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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

SYSTEM PROTECTION OF ISLAND POWER SYSTEM UNDER LARGE SHARES OF RES

Autor: Mónica Vadillo Díaz de Aguilar

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Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

System protection of island power system under large shares of RES

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Fdo.: Mónica Vadillo Díaz de Aguilar Fecha: 12/ 07/ 2022

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

L. Sigrist

Fdo.: Lukas Sigrist Fecha: 12/ 07/ 2022

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Acknowledgement

A mi familia y, en especial, a mi hermano que, a su manera, me ha ayudado durante estos cuatro años de carrera.

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Gracias.

PROTECCIÓN DEL SISTEMA ELÉCTRICO INSULAR CON GRAN PENETRACIÓN DE FUENTES DE ENERGÍA RENOVABLES

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RESUMEN

La creciente penetración de las fuentes de energía renovables afecta a la estabilidad y, en particular, a la estabilidad de frecuencia de los sistemas eléctricos insulares como el de las Islas Canarias. La protección del sistema conlleva, como último recurso, a deslastrar carga por subfrecuencia (UFLS). El objetivo de este proyecto es encontrar el ajuste adecuado de los parámetros del esquema UFLS basado en el margen de estabilidad y comparar su rendimiento con el sistema UFLS convencional. El nuevo modelo se implanta en el sistema de potencia de La Palma para evaluar su efectividad ante pérdidas de generación. Los resultados de este estudio demuestran que la implantación del margen de estabilidad de frecuencia en el esquema UFLS contribuye a mejorar significativamente la eficiencia de los relés de subfrecuencia. Se logra retrasar el deslastre para RoCoF moderados y reducir la carga deslastrada, al mismo tiempo que se preserva la estabilidad de la frecuencia. Asimismo, se presenta un análisis de la sensibilidad del nuevo esquema UFLS, donde se examina el efecto de adoptar un enfoque más conservador, el impacto de la participación de las FER en la generación y la respuesta en frecuencia ante pérdidas consecutivas de grupos generadores.

Palabras clave: Sistemas eléctricos aislados, estabilidad de frecuencia, deslastre de cargas por subfrecuencia.

1. Introducción

La estabilidad de la frecuencia constituye una preocupación importante en los pequeños sistemas eléctricos aislados. El carácter aislado de estos sistemas los hace especialmente sensibles a las perturbaciones. Las incidencias en la red son un evento muy frecuente en sistemas eléctricos pequeños como el de Canarias. Las principales características que dificultan su estabilidad son, en primer lugar, su baja inercia, ya que cuentan con un número reducido de generadores conectados al sistema, y, en segundo lugar, su falta de interconexión (Egido, et al., 2015). Ante un incidente, a diferencia de los sistemas continentales, no pueden ser apoyados por otros sistemas vecinos, y esto los hace más vulnerables a las contingencias. Este tipo de incidencias serán cada vez más complejas de gestionar con la creciente entrada de las renovables, dado que su carácter intermitente, su ausencia de inercia y su falta de contribución al control de frecuencia primario, intensificarán el problema señalado.

Si el control de frecuencia primario no es lo suficientemente rápido para restablecer el equilibrio de potencia y mantener la frecuencia dentro de unos valores aceptables, una práctica habitual, para proteger la estabilidad del sistema eléctrico, es el deslastre de cargas por subfrecuencia (UFLS). Los esquemas UFLS desconectan una cantidad de carga predefinida si la frecuencia y/o el RoCoF caen por debajo de un determinado umbral. Esta práctica reduce el tiempo de recuperación del sistema y el número de clientes afectados. Además, mejora la fiabilidad y la seguridad del sistema eléctrico. Existen varios enfoques y modelos de los esquemas UFLS, pero en todos los casos, un buen esquema UFLS debe ser rápido, sencillo y eficaz para evitar el riesgo de apagones del sistema (Sigrist, 2010). En general, los esquemas UFLS convencionales presentan un buen rendimiento, sin embargo, son bastante inflexibles. En ocasiones, en lugar de proporcionar una solución adecuada a las situaciones de subfrecuencia, crean un problema de sobrefrecuencia por exceso de carga deslastrada. Este problema resulta cada vez más relevante debido a la creciente penetración de la generación de energía desacoplada de la red.

Esta tendencia hacia un consumo energético más sostenible supone un gran reto para las Islas Canarias, ya que cuentan con sistemas eléctricos pequeños y poco mallados que son difíciles de interconectar debido a su geografía. Al tratarse de islas volcánicas, existe una gran profundidad marítima entre ellas, lo cual limita las posibles interconexiones entre islas. En particular, en las islas de La Palma y el Hierro no hay ninguna posibilidad de interconexión (Rodríguez, 2011). Por lo tanto, se verán muy afectadas por la intermitencia y la incertidumbre que introducen las renovables en la red. Para evitar que, en sistemas eléctricos pequeños, como el canario, se comprometa su integridad, se debe trabajar para que la estabilidad de la frecuencia se mantenga en todo momento. Por ello, este proyecto explora el impacto de la implementación de un novedoso esquema UFLS capaz de diferenciar entre situaciones severas y aquellas en las que el desprendimiento de carga puede ser retrasado o evitado.

2. Definición del Proyecto

El objetivo principal de este proyecto es implantar en sistemas de potencia pequeños un nuevo criterio de deslastre en el esquema UFLS actúa. Este permitirá reducir/retrasar la carga deslastrada, prevenir/reducir apagones del sistema eléctrico y conseguir un actuación óptima, robusta y eficiente de los sistemas eléctricos insulares aislados. De esta manera, se podrá prevenir que la integridad del sistema se vea comprometida con el aumento de la penetración de las renovables.

Para lograr estos objetivos, se ha adoptado la siguiente metodología:

- Implementación del nuevo criterio en el modelo UFLS. Para ello, se ha empleado la herramienta de Simulink.
- Ajuste adecuado del nuevo criterio a través escenarios de operación y contingencia (OyC) representativos.
- Comparación del nuevo esquema UFLS con el esquema UFLS convencional estático y semi-adaptativo actual y con una versión optimizada del mismo.
- Análisis de sensibilidad del nuevo esquema UFLS.

3. Modelado

3.1. Modelo del sistema de potencia

El sistema de potencia se ha representado a través del modelo mostrado en la Figura 1 y se ha implementado en Simulink, debido a que este modelo permite representar la frecuencia dinámica de pequeños sistemas eléctricos aislados en el corto plazo con suficiente precisión. El modelo está compuesto por *n* generadores, la demanda, y el esquema de deslastre.

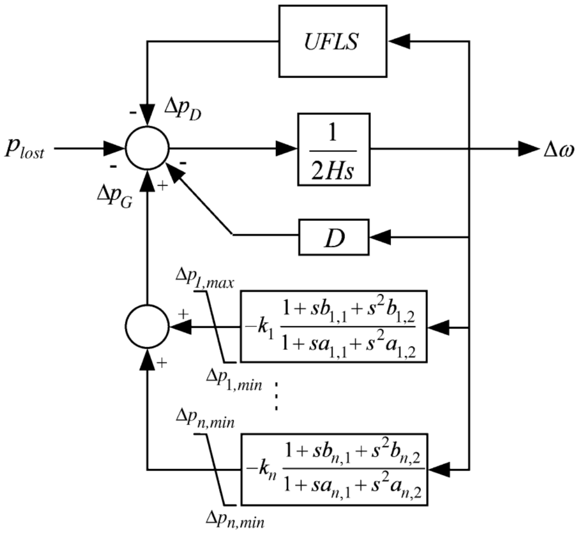

Figura 1. Sistema de frecuencia dinámico del sistema eléctrico (Sigrist, 2010)

3.2. Nuevo criterio de deslastre

El nuevo criterio, margen de estabilidad de frecuencia (M_{thr}), estudiado en este proyecto ha sido propuesto por Rudez (2019). Este tiene el mismo fundamento físico que los esquemas basados en RocoF, pero, sin embargo, la manera en la que los esquemas llegan a la decisión de activación de escalones de deslastre es distinta. En vez de aplicar directamente los umbrales de RoCoF, *M(t)* se calcula en tiempo real dentro de cada relé, y se puede definir como el tiempo restante antes de que la frecuencia viole el límite mínimo permitido (f_{LIM} *=47.5Hz*) (Rudez, Sodin, & Mihalic, 2021). La figura 2 muestra la definición gráfica del nuevo criterio, y puede ser calculado fácilmente como:

$$M(t) = \frac{f_{LIM} - f(t)}{RoCoF(t)} \tag{1}$$

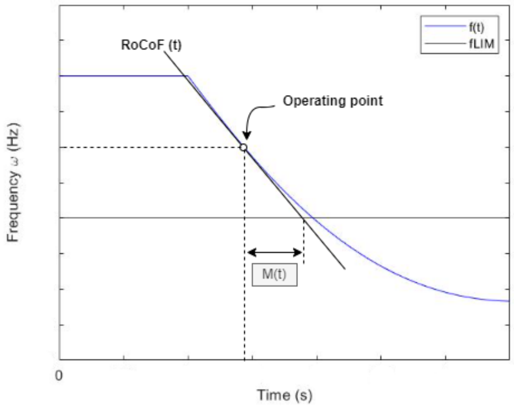

Figura 2. Cálculo del margen de estabilidad M(t)

El margen de estabilidad de la frecuencia predice si f_{LIM} será infringido en el fututo o no. El margen de estabilidad de la frecuencia predice si f_{LIM} será violado en el futuro o no. Un valor grande de *M(t)* indicará un RoCoF pequeño y, por lo tanto, que la frecuencia es prácticamente estable; mientras que, si *M(t)* es pequeño, denotará un valor grande de RoCoF, lo cual indica la necesidad inmediata de deslastre. Por consiguiente, el nuevo criterio parece preservar la conexión de varias cargas y evitar los sobrepasos de frecuencia innecesarios.

4. Diseño del nuevo esquema UFLS

El ajuste del margen de estabilidad de la frecuencia engloba dos tareas. En primer lugar, la elección de un conjunto de escenarios OyC representativos, que caractericen adecuadamente el sistema eléctrico analizado y, en segundo lugar, el ajuste adecuado del nuevo parámetro.

Para configurar M_{thr}, se emplea como caso de estudio el sistema eléctrico de La Palma, y se sigue una metodología experimental iterativa, que consiste en simular los escenarios de contingencia y, mediante un proceso de prueba-error, estimar M_{thr}. Finalmente, para evaluar la eficacia del novedoso esquema UFLS, se compara con los esquemas UFLS convencionales actuales, y se realiza un análisis de sensibilidad. En este se estudia la influencia de la variación del parámetro de diseño f_{LIM}, el efecto de la penetración de las RES y la respuesta en frecuencia ante pérdidas de generación consecutivas.

5. Resultados

5.1. Diseño de M_{thr} con casos representativos

Al realizar el ajuste de M_{thr}, se ha visto que, al seleccionar cuatro escenarios OyC representativos, el modelo no era capaz de detener la caída de frecuencia ante contingencias moderadas de forma efectiva, pues cuatro escenarios no fueron suficiente para representar adecuadamente el sistema eléctrico. Por ello, se ha tomado una contingencia adicional para caracterizar las pérdidas moderadas. Al aumentar el número de escenarios representativos, se ha logrado abarcar un rango de frecuencias más amplio y, consecuentemente, se ha obtenido un esquema UFLS eficiente y robusto.

5.2. Comparación con el esquema UFLS convencional

Con el fin de evaluar la viabilidad y la conveniencia de implementar el margen de estabilidad de frecuencia, M_{thr}, como un nuevo criterio de deslastre de carga, el esquema propuesto se ha comparado con dos esquemas UFLS convencionales estáticos y semi-adaptativos, uno de ellos optimizado (Véase figura 3 y Tabla 1).

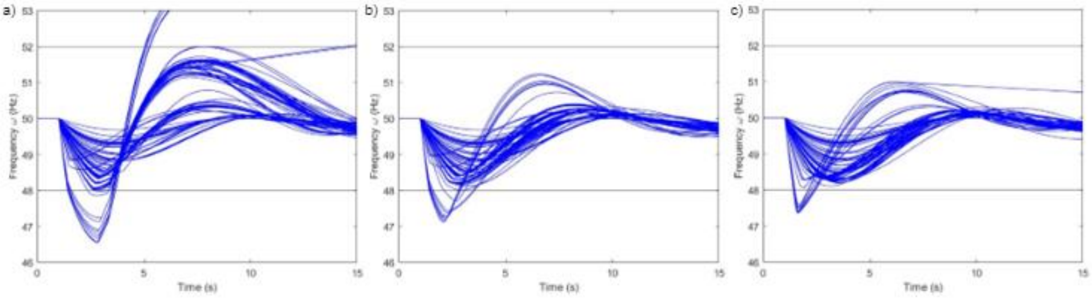

Figura 3. Respuesta de los distintos esquemas UFLS: a) esquema UFLS convencional actual, b) esquema UFLS convencional optimizado and c) nuevo esquema UFLS

	UFLS		
Caso	Potencia total (MW)	Nº Relays	ΣΔωmin (Hz)
Existente	461.70	255	206.67
Optimizado	213.36	121	200.02
Nuevo	169.98	94	200.35

Tabla 1. Comparación de los tres esquemas UFLS

Tanto el esquema UFLS convencional optimizado como el propuesto, ofrecieron la mejor respuesta en frecuencia ante todas las posibles pérdidas de generación del sistema de potencia de La Palma. En ninguno de los casos se produjeron sobrepasos de frecuencia y esta se mantuvo dentro de los límites aceptables de operación. Asimismo, se ha observado que, incluyendo el criterio de margen de estabilidad de frecuencia, se reduce la carga deslastrada considerablemente (aproximadamente un 63% respecto al esquema sin optimizar y un 20% respecto al optimizado).

Finalmente, cabe destacar que los tres esquemas han presentado una acumulación de frecuencia mínima muy similar. En el caso de los esquemas UFLS convencionales, se debe a que, en las contingencias pequeñas los desvíos de frecuencia son menores, pero estas aumentan en el caso de grandes perturbaciones; por lo que en general se compensan. Mientras que, en el nuevo esquema, en el caso de detectar que la frecuencia no es severa, deja que la frecuencia se recupere de forma natural, dando lugar a mayores picos mínimos de frecuencia.

