showed that the lost generation reached 48.421 MW, leaving only 135.579 MW of available generation. Meanwhile, the system load remained at 184 MW, consisting of 174.058 MW for the load and approximately 1.2 MW for power losses, as shown in Table 6.

Table 6. System Condition During Disturbance Without UFLS

No	Description	Power Supply (MW)	Power Consumption (MW)	Total Power (MW)
1	Generation Supply	184		135.579
2	Trip of Units 1–5	-48.421		
3	Transmission Load		75.1	183.5
4	Distribution Load		106.6	
5	System Losses		1.8	
System Condition				Unbalanced System

After testing the system under normal conditions and ensuring that the system parameters match the existing conditions, the next step is testing the trip of PLTMG Arun Units 1–5, in which the system experiences a loss of supply amounting to 48.421 MW.

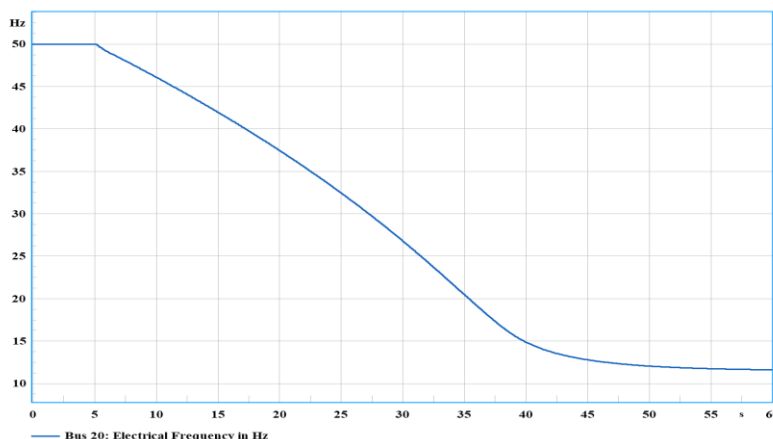


Figure 5. Frequency Condition During Generator Outage Without UFLS

In Figure 5, it can be seen that when the system loses a supply of 48.421 MW at the 5th second, without the use of a UFR relay, the frequency drops to its lowest point of 11.61 Hz. This occurs because no load shedding is applied, causing the system to become unbalanced and eventually collapse, as the system load exceeds the generation capacity and the generators are unable to restore system balance.

3.3 Test Results of Generator Trip for Units 1, 2, 3, 4, and 5 with Installed UFR

The UFLS scheme operated up to Stage 2, as the frequency returned to a safe range after shedding 27.6 MW in Stage 1 and 28.4 MW in Stage 2, eliminating the need for unnecessary load shedding. The load shedding process occurred in stages, starting from the 5th second to the 8th second after the generator trip disturbance at the 5th second. Subsequently, the frequency gradually increased to the safe range and stabilized at 50.12 Hz. This value complies with the ANSI/IEEE C37.106-2003 standard, which specifies an under frequency limit of 50.5-49.5 Hz. Table 7 presents the system conditions during load shedding with the UFR scheme applied.

Table 7. System Condition During Disturbance With UFLS

No	Description	Power Supply (MW)	Power Consumption (MW)	Total Power (MW)
1	Power Generation Supply	184.00		135.579
2	Trip of Generator Units 1–5	-48.421		
3	Transmission Load		75.1	127.5
4	Distribution Load		106.6	
5	System Losses		1.8	
6	Load Shedding		-56.00	
System Frequency				50.12 Hz

Based on the estimated frequency at the moment the circuit breaker fully operates, this value is used as a reference to determine the second and subsequent load shedding stages.

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The first stage of load shedding is set when the system frequency drops to 49.5 Hz. Since the estimated frequency obtained is 49.2 Hz, the load shedding scheme is determined to consist of two stages. The details are presented in Table 8.

Table 8. UFR Trip Stage Sequence

Release Stage	Frequency Settings (Hz)	Load Released (MW)	Load
1	49,5	27.6	AR11, AR17
2	49,2	28.4	AR12, AR16
Total		56	

Figure 6 shows the action list from the simulation under the condition where the UFR is installed in the system.