5.3. Análisis de sensibilidad del nuevo esquema UFLS

Los principales hallazgos obtenidos del análisis de sensibilidad se resumen a continuación:

5.3.1. Variación de f_{LIM}

El nuevo esquema UFLS ha sido configurado para diferentes valores de f_{LIM} comprendidos entre 47.5Hz y 48.3Hz, con el fin de evaluar el efecto en la respuesta dinámica de frecuencia de adoptar un criterio más conservador o, por el contrario, uno menos prudente.

Se concluyó que, cuanto mayor sea f_{LIM}, mayor será el margen de seguridad, antes intervendrá el esquema UFLS y, por tanto, mayor será el riesgo de desconexión de carga innecesaria. En cambio, un diseño menos restrictivo, es decir, con menor f_{LIM}, el momento de deslastre se retrasará, dando lugar a posibles inestabilidades al permitir mayores picos mínimos de frecuencia durante el transitorio.

5.3.2. Impacto de la generación renovable

Con el aumento de la penetración de las energías renovables, se espera que la inercia de los sistemas eléctricos disminuya significativamente, ya que la generación de las FER suele estar desacoplada de la red. Por lo tanto, para las mismas condiciones de generación-demanda, el sistema eléctrico presentará valores de subfrecuencia más bajos y descensos de frecuencia más rápidos (Rudez, Sodin, & Mihalic, 2021). Por tanto, se consideró de gran interés analizar la respuesta dinámica del modelo UFLS propuesto ante variaciones de inercia.

La Figura 4 ilustra la respuesta del sistema eléctrico de La Palma ante todos los escenarios de pérdida de potencia posibles. Se observa que el sistema eléctrico se ve claramente afectado por la penetración de las FER en términos de frecuencia. Al disminuir la inercia, el RoCoF aumenta, los picos de frecuencia mínima son mayores y el sistema eléctrico se vuelve más oscilante. No obstante, a pesar de que la respuesta en frecuencia empeoró, la frecuencia mínima no descendió por debajo de 48Hz durante más de 2s.

Al considerar la generación renovable en las simulaciones, se ha observado la importancia que tiene su inclusión en los despachos de generación a la hora de configurar el nuevo criterio de deslastre. Una mayor penetración de renovables da lugar a mayores valores de RoCoF y, por tanto, a menores márgenes de estabilidad de frecuencia. Consecuentemente, si el efecto de la generación renovable se despreciase en el diseño, podría afectar a su efectividad, puesto que no se contemplaría la severidad real de las contingencias.

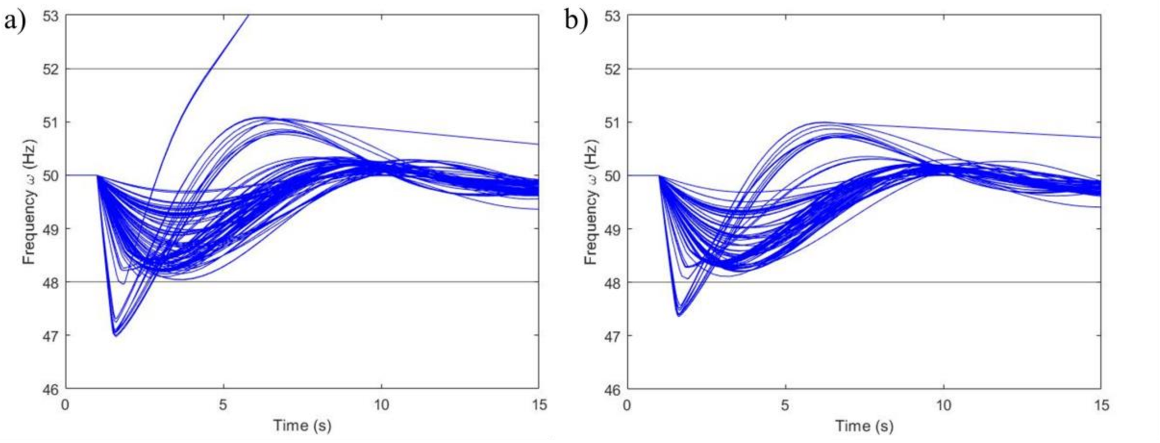

Figura 4. Respuesta del nuevo esquema UFLS (a) con generación renovable (b) sin generación renovable

Al introducir la generación renovable, se ha detectado un aumento global de la cantidad de carga deslastrada. Los motivos que lo justifican son, por un lado, la disminución de la inercia y la reducción de la reserva disponible, y, por otro lado, la aplicación de un esquema UFLS que desprecia a las FER, ya que, si el diseño no se ajusta a las nuevas condiciones de operación (mayor RoCoF y menor $M(t)$), mayor número de escalones de deslastre de carga se activarían.

A modo de resumen, se ha observado la importancia de incluir las FER en los despachos de generación a la hora de ajustar el nuevo criterio de deslastre. Una mayor participación de las energías renovables dará lugar a valores de RoCoF más elevados y, por tanto, a menores márgenes de estabilidad de frecuencia. Por consiguiente, si se desprecia el efecto de la generación renovable a la hora de diseñar el esquema UFLS, podría afectar a su eficacia, ya que no se estaría contemplando la gravedad real de las contingencias.

5.3.3. Contingencias consecutivas

A menudo, la pérdida de una unidad generadora puede conducir a la pérdida de otros generadores y, en el peor de los casos, si las desviaciones de frecuencia no se mantienen dentro del rango de ± 2.5Hz/s (Egido, Sigrist, Lobato, Rouco, & Barrado, 2015), puede conducir a un fallo en cascada, que a su vez resultaría en un colapso del sistema. El disparo consecutivo de generadores es un evento común en los pequeños sistemas eléctricos aislados, por lo que resultó de especial interés evaluar si el modelo propuesto era capaz de hacer frente a varias pérdidas o, por el contrario, se volvía inestable.

Para ello, se ha estudiado la respuesta en frecuencia del sistema eléctrico de La Palma ante dos contingencias consecutivas. Este análisis ha revelado que el diseño resultó ser capaz de recuperar el equilibrio de potencia en el caso de que ambas pérdidas fueran pequeñas o moderadas, mientras que, si alguna de las perturbaciones simuladas fuera grave, el sistema se volvería inestable y, en consecuencia, se produciría un apagón del sistema. El motivo subyacente es que el esquema se configuró para intervenir en caso de una sola pérdida, por lo que los escalones de desconexión de carga diseñados no han sido suficientes para devolver la estabilidad al sistema en caso de producirse interrupciones de generación consecutivas.

6. Conclusiones

Este Proyecto ha tratado de abordar uno de los principales problemas a los que afrontan los pequeños sistemas eléctricos aislados, es decir, la estabilidad de la frecuencia. Para ello, el proyecto se ha centrado en el esquema de deslastre de cargas por subfrecuencia, el cual es comúnmente utilizado como último remedio para mantener la estabilidad de frecuencia.

El objetivo principal ha sido mejorar el esquema UFLS convencional estático y semi-adaptativo mediante la implementación del margen de estabilidad de frecuencia como un nuevo criterio de desconexión.

El margen de estabilidad de frecuencia se ha aplicado con éxito al sistema eléctrico de La Palma y ha mostrado resultados prometedores. Al implementar el nuevo criterio, se ha obtenido un esquema UFLS robusto y eficiente. A continuación, se resumen brevemente los principales hallazgos:

- La adecuada selección de escenarios representativos es crucial para poder hacer una buena caracterización del sistema de potencia.
- El esquema convencional estático y semi-adaptativo optimizado ya presenta una muy buena respuesta ante contingencias.
- El nuevo esquema UFLS logra reducir la carga respecto al esquema UFLS estático y semi-adaptativo convencional (actual y optimizado). Asimismo, es capaz de distinguir situaciones críticas.
- La definición de f_{LIM} es crucial para el diseño del esquema UFLS propuesto y su valor dependerá de las características de cada sistema de potencia.
- La generación renovable no debe ser descartada a la hora de diseñar el esquema UFLS.
- El esquema diseñado es capaz de restaurar el equilibrio de frecuencia ante pérdidas pequeñas o moderadas de generación. Sin embargo, de ser una de las pérdidas severas, el sistema se vuelve inestable tras la segunda pérdida, produciéndose un apagón.

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SYSTEM PROTECTION OF ISLAND POWER SYSTEM UNDER LARGE SHARES OF RES

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Collaborating Entity: IIT – Universidad Pontificia de Comillas

ABSTRACT

Increasing penetration of RES affects stability and, in particular, frequency stability of island power systems like the Canary Islands. System protection involves underfrequency load shedding (UFLS) as a last resort tool. The objective of this project is to find the appropriate tuning of parameters of a novel UFLS scheme based on the frequency stability margin and compare its performance with the conventional UFLS scheme. The innovative model is implemented in the La Palma power system to evaluate its effectiveness in the event of a generator outage. The results of this study demonstrate that the introduction of the frequency stability margin in the UFLS scheme contributes to a significant improvement in the underfrequency relays efficiency. The load shedding is delayed for moderate RoCoF values, and the amount of disconnected load is reduced, while the frequency stability is preserved. Furthermore, a sensitivity analysis of the novel UFLS scheme is presented, where the effect of adopting a more conservative approach, the impact of RES share in the generation mix and the frequency response to consecutive generator tripping, are studied.

Keywords: Island power systems, frequency stability, underfrequency load shedding.

1. Introduction

Frequency stability is a major concern in small isolated power systems. The isolated nature of these systems makes them particularly sensitive to disturbances. Incidents in the grid are a very frequent event in small power system like the Canary Islands. The main features that hamper their stability are, firstly, their low inertia, since they have a small number of generators connected to the system, and secondly, the lack of interconnection (Egido, et al., 2015). In the event of an incident, unlike continental systems, they cannot be supported by other neighbor systems, and this makes them more sensitive to contingencies. This type of incidents will be more complex to manage with the penetration of renewables, given that their intermittent nature, their absence of inertia and their lack of contribution to frequency control, will intensify the outlined problem.

A common practice to protect the power system stability, if the primary frequency control is not sufficiently fast to restore the power balance and to keep frequency within acceptable values, is underfrequency load shedding (UFLS). UFLS schemes shed a predefined amount of load if frequency and/or RoCoF drops below a certain threshold. This practice reduces the recovery time of the system and the number of affected customers. Additionally, it improves the reliability and security of the electrical power system. Several approaches can be found in the literature regarding UFLS schemes, but in any case, a good UFLS scheme should be quick, simple and effective to avoid the risk of blackouts (Sigrist, 2010). In general, conventional UFLS schemes present a good performance, however, they are rather inflexible. Occasionally instead of providing an adequate solution to underfrequency situations, they create an over-frequency problem by over-shedding load. This issue is becoming increasingly relevant to address due to increasing penetration of decoupled power generation.

This tendency towards a sustainable energy consumption poses a major challenge for the Canary Islands, given that they have small and poorly meshed electrical power systems that are difficult to interconnect due to their geographic nature. As they are volcanic islands, the long distance in deep water between them limits interconnections. Particularly, in La Palma and El Hierro, there is no possibility of interconnection (Rodríguez, 2011). Therefore, they will be greatly affected by the intermittency and uncertainty that renewables introduce into the grid. To prevent systems such as the Canary Islands from compromising their integrity, work must be done to ensure that frequency stability is maintained at all times. Hence, this project explores the impact of implementing a novel UFLS scheme able to differentiate between severe situations and those in which load shedding can be delayed or avoided.

2. Project definition

The main objective of this project is to implement a new load shedding criterion in the current UFLS scheme of small isolated power systems to reduce/delay load shedding, prevent/diminish blackouts and to achieve an optimal, robust and efficient performance of the power system. And, therefore, prevent the system integrity from being compromised with the increasing penetration of RES.

To achieve these objectives, the following methodology has been adopted:

- Implementation of the new frequency stability margin threshold in the UFLS scheme. For this purpose, Simulink has been used to configure a block diagram.

- Appropriate adjustment of the new load-shedding criterion through representative operating and contingency (O&C) scenarios.
- Comparison of the novel UFLS scheme with both the conventional UFLS scheme and an optimised version of it.
- Sensitivity analysis of the new UFLS scheme

3. Modelling

3.1. Power system model

The power system has been represented through the model shown in Figure 1 and has been implemented in Simulink, since this model allows simulating the dynamic frequency of small isolated power systems in the short-term with sufficient accuracy. It consists of *n* generators, the demand, and the UFLS scheme.

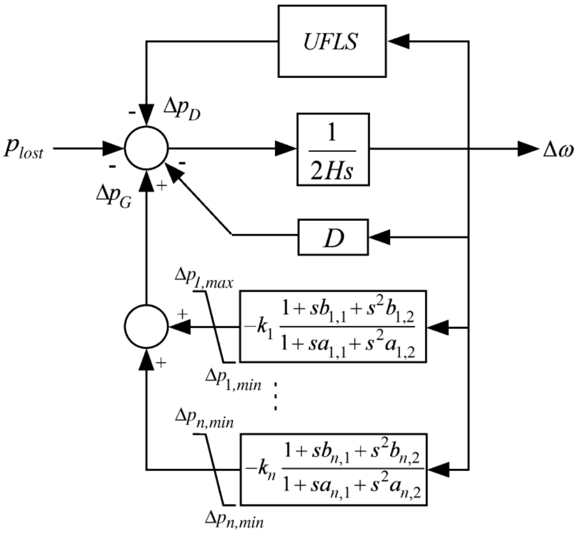

Figure 1. System-frequency dynamic of the power system (Sigrist, 2010)

3.2. New load shedding criterion

The new criterion, frequency stability margin (M_{thr}), studied in this project has been proposed by Rudez (2019). M_{thr} has the same physical reasons as the RoCoF-based schemes, however, the way in which these schemes come to the triggering decision is different. Rather than directly applying RoCoF thresholds, $M(t)$ is calculated in real time within each relay, and it can be defined as the remaining time before the frequency violates the minimum allowed limit ($f_{LIM} = 47.5Hz$) (Rudez, Sodin, & Mihalic, 2021). Figure 2 illustrates the graphical definition of the new threshold, and it can be easily calculated as:

$$M(t) = \frac{f_{LIM} - f(t)}{RoCoF(t)} \quad (1)$$

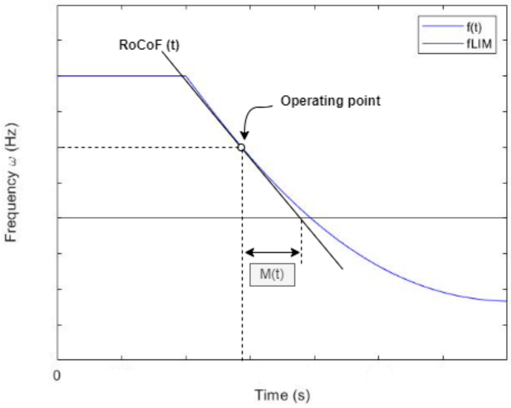

Figure 2. Calculation of the frequency-stability margin M(t)

The frequency stability margin predicts whether f_{LIM} will be violated in the future or not. A large value of M(t) indicates a small RoCoF and, therefore, that the frequency is almost stable; whereas if M(t) is small denotes a big value of RoCoF, which reflects the immediate need of shedding. Thus, the new criterion seems to preserve the supply of several loads and avoids unnecessary frequency overshoot.

4. Design of the novel UFLS scheme

The tuning of the frequency stability margin comprises to tasks. Firstly, the choice of a set of representative O&C scenarios that adequately characterize the power system under study and, secondly, the appropriate adjustment of the new threshold. To tune M_{thr}, the La Palma power system is used as test bench, and an experimental iterative process is followed, which consist in simulating the contingency scenarios and, through a trial-and-error process, to estimate the value of M_{thr}. Finally, to assess the effectiveness of the novel UFLS, it is compared with the current conventional UFLS schemes, and a sensitivity analysis is performed, where the influence of varying the design parameter f_{LIM}, the effect of RES penetration and the frequency response to consecutive outages, are analyzed.

5. Results

5.1. Design of M_{thr} with representative O&C scenarios

From the design method followed, it has been seen that by selecting four O&C scenarios, the model has not been effective to arrest frequency decay under moderate outages, as the chosen contingency events did not provide a good representation of the overall power system. Thus, an additional O&C scenario has been taken to characterize the intermediate O&C scenarios. By increasing number of representative scenarios, a wider frequency range has been covered, and an efficient and robust UFLS scheme has been obtained.

5.2. Comparison with conventional UFLS schemes

In order to evaluate the feasibility and usefulness of implementing the frequency stability margin, M_{thr}, as a new shedding criterion, the proposed scheme has been compared with two conventional static and semi-adaptive UFLS schemes, one of them optimized (See Figure 3 and Table 1).

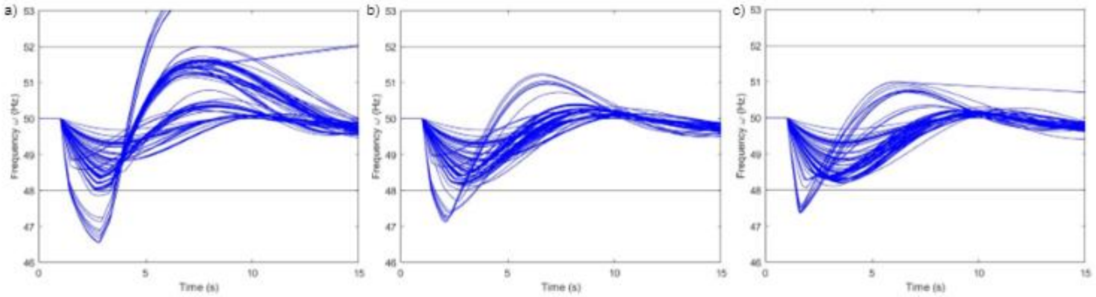

Figure 3. Overall response of the different UFLS scheme configurations. a) existing UFLS scheme, b) optimized conventional UFLS scheme and c) novel UFLS scheme

	UFLS performance		
Case	Total shed (MW)	Nº Relays	ΣΔωmin (Hz)
Existing	461.70	255	206.67
Optimised	213.36	121	200.02
Novel	169.98	94	200.35

Table 1. Comparison of the three UFLS schemes

Both the optimized conventional UFLS scheme and the novel scheme provided the best frequency response to all possible generation outages of the La Palma power system, since in none of the cases there appeared frequency overshoots, and the frequency remained within acceptable limits. Besides, it has been observed that, by including the frequency stability margin, the amount of disconnected load was reduced (approximately 63% with respect to the existing scheme and 20% compared to the optimized scheme).

Finally, it should be noted that the three schemes showed a very similar minimum frequency accumulation. In the case of the conventional schemes, this is explained by the fact that, in the event of small contingencies, the frequency deviations were smaller, but these increased in the case of large disturbances; therefore, in general, they were counterbalanced. Whereas, in the novel scheme, if the frequency decay is found to be non-critical, the scheme allowed the frequency to recover naturally, giving rise to higher minimum frequency peaks.

5.3. Sensitivity analysis

The main findings obtained from the sensitivity analysis are summarized hereafter:

5.3.1. Variation of f_{LIM}

The novel UFLS scheme has been configured for different f_{LIM} values between 47.5Hz and 48.2Hz, to evaluate the effect of adopting a conservative or non-conservative approach on the dynamic frequency response.

From this analysis, it was concluded that the larger the f_{LIM}, the greater the safety margin and the earlier the UFLS scheme will intervene and, thus, the higher the risk of unnecessary load shedding will be. Conversely, if a less constraint design approach was followed, i.e. lower f_{LIM}, load shedding will be delayed, giving rise to possible instabilities by allowing higher minimum frequency peaks during the transient.

5.3.2. Impact of RES generation

With the increasing penetration of renewables, the inertia of power systems is expected to decrease significantly since RES generation is usually decoupled generation. Hence, for the same generation-demand conditions, the power system will present lower underfrequency values and faster frequency decays (Rudez, Sodin, & Mihalic, 2021). Consequently, it was considered of great interest to analyze the dynamic response of the proposed UFLS model to inertia variations.

Figure 4 illustrates the response of the La Palma power system to all possible contingencies. The power system was clearly affected by the penetration of RES in terms of frequency. With decreasing inertia, the RoCoF increases, the minimum frequency peaks are higher, and the power system becomes more oscillating. Nevertheless, although the frequency response worsened, the frequency never dropped below 48Hz for more than 2s.

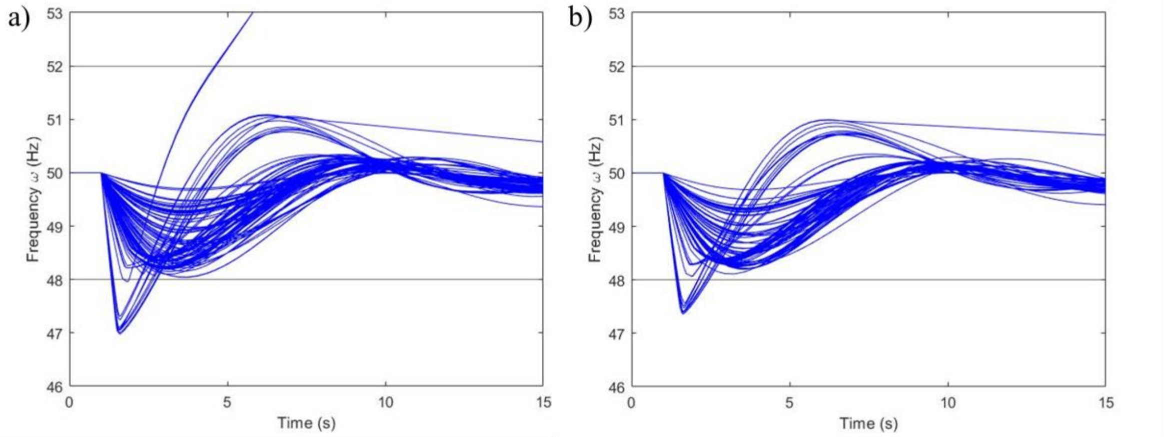

Figure 4. Overall response of the novel UFLS scheme (a) with RES (b) without RES

By introducing renewable generation, it has been found that an overall increase of the load shed. The reasons behind it were, on the one hand, the decline in the inertia and the reduction of available spinning reserve, and, on the other hand, the application of a UFLS scheme that ignores RES, because if the design is not adjusted to the new operating conditions (higher RoCoF and lower M(t)), further load-shedding steps would be activated.

To sum up, it has been observed the importance of its inclusion in the generation dispatches when tuning the new shedding criterion. A higher penetration of renewables results in higher RoCoF values and, therefore, lower frequency stability margins. Consequently, if the effect of renewable generation is neglected when designing the UFLS scheme, it could affect its effectiveness, since the real severity of the contingencies would not be taken into account.

5.3.3. Consecutive generator tripping

Very often, the outage of a generating unit can lead to the loss of other generators and in the worst-case scenario, if frequency deviations are not maintained within ± 2.5 Hz/s range (Egido, Sigrist, Lobato, Rouco, & Barrado, 2015), it can lead to a cascading power failure, which would consequently result in a system blackout. The consecutive generator tripping is a common event in small isolated power systems, thus it was of particular interest to evaluate whether the proposed model was able to cope with several outages or, on the contrary, became unstable.

For this purpose, the frequency response of the La Palma power system to two consecutive contingencies has been studied. From this analysis, it has been found that the design seemed to be capable of recovering the power balance in the event that both losses were small or moderate, whereas, if any of the simulated outages were severe, the system would become unstable and, consequently, a blackout would occur. The reason behind it, is that the scheme was configured to intervene in case of a single outages, hence, the designed load-shedding steps have not been sufficient to restore stability in case of consecutive generator tripping.

6. Conclusions

This project has aimed to address one of the main problems faced by small isolated power systems, i.e. frequency stability. For this purpose, it has been focused on a widely used last-resort tool, the UFLS scheme. In this sense, the main objective has been to improve the conventional static and semi-adaptative UFLS scheme through the implementation of the frequency stability margin as a new shedding threshold.

The new criterion has been successfully applied to the La Palma power system and has shown promising results. By implementing the frequency stability margin threshold, a robust and efficient UFLS scheme was obtained. The main findings of this project were:

- The adequate selection of representative O&C scenarios is crucial for a good characterization of the power system.
- The optimized conventional static and semi-adaptative scheme already provides a very good response to contingencies.
- The novel UFLS scheme is able to reduce the load with respect to the conventional static and semi-adaptative UFLS schemes and the optimized version of this. Further, it is able to distinguish between critical and no-critical scenarios.
- The design of f_{LIM} is crucial and will depend on the characteristics of each power system.
- RES generation should not be neglected when designing the UFLS scheme.
- The M-based scheme is capable of restoring frequency balance in the face of small or moderate outages. However, if one of the power losses is severe, the system becomes unstable after the second perturbance, causing a system blackout.

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Chapter 1. INTRODUCTION

1.1 PROBLEM STATEMENT

Energy is essential for economic and social development. With population growth, the demand for energy has increased, and this demand continues to be largely met by fossil fuels. This has led to a major impact on the environment, on people's health and has resulted in energy unsustainability. The path to reducing/eradicating its effects lies mainly in producing energy in a more sustainable way. The European Union and its Member States have committed to reduce greenhouse gas emissions at national level and to boost the share of renewable energy sources (RES) and improve its efficiency (EU Concil, 2016).

As a result, and with the depletion of fossil fuels, the implementation of non-conventional renewable energies, (i.e. geothermal, solar, wind, hydro or tidal energy) is gathering pace in recent years. The increasing penetration of RES reduces operation costs due to lower variable costs, but it affects in turn system operation. Renewable sources are characterized by having intermittent and highly variable generation, as they depend on weather changes and climatic conditions (daylight hours, solar radiation, wind speed, etc.). These unpredictable variations present major problems for systems with larger penetration of RES as for instance conventional generators need to cope with larger net demand variations and thus barriers for the deployment of wind and photovoltaic technology. The increasing penetration of RES affects system stability in general and frequency stability in particular, since RES generation substitutes conventional synchronous generation providing inertia and most of primary and secondary voltage and frequency controls. The higher the RES penetration, the greater the probability of system problems if appropriate measures are not taken, as it is more difficult to maintain a balance between generation and demand.

These problems affect continental systems to a lesser extent due to their sheer size, robustness and the large meshed network. Nevertheless, frequency instability strongly affects isolated systems, as they are very sensitive to active power imbalances such as generation outages given their small size and the relatively large size of generators. Their isolated nature makes them particularly vulnerable to the rapid variations generated by wind and photovoltaic power. For example, at present, frequency stability in the Canary Islands' power system is expected to worsen due to a higher probability of imbalance (REE, 2020). Consequently, demand supply may be affected, and thus advanced frequency controls are required.

The purpose of this project is, therefore, to addresses the problem of system protection of small isolated power system under large shares of RES through underfrequency load shedding schemes (UFLS). UFLS schemes are a remedy to restore the frequency stability if frequency drops below the operating point during a large contingency and to avoid a complete system collapse. Thus, it is crucial to improve the robustness and efficiency of UFLS schemes of small isolated power systems.

1.1.1 FREQUENCY STABILITY IN SMALL ISOLATED POWER SYSTEMS

Frequency stability is the ability of the system to maintain the frequency within an acceptable range after a disturbance that caused an imbalance between power demand and generation. When an incident occurs, the primary frequency controls initially act and try to re-establish the power balance. However, the reserve of the equipment is not always sufficient to cope with the contingency. This is a major challenge in isolated power systems, as they are not interconnected with other electrical power systems (EPS), the power supply of any individual generating unit constitutes a substantial part of the total demand (Sigrist, 2010). For instance, in the La Palma (Canary Islands) EPS, a single generator can meet up to 51.68% of the demand.

The characteristics of small isolated systems make them particularly vulnerable to large disturbances, which affects their security and reliability. The main features that hamper their stability are, firstly, their low inertia, since they have a small number of generators connected to the system. When a generator is lost, the initial frequency drop can be drastic. In this situation, in addition to losing inertia, a large amount of generation can be lost; these two issues contribute to increase the frequency decay (Egido, Fernández-Bernal, Centeno, &

Rouco, 2009), and this requires a higher frequency regulation of the reserves to prevent the frequency from dropping below $f_{LIM}=47.5Hz$. Secondly, the lack of interconnection. In the event of an incident, unlike continental systems, they cannot be supported by other neighbor systems, and this makes them more sensitive to contingencies.

Typically, instability occurs in the form of a continuous drop in frequency or prolonged frequency oscillations that cause the generating units to trip. It is mainly originated by inadequate equipment response or insufficient spinning reserves (Sigrist, 2010). Furthermore, another important factor that contributes negatively to frequency stability is poor coordination of control and protection equipment. Generators have underfrequency protection devices that are activated in the event of underfrequency conditions. If additional countermeasures such as load shedding schemes fail, the generator protection equipment is activated, and the power system collapses due to instability.