Name	Time	Object	Out of Service	Object modified
Switch Event	5,	G 01	<input type="checkbox"/>	06/08/2025 03:57:39
Switch Event(1)	5,971667	Switch Lhokseumawe 2	<input type="checkbox"/>	11/08/2025 22:07:00
Switch Event(2)	6,113333	Switch Lhokseumawe 1	<input type="checkbox"/>	11/08/2025 22:07:00

Figure 6. Action List Load Shedding

After testing the trip of PLTMG Arun Units 1–5 without UFLS, in which the system experiences a loss of supply amounting to 48.421 MW, the next step is testing the trip of PLTMG Arun Units 1–5, with UFLS.

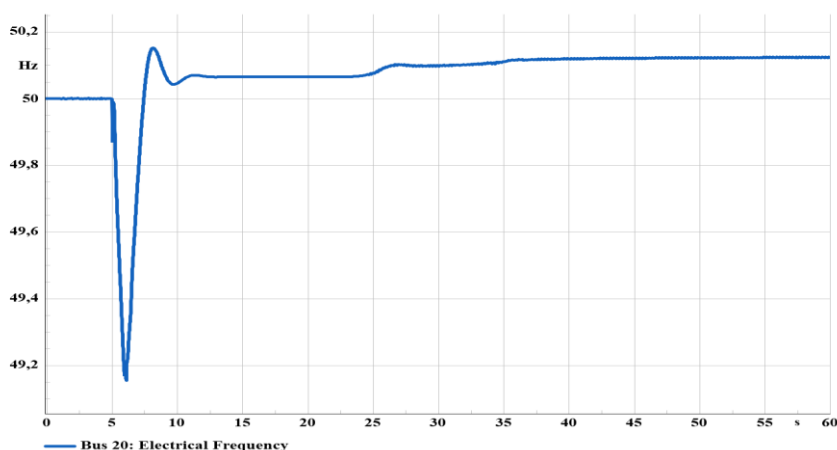


Figure 7. Frequency Condition During Generator Outage With UFLS

As shown in Figure 7, the frequency response during the generator trip of Units 1–5 with the installed Under Frequency Relay (UFR) demonstrates a stable recovery behavior following the disturbance. At approximately the 5th second, the generator outage causes an immediate frequency drop from the nominal value of 50 Hz to around 49.16 Hz due to the sudden loss of 48.421 MW generation. However, the UFR scheme activates staged load shedding, where the first stage is triggered at 49.5 Hz and the second stage at 49.2 Hz, resulting in a total released load of 56 MW. This corrective action successfully halts the frequency decline and restores the generation load balance. Subsequently, the frequency exhibits a transient overshoot reaching approximately 50.15 Hz before gradually settling to a

steady state value of about 50.12 Hz within a few seconds. The observed response confirms that the implemented UFR scheme effectively mitigates the disturbance impact, prevents system collapse, and maintains frequency stability within the acceptable operating limits specified by ANSI/IEEE C37.106-2003.

3.4 Comparison Results Before and After Load Shedding

Based on the simulation results shown in Table 9, a significant difference can be observed between the system condition without load shedding and with load shedding using the UFR.

Table 9. Comparison Before and After Under Frequency Load Shedding

Time (s)	Before Load Shedding	After Load Shedding
1	50	50
2	50	50
3	50	50
4	50	50
5	50	50
5.98	49.14	49.19
6.98	48.41	49.73
7.98	47.66	50.14
8.98	46.89	50.08
9.98	46.11	50.04
10.98	45.31	50.07
11.98	44.5	50.07
12.98	43.67	50.06
13.98	42.84	50.07
14.98	41.99	50.07
15.98	41.12	50.07

The comparison graph between before and after removing the load can be seen in Figure 8 here below:

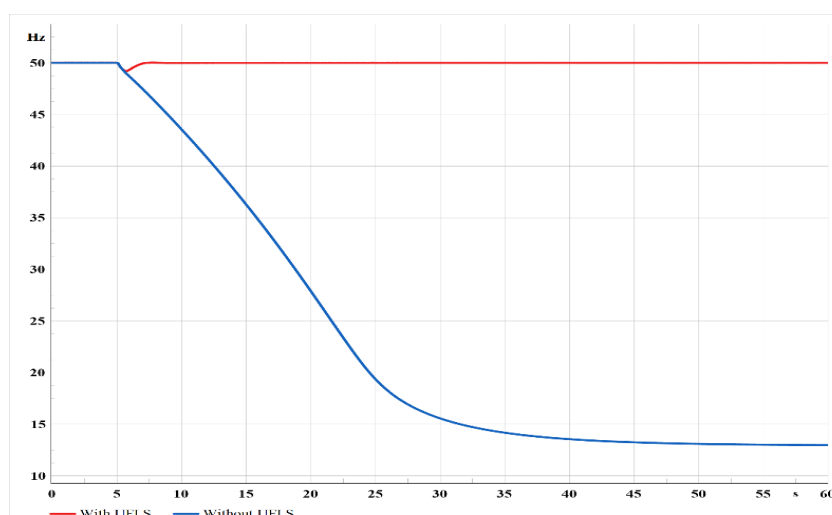


Figure 8. Frequency Comparison Before and After UFLS

In the condition without load shedding, the system frequency experienced a drastic drop immediately after the disturbance. Starting at the 5th second, the frequency decreased from 50 Hz to 49.14 Hz at 5.98 seconds, and continued to decline rapidly, reaching 41.12 Hz at

15.98 seconds, ultimately causing the system to collapse. This decline indicates an imbalance between generated power and load demand, rendering the system unable to maintain frequency stability.

Conversely, under the condition with load shedding controlled by the Under Frequency Relay (UFR), the system frequency remained stable in the range of 50.07–50.08 Hz despite the disturbance. This demonstrates that staged and planned load shedding can restore the power balance in the system, thereby preventing frequency decline.

This comparison indicates that load shedding strategies play a crucial role in preventing significant frequency drops, maintaining power system stability, and avoiding potential total blackouts. The coordinated implementation of UFR has been proven to provide a rapid response to frequency decline, maintaining the system frequency within the safe limit specified by ANSI/IEEE C37.106-2003, which is no less than 49.5 Hz.

The simulation results demonstrate several advantages of the proposed staged Under Frequency Load Shedding (UFLS) scheme compared to conventional approaches reported in previous studies. First, this research employs actual operational data from the Arun Substation, enabling a more realistic representation of system behavior during large generation loss events. Second, the dynamic simulation provides quantitative evaluation of frequency recovery performance, showing that the implemented UFR scheme successfully arrests frequency decline and restores system stability within a short time frame. Third, the study presents coordinated relay parameter settings, including frequency thresholds, pickup delays, and staged load shedding capacity, which ensure optimal balance between frequency stabilization and service continuity.

Compared to earlier studies that mainly focus on generic UFLS design, this work offers a comprehensive assessment that integrates real system modeling, staged load shedding strategy, and disturbance-based performance evaluation. The results confirm that the proposed scheme not only prevents system collapse but also minimizes unnecessary load disconnection while maintaining frequency within acceptable operating limits. Therefore, the findings provide practical technical guidance for utility operators in determining optimal UFR settings and enhancing power system resilience against sudden generation outages.

4. CONCLUSION

This study presented a comprehensive dynamic assessment of a staged Under Frequency Load Shedding (UFLS) scheme implemented through Under Frequency Relay (UFR) coordination at the Arun substation using the DIgSILENT PowerFactory platform. The investigation focused on evaluating system resilience under severe generation trip disturbances involving multiple generating units. Simulation results demonstrated that, in the absence of UFLS, a generation loss of 48.421 MW led to a rapid frequency collapse below 42 Hz within approximately 16 s, indicating a high probability of cascading outages and system blackout. Conversely, the proposed staged UFLS strategy effectively mitigated frequency deterioration, limiting the minimum frequency to 48.62 Hz and restoring system stability to 50.12 Hz within about 3 s. These results confirm the capability of the designed UFLS scheme to enhance transient frequency response, reduce recovery time, and prevent instability propagation. The main contribution of this work lies in the development of a coordinated UFLS configuration that integrates realistic generator dynamics, feeder load characteristics, and system inertia representation within a substation level study framework. Compared with conventional UFLS implementations reported in previous studies, the proposed approach

provides improved frequency containment performance and faster stabilization under multi unit generation outages.

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