In the case of the Canary Islands, maintaining frequency stability is even more challenging, given that they have small and poorly meshed EPSs that are difficult to interconnect due to their geographic nature. As they are volcanic islands, the long distance in deep water between them limits interconnections. Particularly, in La Palma and El Hierro, there is no possibility of interconnection (Rodríguez, 2011). Subsequently, working towards an optimal, robust and efficient performance of its power system is essential to prevent it from becoming jeopardized with the increasing penetration of RES.

1.1.2 INCREASING PENETRATION OF RES IN THE CANARY ISLANDS

In recent years there has been a growing demand to increase the share of renewable energy in the energy market. Indeed, it is aimed that by 2030 the share of renewables should significantly increase in the global energy mix, that the global rate of improvement in energy efficiency should be doubled and that energy supply infrastructures should be improved. These goals, set by United Nations (2015), seek to make an efficient and sustainable use of natural resource management, to reduce dependence on non-renewable energy resources and to lower greenhouse gas emissions. These objectives are less challenging in continental systems due to their sheer size, robustness and their large meshed network. Nevertheless, they are a major issue for small isolated electrical power system.

In small isolated electrical power systems, typical RES are wind and solar energy. For instance, in 2020, the installed wind and solar power capacity generation of the Canary Islands amounted to 639.49 MW, which accounts for 19.01% of total generation (Government of the Canary Islands, 2020). This figure is expected to increase up to 3,350 MW by 2030 (Government of the Canary Islands, 2022). The purpose is to accelerate the development of renewables and to reduce the vulnerability and high energy dependency of the outermost territories (ORs) of the European Union, which include the Canary Islands. According to the PTECan forecast (2022), by 2030 the Canary Islands will be able to contribute 62% to the power sector with renewables, compared to the 19.9% that they currently provide (Government of the Canary Islands, 2022).

Increasing the penetration of RES may affect the ability of the system to control frequency if no appropriate countermeasures are taken. The replacement of conventional generation plants by wind or photovoltaic plants decreases both the number of generating units that can participate in primary frequency regulation and the overall inertia of renewables (Tielens & Van Hertem, 2012). Furthermore, with decreasing inertia, the initial rate of frequency (RoCoF) increases, which jeopardize system stability in the event of a disturbance. One possible countermeasure is to enable RES to participate in primary frequency regulation through either mandatory or incentive-based schemes.

The impact of intermittent generation on power-system stability depends on the technology employed for both wind and solar power generation. Wind turbines can be of constant or variable speed. The latter is more efficient and nowadays is the most commonly used. Variable speed wind generators include doubly fed induction generators (DFIGs) and full-converter units. Variable speed wind turbines are generally connected to the network by power electronic convertors, that effectively decouple wind turbine inertia to moderate system transients (Dreidy, Mokhlis, & Mekhilef, 2017). As they are decoupled from the grid, despite storing kinetic energy in the blades and generator rotors, they do not provide an inertial response during a frequency event without any further control.

Solar energy can be classified into photovoltaic (PV) and solar-thermal energy, with PV being widely used in small isolated power systems (Nayeripour & Kheshti, 2011). Photovoltaic plants are made up of PV modules and inverters, which decouple the PV modules from the power system. The solar panels consist of several solar cells that transform solar radiation, whereas inverters convert direct current into alternating current. In contrast to wind turbines, solar panels have no rotating mass, thus, they are *per se* inertialess.

As seen before, frequency response depends on the magnitude of the power imbalance, the available spinning reserve and the overall system performance. Decoupled generation technologies directly affect these conditions. Firstly, frequency control is limited, i.e., to participate in frequency control, they must be able to maintain a margin between the available intermittent power and the actual power delivered. This margin is usually small and therefore their reserve contribution is very limited. Secondly, as they are mechanically decoupled, they do not provide any inertial response. Hence, the frequency stability in small grids with a high capacity of renewable energy is an urgent issue that should be addressed.

The Canary Islands have extraordinary climatic conditions for the penetration of renewables. In the coming years, generation from uncontrolled and intermittent sources will be predominant. For this reason, improvements must be made to the load shedding control system in order to ensure that the power system is safe and reliable at all times. This project aims to enhance the conventional UFLS scheme through the implementation of a recently proposed load shedding criterion (Rudez & Mihalic, 2019) that seems to be able to identify critical events and avoid unnecessary load shedding. It should be noted that, besides seeking to facilitate the penetration of RES, the base case that will be used does not consider renewable generation, as the aim is to improve the current load shedding scheme to make the inclusion of renewables smoother.

1.2 STATE OF THE ART

The electrical power system of the Canary Islands has six small and slightly meshed isolated electrical systems. The transmission grid of the Canary Archipelago consists of lines and substations with voltages equal to or greater than 66kV, electrical interconnections between islands and 220/132/66kV transformers (REE, 2016).

The isolated nature of these systems makes them particularly sensitive to disturbances. Incidents in the grid are a very frequent event in the Canary Islands. Between 2013 and 2020, more than 200 grid contingencies were recorded (Government of the Canary Islands, 2020). Indeed, in Tenerife there were even two cases of blackouts in a period of less than 10 months between 2019 and 2020 (Vega, 2020). This type of incidents will be more complex to manage with the penetration of renewables, given that their intermittent nature and their lack of contribution to frequency control will intensify the outlined problem.

As seen before, in small isolated power systems, in the event of large contingencies, the primary frequency control is not always sufficiently fast to restore the power balance and to keep frequency within acceptable values. Moreover, the available reserve may be insufficient to cover the loss of generation. Therefore, a common practice to readjust power equilibrium is load shedding.

1.2.1 REVIEW OF UNDERFREQUENCY LOAD SHEDDING PRACTICES

UFLS schemes are the ultimate tool used to protect the power system in the event of a major disturbance that could lead to a dangerous underfrequency situation. These schemes shed a predefined amount of load if frequency and/or RoCoF drops below a certain threshold. This practice reduces the recovery time of the system and the number of affected customers. Additionally, it improves the reliability and security of the EPS.

1.2.1.1 Type of UFLS schemes

There are several types of UFLS schemes in the literature. These can be broadly classified into manual and automatic. Manual UFLS actions are typically taken for frequency restoration problems and scarcely intervene in the limitation of frequency deviations. Conversely, automatic schemes are mainly used to arrest frequency decay and restore the generation-demand equilibrium in the steady-state. Automatic UFLS schemes can be further divided into conventional and advanced. Figure 1 gives an overview of the UFLS schemes classification. Note that there are two ways to design and implement a UFLS: centralized and decentralized control. Advanced schemes are generally centralized; thus, they require the collection and transmission of global information (Xu, Liu, & Gong, 2011). They do not assume predefined amounts of shedable load, but the load to be shed is estimated in function of at least the RoCoF. Conventional schemes by contrast are decentralized, and they take decisions based on local measurements without communication (Sigrist, Rouco, & Echavarren, 2018).

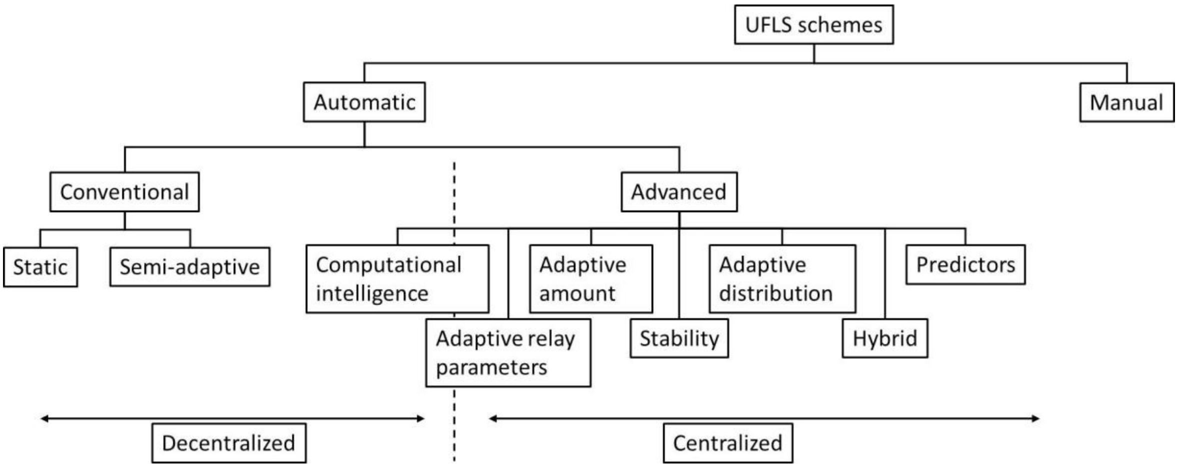

Figure 1. Classification of UFLS (Sigrist, Rouco, & Echavarren, 2018)

Advanced schemes, besides taking frequency and RoCoF into account, use additional information and measurements such as power generation, voltage, etc. to tune the load that needs to be shed. These schemes are highly adaptive, since they adjust their performance according to the power system conditions. Nonetheless, to date, the most commonly used schemes are the conventional ones (Sigrist, Rouco, & Echavarren, 2018). Therefore, this project will be focused on conventional UFLS schemes.

Conventional UFLS schemes are based upon a local or distributed architecture. Two types can de differentiated: static and/or semi-adaptative. Both of them use type 81 frequency relays and semi-adaptative schemes additionally employ RoCoF relays. The relays disconnect a predefined amount of load by sending a trigger signal to the breaker if frequency and/or RoCoF drop and remain below their respective thresholds for a given time (Sigrist, Rouco, & Echavarren, 2018).

The operation of static UFLS schemes is based on the measurement of frequency deviation. The relay parameters and the load to be disconnected are determined by off-line contingency simulations. Although this system is quick and easy to implement, it has the risk of over- or undershedding load in response to contingencies for which it was not previously designed. While the semi-adaptative UFLS schemes additionally measure the RoCoF, resulting in an improvement over the previous scheme. This new threshold makes it possible to differentiate between small and large incidents. It also means a faster frequency response, as load shedding is done earlier in case of large disturbances. Consequently, most UFLS schemes are currently a combination of the static and semi-adaptative schemes. However, even though it provides a better response, it does not solve the problem of over-delay.

The conventional semi-adaptative UFLS scheme disconnects the load in order to re-establish the balance between power generation and demand. The frequency and RoCoF thresholds and the intentional time delays determine the shedding instants. These criteria are step-dependent, as each step establish a percentage of load to be shed, according to the medium voltage feeder (in small power systems). Once the frequency falls below the threshold, the load is shed, in case it remains violated after the intentional delay has elapsed. The UFLS scheme is aimed to disconnect the minimum amount of load to prevent the system from collapsing, this shedding should be such that the load is less than or equal to the generation loss. The load shedding requirements depends on each power system, in accordance with its characteristics, frequency thresholds and load shedding restrictions are defined. For small isolated power systems, the load location criterion for shedding does not generally apply, while the minimum and maximum frequency ranges depend on each system. A typical minimum value is 48 Hz. It should be noted that the frequency thresholds should be coordinated with the turbine underfrequency protections to avoid overshedding and over-frequency scenarios (Acosta, et al., 2020).

In addition, the implementation of RoCoF raises new problems. Primarily, the frequency and RoCoF are not uniform, but change depending on the area and bus. Besides, the RoCoF measurement is further distorted by local dynamics, and it is strongly affected by the internal oscillations of the machine. Likewise, its computation is inaccurate and slow for RoCoF measurements with low frequency oscillations.

1.2.1.2 Design of conventional UFLS schemes

At present, several methods for tuning the conventional UFLS have been reported in the literature, but there is no generally accepted systematic methodology for their design. Typical criteria are the number of steps, step size, frequency threshold, etc. The design is done in two steps: (i) selection of operating and contingency (O&C) scenarios and (ii) tuning of UFLS scheme parameters (Sigrist, Rouco, & Echavarren, 2018).

The appropriate selection of the O&C scenarios is crucial since it influences the tuning of parameters. The scenarios must consider the different levels of demand; thus, the loss of large, small and medium-size generation units is contemplated for the different system conditions. It should be noted that aside from the severity of the contingency, other elements such as the availability of spinning reserve, the inertia or the generation mix must be taken into account, as the operating point affects the response of the system.

Regarding parameter setting, a distinction can currently be made between experimental and optimal designs. Both of them are derived from simulations, which evaluate the system response to hypothetical incidents. Experimental designs are based on trial-and-error processes or on the best scheme among a set of systems. This method has, however, a downside, it does not guarantee that the minimum load is disconnected. Whereas the optimal design applies optimisation techniques to adjust the parameter settings of the UFLS scheme. A review of the literature shows that different algorithms have been used to tune the parameters of the objective function (minimise the amount of load shed). Deterministic algorithms (steepest descent and quasi-Newton methods) have been implemented (Sigrist, Rouco, & Echavarren, 2018). Likewise, due to the discontinuous and non-linear nature of the problem, heuristic algorithms have been applied, which seem to be more suitable for optimizing the objective function. Further, probabilistic approaches have been adopted to quantify the load or active power imbalance variations.

Finally, as mentioned before, the correct performance of UFLS schemes highly depends on the appropriate tuning, and this relies on taking in account appropriately the power system dynamic. A good UFLS scheme should be quick, simple and effective to avoid the risk of blackouts (Sigrist, 2010). In general, conventional UFLS schemes present a good performance, however, they are rather inflexible. Occasionally instead of providing an adequate solution to underfrequency situations, they create an over-frequency problem by over-shedding load. This issue is becoming increasingly relevant to address because the penetration of decoupled power generation (DPG) is enhancing the risk of frequency instability due to their intermittency and lack of inertial response. Hence, a UFLS scheme able to differentiate between severe situations and those in which load shedding can be delayed or avoided is needed.

1.3 OBJECTIVES

This project addresses one of the major problems faced by small isolated power systems, i.e. frequency stability. The work will be focused on the ultimate remedy for power generation-demand mismatches, the UFLS scheme. Conventional static and semi-adaptive scheme will be improved by implementing a new load shedding criterion to reduce/prevent blackouts, avoid unnecessary load shedding and favor the increased penetration of RES. This criterion has been firstly proposed by Rudez (2019) and is based on the frequency stability margin. More concisely, the objectives are:

- The implementation of the frequency stability margin based shedding criterion within conventional UFLS schemes.
- The tuning of the new parameter introduced.
- A comparative analysis of the effectiveness of its inclusion with current conventional UFLS schemes.
- The analysis of the impact of varying design parameters and the inertia of the system.

1.4 METHODOLOGY

With a view to achieving the defined objectives, a review of the current load shedding modelling will be carried out, and the new load shedding criterion, frequency stability margin, proposed by Urban Rudez (2021), will be introduced.

In order to implement and adjust this new criterion, the electrical power system of the island of La Palma (Canary Islands) will be used as a test bench. Several simulations will be carried out with Matlab and Simulink. To adjust the frequency stability margin, the steps introduced by Rudez (2021), and the methodology of Sigrist (2010) will be combined.

Once this new criterion has been implemented and adjusted, a comparison will be made between its performance and that of the current scheme, both the existing and an optimized version. Subsequently, the effectiveness of its response to different scenarios will be tested: with RES penetration, and consecutive contingencies. Furthermore, the effect of varying the design parameter f_{LIM} will be studied.

1.5 STRUCTURE OF THE DOCUMENT

This document consists of five chapter. Chapter 2 describes the model of the power system used for the simulation. Then, the new load shedding criterion is explained, and the changes needed to implement it in the current conventional UFLS scheme are outline.

In chapter 3, the design criteria for the novel UFLS scheme tuning are presented. Furthermore, an exhaustive analysis of the new shedding method is carried out through a comparison between the existing practices, and the response to variations in design parameters.

Chapter 4 provides the conclusions of the project and highlights its principal contributions. Additionally, suggestions for future research are given.

Finally, chapter 5 contains the references.

Chapter 2. MODELLING

In this chapter the model used to represent and simulate small isolated power systems will be presented. The non-linear multi-generator system frequency dynamics (SFD) model, proposed in Sigrist (2010), will be used for the analysis and design of UFLS schemes, as it allows to reflect short-term frequency dynamics of small power systems. Furthermore, the operating principles of the conventional UFLS scheme employed to arrest frequency will be explained. Afterwards, a detailed overview of the recently proposed load shedding criterion (Rudez & Mihalic, 2019) will be provided, where the principles of the M-based criterion, the modifications required to implement it to the current power system model, as well as the design criteria to be followed, will be presented. Finally, the chapter will conclude with an application example to validate the performance of the proposed model.

2.1 POWER SYSTEM MODELLING

The SFD model is able to reflect short-term frequency dynamics of small isolated power systems with sufficient accuracy. Figure 2 details the power system model which consists of n generating units. Each generator is represented by a second order model approximation of its turbine-governor system. Indeed, frequency dynamics are dominated by rotor and turbine-governor system dynamics. The excitation and generator transients can be neglected for being much faster than turbine-governor dynamics. Steam turbines can typically be modelled by first-order models; however, generation mix contains gas-driven and diesel-driven turbines as well, which may require higher order models (Sigrist, Egido, & Rouco, 2012).

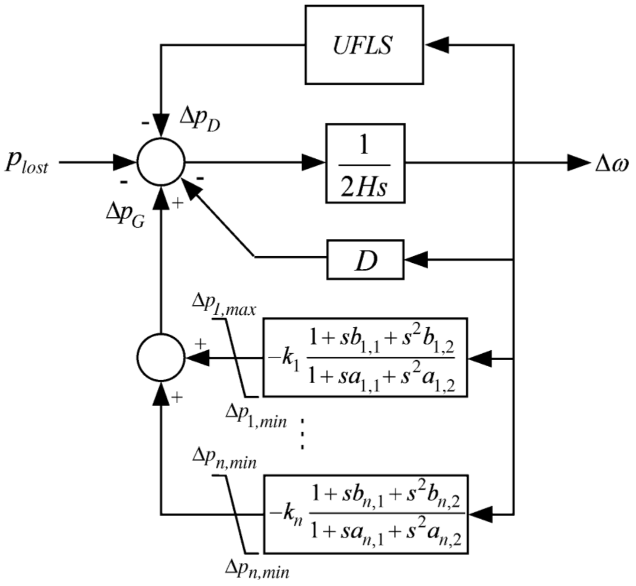

Figure 2. System-frequency dynamic of the power system (Sigrist, 2010)

Figure 2 identifies the parameters of this model. These include the equivalent inertia, H_{eq}, which can be determined, since frequency can be considered uniform, and it can be defined as:

$$H_{eq} = \sum_{i=1}^{n} \frac{H_i \cdot M_{base,i}}{S_{base}} \tag{1}$$

where H_i is the inertia in (s), $M_{base,i}$ is the base of the rating of the *ith* generating unit in (MW) and S_{base} is the sum of the ratings of all generators in (MW). Moreover, the following equation estimates the initial RoCoF:

$$\Delta\dot{\omega}_0 = -\frac{\Delta p_{loss}}{2H_{eq}} \tag{2}$$

From this equation, the effect of the equivalent inertia on the dynamic frequency response can be seen. It can be inferred that a reduced inertia will result in a higher initial frequency decay. Inertia also affects the minimum frequency.

The load-damping factor, *D*, is also one of the model parameters, however, it can usually be neglected, given that its effect in steady state is small compared to the droop of the turbine-governor systems (Sigrist, 2010). This can be demonstrated by the following equation:

$$\Delta\omega_{ss} = -\frac{\Delta p_{loss}}{\sum_{i=1}^{n} k_{g,i} + D} \tag{3}$$

where $\Delta\omega_{ss}$ is the steady-state frequency deviation and $k_{g,i}$ the *ith* generator model gain on S_{base}. From this equation, it can be stated that the impact of the load-damping factor is negligible compared to the gain of the turbine-governor system, since $\sum_{i=1}^{n} k_{g,i}$ is larger than D.

Furthermore, for each generator *g*, the gain k_g and parameters $a_{g,1}$, $a_{g,2}$, $b_{g,1}$ and $b_{g,2}$, are defined, these elements can be derived from more precise models or field tests. Additionally, the model includes generator-output boundaries, because primary spinning reserved are limited, thus, $\Delta p_{g,min}$ and $\Delta p_{g,max}$ are also considered.

The model presented in Figure 2 and explained above will be implemented by means of Simulink as a block diagram. The parameters required by this tool to run the simulations are stored in excel files, which contain the parameters of the generators, the different generation dispatch scenarios, the parameters of the energy store system (not considered in this project) and the data of the UFLS scheme. APPENDIX I: provides the detailed block diagram of the power system model implemented in Simulink.

2.2 MODELLING OF CONVENTIONAL UFLS

The conventional and automatic UFLS scheme, which combines static and semi-adaptative shedding criteria, is a widely used method in small isolated power systems to arrest frequency decay. The shedding scheme disconnects load in order to re-establish the balance between power generation and demand. The frequency and RoCoF thresholds and the intentional time delays determine the shedding instants. These criteria are step-dependent, as each step establish a percentage of load to be shed, according to the medium voltage feeder. Once the frequency falls below the threshold, the load is shed, in case it remains violated after the intentional delay has elapsed.

The UFLS scheme operating principle is depicted in Figure 3 and is as follows; in the event of a disturbance, the coupled control of the system receives information of the frequency deviation caused by the loss of generation. The UFLS scheme measures locally at the UF and the RoCoF relays both the frequency deviation and the rate of frequency decay and compares them with the predefined threshold, respectively. As soon as the first threshold is reached, an intentional delay is activated, so that the system has the chance to let the frequency recover naturally after a few instants. In those cases where frequency and/or RoCoF remain below the threshold, the relay is actioned. Once the trigger signal is sent, a final inherent delay in the breaker is activated, corresponding to the time it takes for the trip signal to become effective. Thus, the system takes a time, equal to the sum of both delays, to actuate. Note that the objective of the UFLS scheme is not to restore frequency, but to arrest frequency decay. Consequently, the system does not contemplate the reconnexion of the shed load. The detailed model of the conventional UFLS scheme that will be simulated can be found in APPENDIX I:.

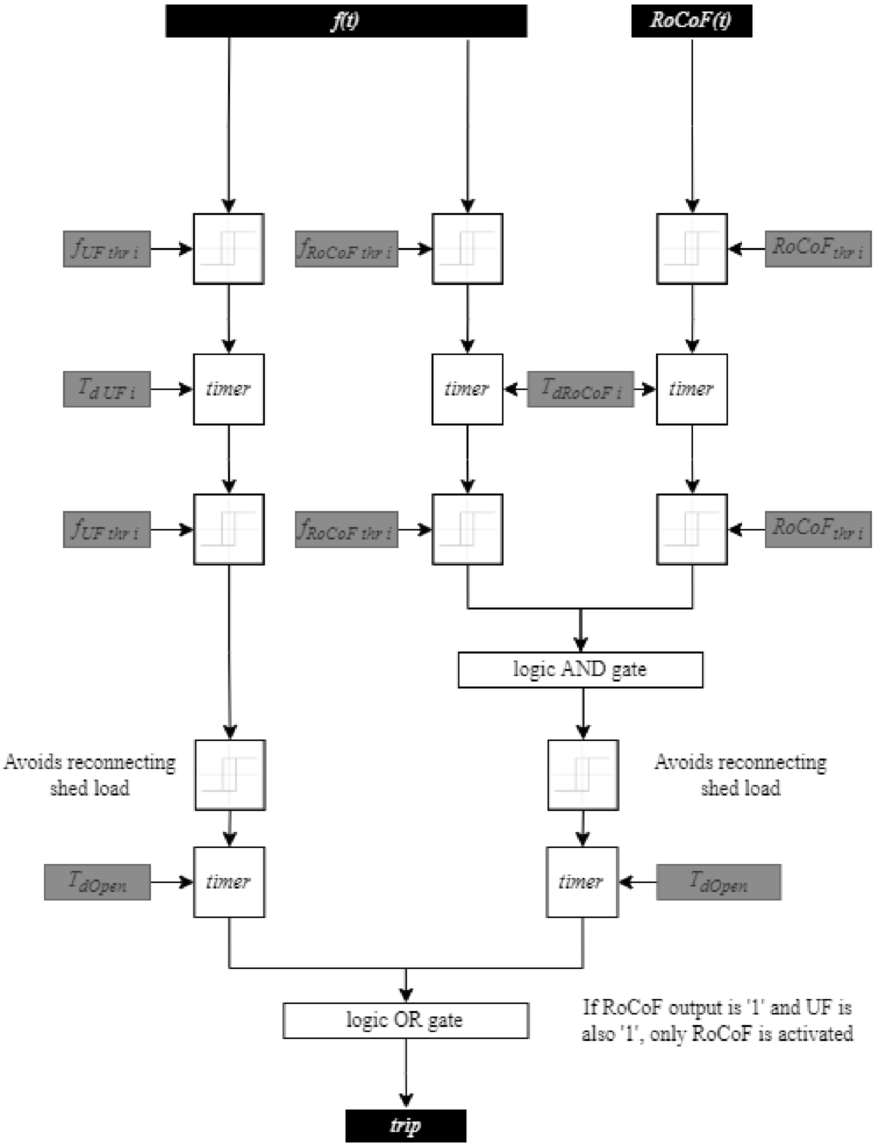

Figure 3. Logical block diagram of the operating principle of the conventional UFLS scheme

2.3 M-BASED UFLS CRITERION

As mentioned before, a shortcoming of the conventional UFLS is the difficulty of detecting conditions where shedding could be delayed or avoided without jeopardizing the electrical power system frequency stability. Therefore, it is intended to explore the proposal of Rudez (2019) to determine if it is effective to solve the outlined problem.

2.3.1 PRINCIPLES OF M-BASED CRITERION

The new shedding criterion proposed by Rudez (2019) is intended to avoid overshedding. It allows to recognize the conditions under which load shedding could be delayed without compromising frequency stability. The proposal introduces at each stage a new shedding criterion to avoid load disconnection when there is still sufficient margin for action. It has the same physical reason as the RoCoF-based schemes, however, the way in which these schemes come to the triggering decision is different. Rather than directly applying the RoCoF thresholds, RoCoF is used to predict the frequency stability margin, *M(t)*, which is determined in real time within each relay. *M(t)* can be defined as the remaining time before frequency violates the minimum allowable limit (f_{LIM} *=47.5Hz*) (Rudez, Sodin, & Mihalic, 2021). Its structure is depicted graphically in Figure 4. Calculation of the frequency-stability margin M(t) Figure 4 and it can be easily calculated as:

$$M(t) = \frac{f_{LIM} - f(t)}{RoCoF(t)} \tag{4}$$

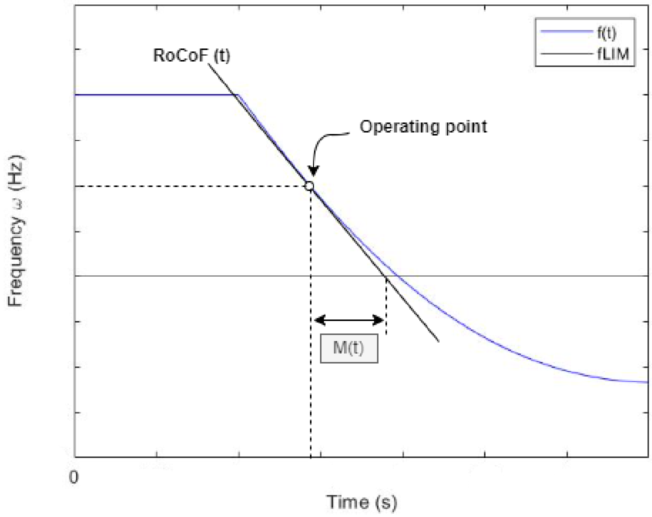

Figure 4. Calculation of the frequency-stability margin M(t)

From equation (4) it can be inferred that, if frequency decay, *RoCoF(t)*, was constant, then the frequency stability margin would represent the time until frequency reaches a given threshold. Indeed, during the first instants, RoCoF is about constant. RoCoF decreases in absolute terms during the frequency transient due to the primary frequency regulation action. If frequency stayed above f_{LIM}, then $M(t)$ would initially decrease and then it would start increasing until ∞ when $RoCoF(t) = 0$ in the steady state.

Figure 5 illustrates various simulations of the frequency dynamic response of a power system in the event of a disturbance. The $f(t)$-$M(t)$ diagram reveals that if frequency violates f_{LIM}, the trajectories converge towards the origin; whereas, if the stability constraint is satisfied, the trajectory is sooner or later redirected towards the right-hand side of the graph, which corresponds to large values of $M(t)$, given that when frequency remains stable, $RoCoF(t)$ is very small. Indeed, in steady-state conditions, the operating point does not appear in the diagram, since $M(t)$ tends towards infinite ($f(t) = 0$ and $RocoF(t) = 0$, then $M(t) = \infty$). Hence, from Figure 5(a), it can be deduced that whilst the trajectory does not converge to the origin, load shedding can be avoided.

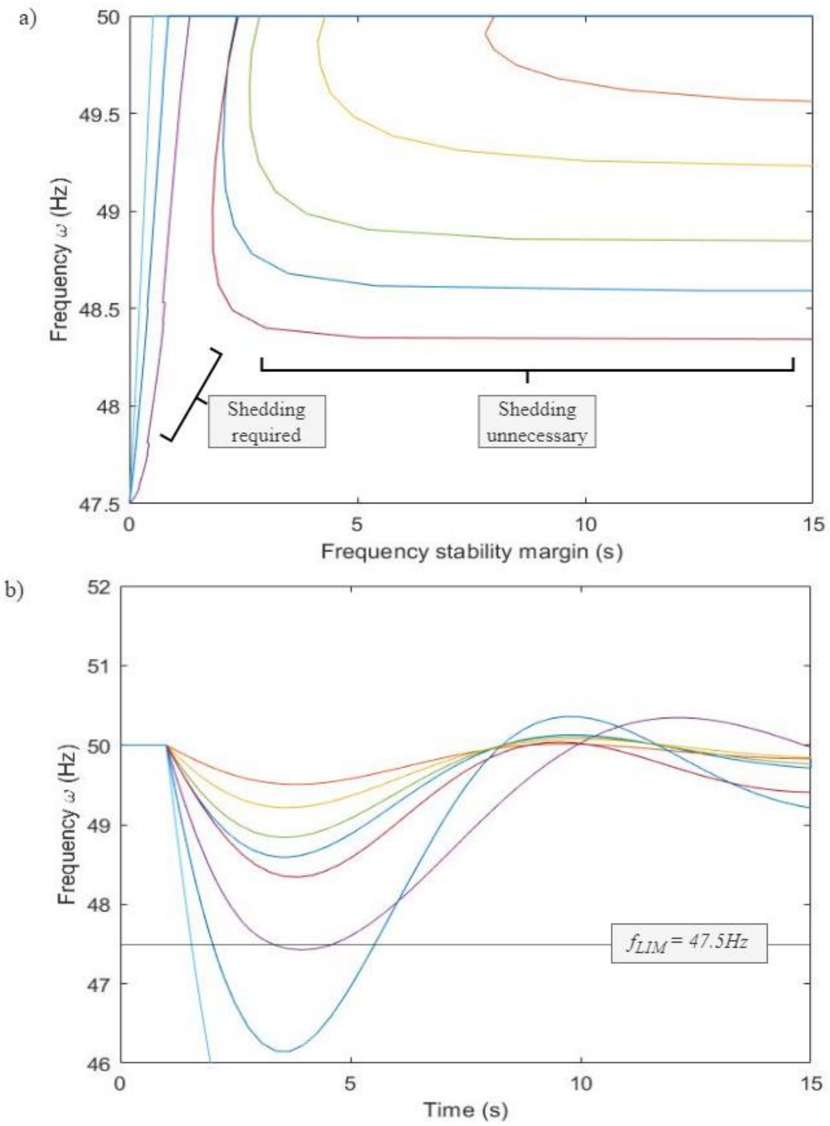

Figure 5. Electrical power system frequency response: (a) f(t)-M(t) and (b) f(t)-t

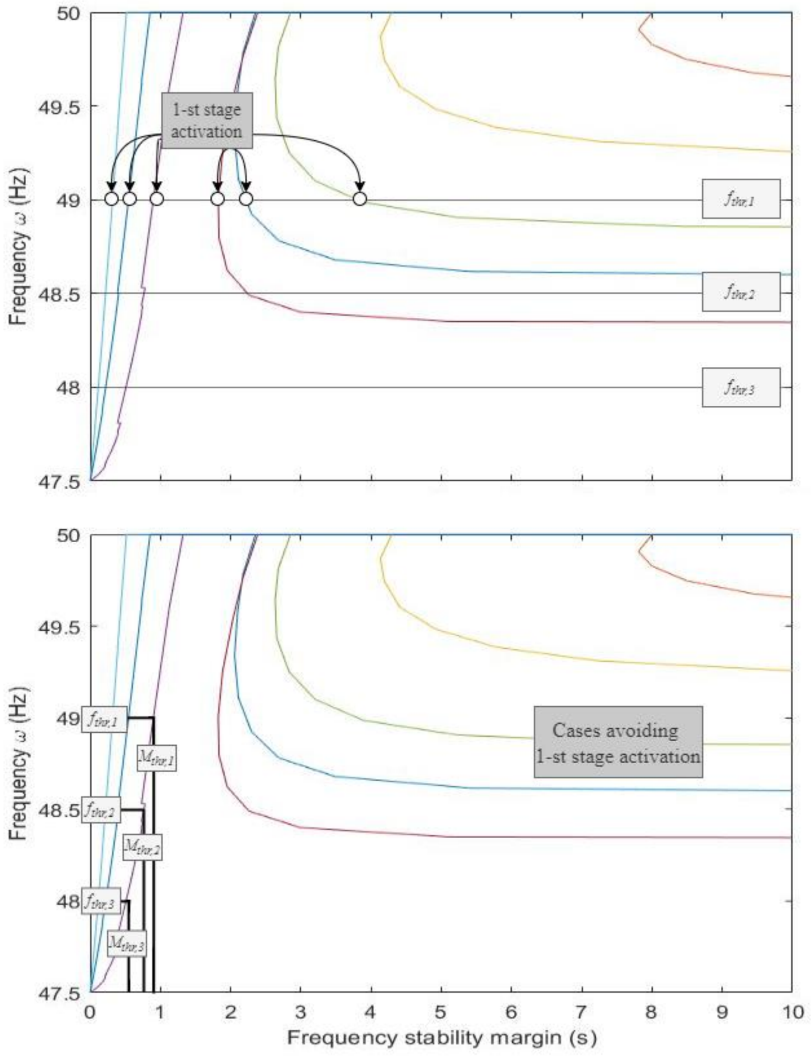

Figure 6. (a)Traditional-static and (b) novel setting of the UFLS scheme

As stated before, the M-based criterion makes static UFLS scheme more adaptative similarly to semi-adaptive UFLS schemes. This can be demonstrated by comparing the novel UFLS scheme with the conventional UFLS practices. The latter is depicted in Figure 6(a) by individual horizontal lines, each of them corresponds to a shedding stage. It can be deduced that, regardless of the system state, if $f(t) = f_{thr,1}$, the first shedding step will be activated. This is unnecessary, since, as it can be seen in Figure 6 (b), there are some scenarios in which the frequency can be stabilized by the frequency control without the need to disconnect load.

The frequency stability margin predicts whether f_{LIM} will be violated in the future or not. A large value of *M(t)* indicates a small RoCoF and, therefore, that the frequency is almost stable; whereas if *M(t)* is small denotes a big value of RoCoF, which reflects the immediate need of shedding.

This new criterion allows to preserve the supply of several loads and avoids unnecessary frequency overshoot. Furthermore, according to the results obtained by Rudez (2021), the proposed scheme seems to be more robust than a static UFLS scheme and thereby may prevent blackouts more effectively, a phenomenon that is more common in isolated power systems given their weakly meshed electrical infrastructure. The inflexibility problem can, thus, be overcome and the operational efficiency of the UFLS scheme can be enhanced.

However, the performance of the M-based criterion depends on the stability margin thresholds. An appropriate selection of the stability margin may indeed lead to more robust UFLS scheme. A further question that arises in this context is whether changes in the power system such as changing system inertia or different disturbances affect the performance negatively and to which extent.

2.3.2 SCHEME MODELLING

In this section, a simplified modelling of the model proposed by Rudez (2021) will be shown. For this purpose, the static and semi-adaptive UFLS schemes as used in Sigrist (2010) and shown in Figure 3 will be modified. The underfrequency relay and the RoCoF blocks described in 152.2 are replaced by a single frequency protection scheme. Figure 7 shows a representation of this logic block diagram which contains all the essential elements for the implementation of the new threshold. The detailed model of the UFLS scheme that will be used for the simulation can be found in APPENDIX I:.

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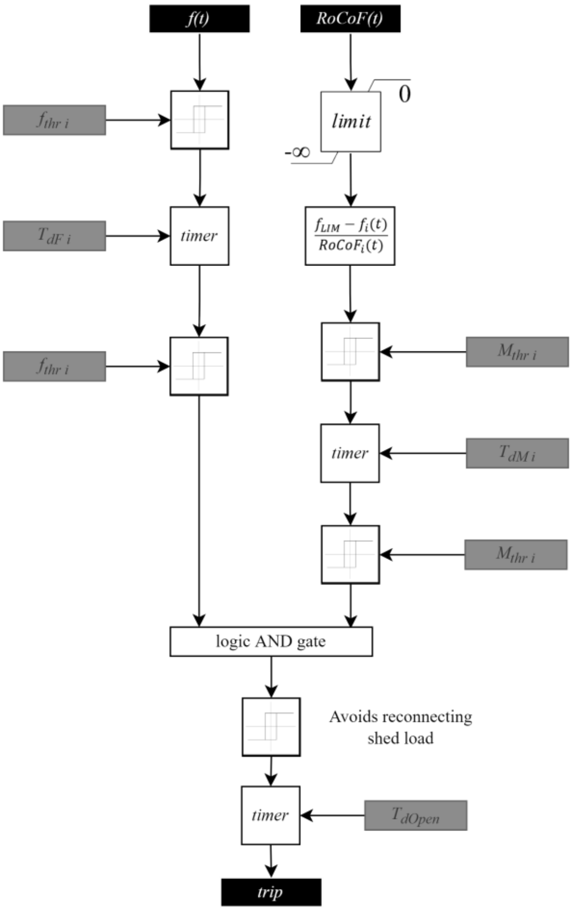

Figure 7. Logical block diagram for the realization of the suggested modification

The input variables are *f(t)* and *RoCoF(t)*. Contrary to Rudez (2021), a single measurement of *RoCoF(t)* will be made since the distinction between 'fast' and 'slow' is only significant in terms of measurement accuracy and the simulation involves ideal (noise-less) frequency measurement. Moreover, given that the relevant parts of the frequency response are those in which frequency decays, only negative values of *RoCoF(t)* will be considered. Subsequently, equation (4) applied to calculate the frequency stability margin, *M(t)*. Then, both *f(t)* and *M(t)* are compared with their respective threshold. The corresponding hysteresis block return a '1' if an individual threshold is infringed and a '0' otherwise. Thereafter, a time delay is activated and once the duration of each threshold violation lasts long enough (T_{dF} or T_{dM}), the block outputs are set to '1', respectively. In case that both of them return a '1', the shedding step is activated. Preceding the breaker trip, a block is placed to prevent any shed group from reconnecting once frequency stability has recovered, because the aim of the UFLS is not to reach $f=50Hz$ in steady time, but to restore the power equilibrium. Finally, the last time delay represents the time it takes for the relay to activate once the signal has been sent. This block is essential, because if it were not included, the model would not be realistic, since in real life this step is not immediate.

2.3.3 UFLS DESIGN

A good UFLS design must meet two characteristics: robustness and efficiency. Efficiency is attained by tuning a scheme that minimizes the load shed without jeopardizing system stability. While robustness is achieved by selecting the appropriate representative scenarios, in this project, the O&C scenarios chosen by Sigrist (2010) through clustering techniques will be used.

The configuration of each UFLS stage involves i) frequency threshold ($f_{thr,i}$) ii) intentional delays (T_{dF}, T_{dM}) iii) amount of disconnected load and iv) frequency stability margin ($M_{thr,i}$).

The first frequency threshold should not be set too high to ensure that no unnecessary load is shed during transient or small incidents. Typically, for small isolated power systems, frequency should remain within 47.5 Hz and 52 Hz (METyAD, 2018), and frequency thresholds should be comprised between 47 and 49 Hz. Therefore, in this project frequency thresholds are linearly distributed between 48 Hz and 49 Hz, i.e., for six steps, $\Delta\omega_{thr} = 0.2$ Hz.

Time delays are critical with respect to the performance of an UFLS scheme, they are introduced to override transients and reduce load shedding. Nonetheless, they should be cautiously applied, since excessive time delays can lead to large frequency deviations. To simplify the design of the shedding scheme, time delays are maintained constant and equal to 100ms for $f_{thr,i}$ and $M_{thr,I}$, as Rudez (2021) proposed. Furthermore, an additional time delay exists, which cannot be tuned, since it represents the opening signal delay. A typical value to characterize it is 200ms.

The number of steps and their size are also key in the design of the UFLS scheme. The number of steps depend on each power system and their installed power capacity. Typically, three to six stages are implemented for small isolated power systems. Besides, if the step size is too small, undershedding occurs for large perturbances; while if it is too large, overshedding occurs for small perturbances (Sigrist, 2010). For small EPSs, like the La Palma power system, the step size is usually defined by the utility and also depends on the feeder connected to the relays, so it will be difficult to find feeder blocks that sum up to the desired step size (Sigrist, 2010). Thus, a size of 5-15% per step is generally set (Sigrist, Rouco, & Echavarren, 2018).

Once theses parameters are determined, the frequency stability margin is tuned. The first step to adjust M_{thr} is to select f_{LIM}. REE (2005) sets the minimum frequency limit to 47.5 Hz during 3s, however, a more conservative value is taken here to achieve some security margin (48 Hz during 2s). The reason behind it is that small isolated power systems are very sensitive to contingencies and, hence, they exhibit more oscillations and drastic RoCoF, compared to large meshed power systems. Consequently, taking a conservative value ensures that, once the thresholds are violated and the activation signal is sent, the system does not become unstable while the opening time delay elapses.

Figure 8 illustrates the flowchart employed to obtain M_{thr}, this is an adapted version of the one proposed by Rudez (2021). Rudez considers homogeneous deficits of active power, which is not representative of real contingencies in power systems. Therefore, the tuning approach followed in this project is based on representative operating and contingency scenarios. The logic applied consists, first, in simulating and ranking a set of representative O&C scenarios from least severe to most extreme in terms of f_{min}. Afterwards, the least severe case is taken and simulated first. Then, the frequency response is compared to f_{LIM}, if $f_{min} > f_{LIM}$, the next scenario is simulated. Otherwise, $f(t)$-$M(t)$ is plotted and the value of $M_{thr,i}$. is estimated. Finally, the first UFLS step is activated. If after triggering the first stage it still violates f_{LIM}, the process of representation and definition of M_{thr} is repeated and a new UFLS stage is activated until $f_{min} > f_{LIM}$ in all scenarios.

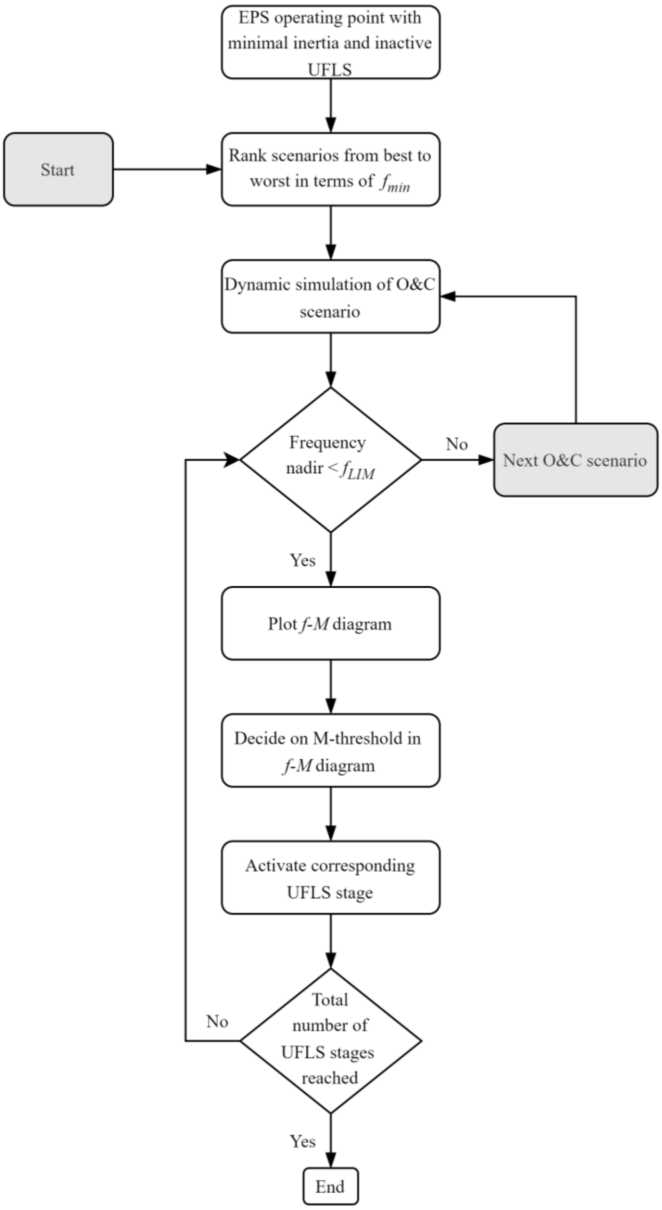

Figure 8. Flowchart for setting $M_{thr,i}$

2.4 APPLICATION EXAMPLE

To illustrate the performance of the proposed M-based UFLS scheme presented in section 2.3, the frequency stability margin threshold will be applied to four O&C scenarios of the La Palma power system. The selected generation dispatch scenarios are 25 and 26, which correspond to peak and valley power demand scenarios, and the chosen contingencies are the loss of the largest and the smallest generation units, respectively. The outages of generators G13 and G17 for generation dispatch 25, and the outages of G11 and G17 for generation dispatch 26 are simulated. Table 1 shows detailed information on the selected O&C scenarios.

Scenario	Generator	Pdem (MW)	Ploss (MW) (%)
25	G13	18.09	2.35 (12.99)
25	G17	18.09	9.16 (50.64)
26	G11	37.1	2.35 (6.33)
26	G17	37.1	11.38 (30.67)

Table 1. Operating and contingency scenarios of the La Palma power system

The UFLS scheme has been configured considering $f_{LIM} = 48Hz$. Table 2 displays the novel UFLS scheme of the La Palma power system. Section 3.3 will provide a detailed explanation of how the parameters have been tuned.

UFLS relays							
Stage	Substation	ω (Hz)	M (s)	$t_{int, F}$ (s)	$t_{int, M}$ (s)	t_{open} (s)	Step size (%)
1	2101	49.0	0.73	0.1	0.1	0.2	7.1
2	2102	48.8	0.39	0.1	0.1	0.2	0.6
3	3101	48.8	0.39	0.1	0.1	0.2	14.5
4	2103	48.6	0.13	0.1	0.1	0.2	3.6
5	1101	48.6	0.13	0.1	0.1	0.2	7.3
6	1111	48.4	0.087	0.1	0.1	0.2	13.6

Table 2. Novel UFLS scheme of the La Palma power system

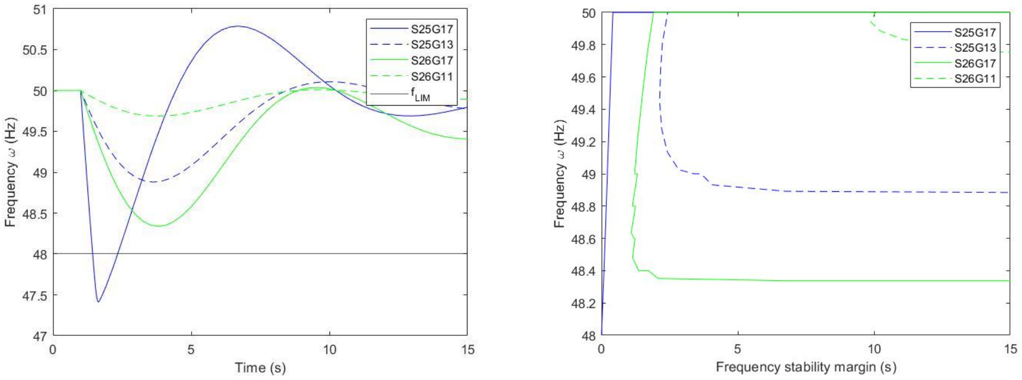

Figure 9. Model responses of the novel UFLS scheme of the La Palma power system

The results displayed in Table 3 show that the novel scheme is capable of distinguishing between critical and non-critical conditions. In Figure 9 it can be observed that the S25G17 disturbance is very severe. During this incident, almost half of the power system generation is lost and frequency decays rapidly. The UFLS scheme detects this drastic incident and takes action by activating all the shedding stages. In the other scenarios, frequency stability is maintained and it can be seen in the *f(t)-M(t)* diagram how the trajectories are naturally re-directed back towards the right-hand side of the graph. The power system recovers smoothly with the help of primary control, the generating units are able to restore the power balance with their spinning reserve.

Scenario	Generator (MW) (%)	ω_{min} (Hz)	ω_{max} (Hz)	#Relays	Pshed (MW)
25	2.35 (12.99)	48.88	50.11	0	0
25	9.16 (50.64)	47.41	50.78	6	8.45
26	2.35 (6.33)	49.69	50.01	0	0
26	11.38 (30.67)	48.34	50.04	0	0

Table 3. Performance of the novel UFLS scheme of the La Palma power system

In order to understand and test the operation of the novel UFLS scheme, the most drastic event shown above will be analyzed in detail. At instant t = 1 s, when both power generation and demand are 18.09 MW, G17 is lost, i.e. 50.64% of the generation is tripped. Due to the power imbalance, frequency drops drastically. The UFLS scheme measures the frequency and calculates the frequency stability margin in real time. These values are continuously compared with the defined thresholds, respectively, and if both are violated after the intentional delay has elapsed, the corresponding load is shed Table 4 outlines some representative instants of the dynamic frequency response. The left-hand side of the table shows the values of frequency and frequency stability margin, while the right-hand side presents the points at which the load is triggered. By comparing Table 4 with Table 2, it can be seen that, even though $M_{thr,1}$ before $f_1=49.0\ Hz$ is reached, the UFLS scheme waits until $t=1.211s$ (i.e. when both thresholds are violated) to activated the shedding steps. Furthermore, the effect of the two time delays can be appreciated in Table 4. Once both delays have elapsed, the system sends the trigger signal. Finally, it can be noted that for $f(t) = 48.0Hz$ $M(t)=0$, which is consistent with the definition of this parameter (equation (4)).

S25C17				
			UFLS scheme	
t (s)	f (Hz)	M (s)	stage	t(s)
1.125	49.40	0.296		
1.211	**49.00**	**0.214**	**1**	**1.493**
1.255	**48.80**	**0.174**	**2,3**	**1.539**
1.260	48.78	0.170		
1.299	48.60	0.133		
1.302	**48.58**	**0.130**	**4,5**	**1.582**
1.344	48.40	0.090		
1.344	48.40	0.091		
1.347	**48.38**	**0.087**	**6**	**1.620**
1.436	48.00	0.000		

Table 4. Frequency response of S25C17

Chapter 3. RESULTS

After modelling the power system and explaining in detail the new shedding criterion, the design of the novel UFLS scheme for a set of representative disturbance is carried out. In this chapter, the method for tuning the new parameter will be described. Furthermore, the selection of the O&C scenarios and their relevance in the results will be explained. Next. a comparison with the existing designs will be presented and, finally, the impact of decoupled power generation, of varying f_{LIM} on frequency stability and the performance of the novel UFLS scheme under multiple contingencies will be addressed.

3.1 DESCRIPTION OF THE POWER SYSTEM

The model described in section 2.1 will be applied to the La Palma power system, which is a small power system that consists of eleven generators. The generation parameters are displayed in Table 5 (Sigrist, 2010). The La Palma power system will be represented through a block diagram with the Simulink tool (see APPENDIX I:). It is modelled with a single bus to which all demand and generations are connected. It has the following inputs: the turbine-governor system, which in case of an incident will provide with their spinning reserve to recover the power equilibrium; the energy storage system, although it is not considered in this project; the perturbance, i.e. the outage of a generating unit, and finally, the UFLS scheme, which will intervene when the primary frequency control is insufficient to cope with the disturbance. Whereas the output of the model is the frequency response, which is determined through the inputs mentioned above and the inertia of the rotor. Note that the replacement of the conventional UFLS scheme by the novel UFLS scheme will only affect the UFLS block, the other blocks will remain the same.

Generator	H (s)	K	b1 (s)	b2 (s)	a1 (s)	a2 (s)	Pmin (MW)	Pmax (MW)
G11	1.75	20	1.44	0	18.60	3.98	2.5	4.0
G12	1.75	20	1.44	0	18.60	3.98	2.5	4.0
G13	1.75	20	1.44	0	18.60	3.98	2.5	4.0
G14	1.73	20	1.44	0	18.60	3.98	3.0	4.5
G15	2.16	20	1.32	0	18.40	2.7	3.5	7.0
G16	1.88	20	1.43	0	18.70	3.85	3.5	7.0
G17	2.10	20	1.32	0	18.30	2.71	7.0	12.0
G18	6.50	21.25	0.89	0	5.66	3.48	0.0	22.8
G19	2.10	20	1.32	0	18.30	2.71	7.0	12.0
G20	2.10	20	1.32	0	18.30	2.71	7.0	12.0
G21	2.10	20	1.32	0	18.30	2.71	7.0	12.0

Table 5. Parameters of the generator models of the La Palma power system (Sigrist, Egido, & Rouco, 2012)

S. O. C.	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20	G21	$P_{G_{tot}} = P_{D_{tot}}$
1	2.35	0.00	2.35	0.00	3.29	3.69	10.41	0.00	0.00	0.00	0.00	22.09
2	0.00	0.00	2.35	0.00	3.29	4.26	9.26	0.00	0.00	0.00	0.00	19.16
3	0.00	0.00	2.35	0.00	3.29	3.29	9.55	0.00	0.00	0.00	0.00	18.48
4	0.00	0.00	2.35	0.00	3.29	3.69	8.96	0.00	0.00	0.00	0.00	18.29
5	0.00	0.00	2.35	0.00	3.29	3.29	9.35	0.00	0.00	0.00	0.00	18.28
6	0.00	0.00	2.35	0.00	3.29	3.29	9.61	0.00	0.00	0.00	0.00	18.54
7	2.35	0.00	2.35	0.00	3.29	3.29	10.02	0.00	0.00	0.00	0.00	21.30
8	2.53	0.00	2.53	0.00	5.84	5.84	0.00	0.00	6.63	4.00	0.00	27.37
9	2.35	0.00	2.35	2.82	4.92	4.92	0.00	0.00	6.63	6.70	0.00	30.69
10	2.41	0.00	2.41	2.82	5.59	5.59	0.00	0.00	6.63	6.70	0.00	32.15
11	2.46	0.00	2.46	2.82	5.69	5.69	0.00	0.00	6.63	6.70	0.00	32.45
12	2.49	0.00	2.49	2.82	5.77	5.77	0.00	0.00	6.63	6.70	0.00	32.67
13	2.58	0.00	2.58	2.82	5.96	5.96	0.00	0.00	6.63	6.70	0.00	33.23
14	2.40	0.00	2.40	2.82	5.56	5.56	0.00	0.00	6.63	6.70	0.00	32.07
15	2.35	2.35	2.35	2.82	5.12	5.12	0.00	0.00	6.63	4.00	0.00	30.74
16	2.35	2.35	2.35	2.82	4.74	4.74	0.00	0.00	6.63	4.00	0.00	29.98
17	2.35	2.35	2.35	2.82	4.22	4.22	0.00	0.00	6.63	4.00	0.00	28.94
18	2.35	2.35	2.35	0.00	3.29	3.29	9.21	0.00	6.63	0.00	0.00	29.47
19	2.35	2.35	2.35	0.00	3.29	3.29	8.68	0.00	6.63	0.00	0.00	28.94
20	2.35	2.35	2.35	0.00	3.29	3.29	9.35	0.00	6.63	0.00	0.00	29.61
21	2.35	2.35	2.35	0.00	3.71	3.71	11.38	0.00	6.63	0.00	0.00	32.48
22	2.35	2.35	2.35	0.00	3.58	3.58	11.38	4.85	6.63	0.00	0.00	37.07
23	2.35	2.35	2.35	0.00	3.63	3.63	11.38	0.00	6.63	0.00	0.00	32.32
24	2.35	2.35	2.35	0.00	3.29	3.29	6.63	0.00	6.63	0.00	0.00	26.89
25	0.00	0.00	2.35	0.00	3.29	3.29	9.16	0.00	0.00	0.00	0.00	18.09
26	2.35	2.35	2.35	0.00	3.58	3.58	11.38	4.85	6.66	0.00	0.00	37.10

Table 6. Generation dispatch scenarios of the La Palma power system without decoupled power (Sigrist, 2010)

The different generation dispatch scenarios of the La Palma power system without taking decoupled generation into account are depicted in Table 6. These parameters will be used to model the novel UFLS scheme through representative O&C scenarios and to finally check the validity of its response to all possible operating and contingency scenarios.

Table 7Table 7. Existing UFLS scheme of the La Palma power system Table 7 displays the existing UFLS of the La Palma power system, whereas Table 8Table 8 details the optimized UFLS scheme. In both cases, the UFLS stages are sorted in order of priority of load shedding, i.e. non critical loads should be shed first (typically residential, commercial and smaller industries customers), whereas critical ones (typically public safety, and health, large industrial customer, etc.) will be ultimately disconnected.

Underfrequency relays					
Stage	ω (Hz)	t_{int} (s)	t_{open} (s)	Step size (%)	Cumulative (%)
1	48.81	0.6	0.2	7.1	7.1
2	48.81	0.9	0.2	0.6	7.7
3	48.66	1.3	0.2	14.5	22.2
4	48.66	1.8	0.2	3.6	25.8
5	48.66	2.3	0.2	7.3	33.1
6	48.00	1.2	0.2	13.6	46.7
7	48.00	1.7	0.2	12.5	59.2
8	47.00	1.8	0.2	4.2	63.4
9	47.00	2.1	0.2	15.1	78.5
10	47.00	2.4	0.2	20.5	99.0

RoCoF relays						
Stage	ω (Hz)	$d\omega/dt$ (Hz/s)	t_{int} (s)	t_{open} (s)	Step size (%)	Cumulative (%)
1	49.50	-1.8	0.1	0.2	7.1	7.1
2	49.50	-1.8	0.1	0.2	0.6	7.7
3	49.50	-1.8	0.1	0.2	14.5	22.2
4	49.50	-1.8	0.1	0.2	3.6	25.8

Table 7. Existing UFLS scheme of the La Palma power system (Sigrist, 2010)

The model shown in Table 8Table 8 was obtained from (Sigrist, 2010), where Sigrist optimized the existing UFLS scheme of the La Palma power system, by means of the adaptative Annealing algorithm. The values of 'topen' and 'Step size' remained the same, while the rest of the parameters were optimized. Moreover, he adopted a more conservative approach by tuning the scheme with a more restrictive minimum allowable frequency (48Hz for maximum 2s). Finally, note that only six stages (bold type values) were optimized. The reason behind this is that in the La Palma power system, the worst-case scenario involves a loss of 51.83% generation (scenario 6, group 17) and, thus, six load shedding steps are sufficient to stabilize frequency. This model has been proven to be more robust and efficient, it significantly reduces shedding errors, decreases frequency deviation, and additionally lowers the amount of load shed (Sigrist, 2010).

Underfrequency relays					
Stage	ω (Hz)	t_{int} (s)	t_{open} (s)	Step size (%)	Cumulative (%)
1	**48.20**	**0.49**	**0.2**	**7.1**	**7.1**
2	**48.08**	**0.21**	**0.2**	**0.6**	**7.7**
3	**47.98**	**0.23**	**0.2**	**14.5**	**22.2**
4	**47.81**	**0.50**	**0.2**	**3.6**	**25.8**
5	**47.60**	**0.15**	**0.2**	**7.3**	**33.1**
6	**47.44**	**0.0**	**0.2**	**13.6**	**46.7**
7	-	-	0.2	12.5	59.2
8	-	-	0.2	4.2	63.4
9	-	-	0.2	15.1	78.5
10	-	-	0.2	20.5	99.0

RoCoF relays						
Stage	ω (Hz)	$d\omega/dt$ (Hz/s)	t_{int} (s)	t_{open} (s)	Step size (%)	Cumulative (%)
1	**49.55**	**-2.1**	**0.05**	**0.2**	**7.1**	**7.1**
2	**49.55**	**-2.1**	**0.05**	**0.2**	**0.6**	**7.7**
3	**49.55**	**-2.1**	**0.05**	**0.2**	**14.5**	**22.2**
4	**49.55**	**-2.1**	**0.05**	**0.2**	**3.6**	**25.8**

Table 8. Optimized UFLS scheme of the La Palma power system (Sigrist, 2010)

3.2 DESIGN BASED ON FOUR O&C SCENARIOS

As seen before, the selected representative O&C scenarios are a key element in the design of robust UFLS schemes. Table 9Table 9 provides detailed information on the 4 chosen scenarios.

Nº Case	Scenario	Generator	Pdem (MW)	Ploss (MW) (%)	ω_{min} (Hz)
1	3	G17	18.48	9.55 (51.68)	-
2	10	G20	32.15	6.70 (20.84)	47.77
3	15	G11	30.74	2.35 (7.64)	49.40
4	16	G16	29.98	4.74 (15.81)	48.70

Table 9. Representative operating and contingency scenarios

From Table 9Table 9 it can be deduced that out of the 4 scenarios, only 2 will be used to tune M_{thr}, since in the last two, the minimum frequency is kept above $f_{LIM} = 48.0Hz$ without applying any additional control. By following the steps described in the previous section and simulating the 164 possible contingencies with the configuration obtained, the resulting response is as follows:

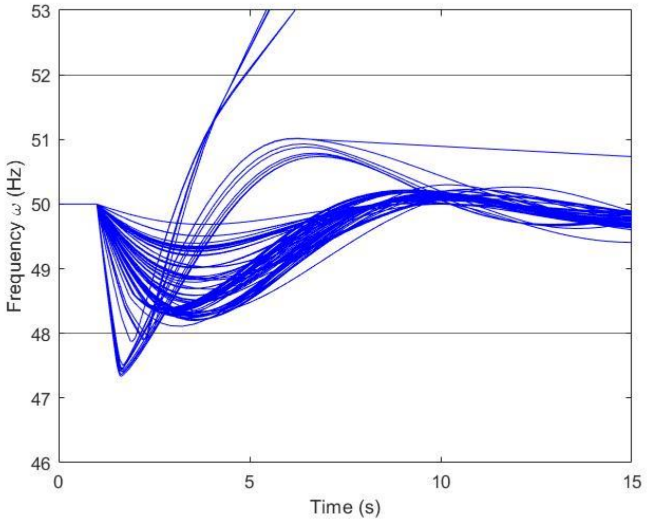

Figure 10. Response of the power system to all possible outages for all operating conditions with the novel UFLS scheme of the La Palma power system tuned with 4 contingencies

There is overshedding in various cases. This suggests that the configuration designed from the two scenarios does not fit for all cases and is not sufficiently robust. The setting of the intermediate cases is affected by the large different of power loss in the cases that have been studied. The fact that the minimum frequency of Case 2 is close to 48.0Hz, suggests that the thresholds of the medium disturbances have been design mainly using Case 1, which is very sever, as it entails a loss of more than 50% of total generation. For all these reasons, to achieve a correct and robust setting, it is convenient to choose an additional representative event that contemplates the intermediate cases.

3.3 DESIGN BASED ON FIVE O&C SCENARIOS

In the previous section, the UFLS scheme was configured with two extreme events, a moderate and a drastic power loss. Therefore, a new scenario was considered to cover a wider frequency range and, hence, provide an accurate setting for the intermediate cases. The selection criterion consisted of searching for a disturbance with a power loss within the range of 20.84% to 51.68%. Additionally, it was checked whether there was overshedding for the design obtained in 3.2. The scenarios that met both criteria implied the loss of G17. Finally, the outage of generator G17 for generation dispatch 20 was chosen. The characteristics of the final set of representative O&C scenario are presented in Table 10.

Nº Case	Scenario	Generator	Pdem (MW)	Ploss (MW) (%)	ω_{min} (Hz)
1	3	G17	18.48	9.55 (51.68)	-
2	10	G20	32.15	6.70 (20.84)	47.77
3	15	G11	30.74	2.35 (7.64)	49.40
4	16	G16	29.98	4.74 (15.81)	48.70
5	20	G17	29.61	9.35 (31.58)	46.84

Table 10. Detailed information on the additional O&C scenario

The tuning methodology described in 2.3.3 was applied with the new incident and the following design of the UFLS scheme was obtained:

UFLS relays							
Stage	Substation	ω_{thr} (Hz)	M_{thr} (s)	$t_{int, F}$ (s)	$t_{int, M}$ (s)	t_{open} (s)	Step size (%)
1	2101	49.0	0.730	0.1	0.1	0.2	7.1
2	2102	48.8	0.390	0.1	0.1	0.2	0.6
3	3101	48.8	0.390	0.1	0.1	0.2	14.5
4	2103	48.6	0.130	0.1	0.1	0.2	3.6
5	1101	48.6	0.130	0.1	0.1	0.2	7.3
6	1111	48.4	0.087	0.1	0.1	0.2	13.6

Table 11. Novel UFLS scheme of the La Palma power system

In can be seen that the maxim value of $M_{thr,i}$ obtained is 0.730 s, which is considerably below the maximum limit defined by Rudez (2021), $M_{thr}=2s$, to ensure that load shedding is minimized. This large difference between the thresholds is caused by the fact that Rudez took as a case study a system with an equivalent inertia of $H_{eq} = 6s$, whereas the inertia of the representative O&C scenarios of the La Palma power system was approximately $H_{eq} = 1.95s$. Due to the lower inertia, the frequency drop is faster, and the system becomes more unstable in the event of a contingency. Therefore, the La Palma power system presents a larger *RoCoF(t)* and, hence, smaller *M(t)*. Another factor that causes *M(t)* to decrease is the fact that a more conservative f_{LIM} has been applied. Thereby, it can be concluded that the design of $M_{thr,i}$ is highly dependent on the characteristics of the power system under study.

Regarding the final design of the novel UFLS, it should be outlined that, given that the greatest contingency of the O&C scenarios implied a loss of 51.68%, the total number of UFLS stages needed to tune $M_{thr,i}$ were six (i.e. 46.7% of cumulative load). In addition, the frequency thresholds were set between 49.0 and 48.4 Hz, contrary to what was proposed in section 2.3.3 (48.0 – 49.0 Hz). The reason behind it is that if $f_{thr} = 48.0Hz$ is set, the stability of the power system could be compromise, because, on the one hand, a very small threshold of M_{thr} would be defined ($M_{thr,i}=0s$), causing the load-shedding to be significantly delayed and, on the other hand, the frequency might fall below f_{LIM} while the time delays elapse. Furthermore, no step was designed for $f_{thr} = 48.2Hz$ since, after several tests, it was found that the configuration shown in Table 11 was the one that offered the best performance. Finally, given that step 2 and 4 implied a lower amount of load to be shed compared to the other UFLS steps, in the final setting it was decided to combine both step 2 and 3, and 4 and 5, respectively, hence they were tuned with the same values of f_{thr} and M_{thr}.

Figure 11. Responses of the power system to all possible outages for all operating conditions with the novel UFLS scheme of the La Palma power systemFigure 11 shows the system response to all possible operating and contingency scenarios. It can be inferred that the novel UFLS scheme exhibits a good response to the disturbances. The maximum allowable frequency is not exceeded, while the minimum frequency is barely violated for less than 2s, which is within the specified range. Further, there is a clear improvement over the response shown in Figure 10Figure 10, because there is no overshedding in any scenario.

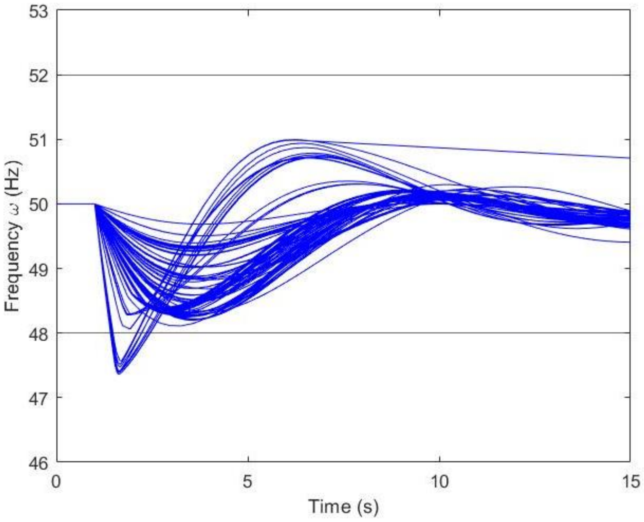

Figure 11. Responses of the power system to all possible outages for all operating conditions with the novel UFLS scheme of the La Palma power system

Note that both in Figure 10 and Figure 11 there is an event in which the system takes longer to stabilize. For this disturbance, G17, the generator with the largest spinning reserve and the highest generation (47.04% of total generation), is triggered. A possible explanation for this behavior is the fact that, when the generating unit is lost, frequency drops sharply reaching in the first instants a RoCoF of -4.35 Hz/s, while the allowable range of operation during the transient is between -1.0Hz/s and -2.0Hz/s (Sigrist, Rouco, & Echavarren, 2018). Load shedding stops frequency decay and frequency overshoots above its nominal value, where the remaining the generating units need to reduce generation. Some units are close to their minimum value, slowing down the dynamic response. Nonetheless, the overall performance of the system is good, as the UFLS scheme is able to cope with the perturbance and, although it takes longer to recover the power equilibrium, the disconnected load (46.70% of total demand) is lower than the power loss.

3.4 COMPARISON WITH CONVENTIONAL STATIC UFLS SCHEMES

This section will compare the proposed model with the current UFLS scheme and an optimized version of the existing scheme. The aim is to evaluate the feasibility and usefulness of implementing the frequency stability margin, M_{thr}, as a new shedding criterion. As previously stated, the main objective of the novel scheme is to reduce the disconnected load. It avoids shedding load in situations in which the system is able to recover naturally, and it is able to rapidly act in the event of severe contingencies, i.e. drastic drops of RoCoF; while at the same time preserves the security and reliability of the power system.

		Existing UFLS scheme		Optimized UFLS scheme		Novel UFLS scheme	
Scenario	Generator (MW) (%)	ω_{min} (Hz)	Pshed (MW)	ω_{min} (Hz)	Pshed (MW)	ω_{min} (Hz)	Pshed (MW)
3	9.55 (51.68)	46.58	10.95	47.13	8.63	47.36	8.63
10	6.70 (20.84)	48.05	7.13	48.21	6.71	48.35	2.10
15	2.35 (7.64)	49.40	0	49.40	0	49.40	0
16	4.74 (15.81)	48.69	2.31	48.7	0	48.7	0
20	9.35 (31.58)	48.83	7.63	48.96	7.64	48.28	6.58

Table 12. Comparison of the performance of the three UFLS schemes of the La Palma power system

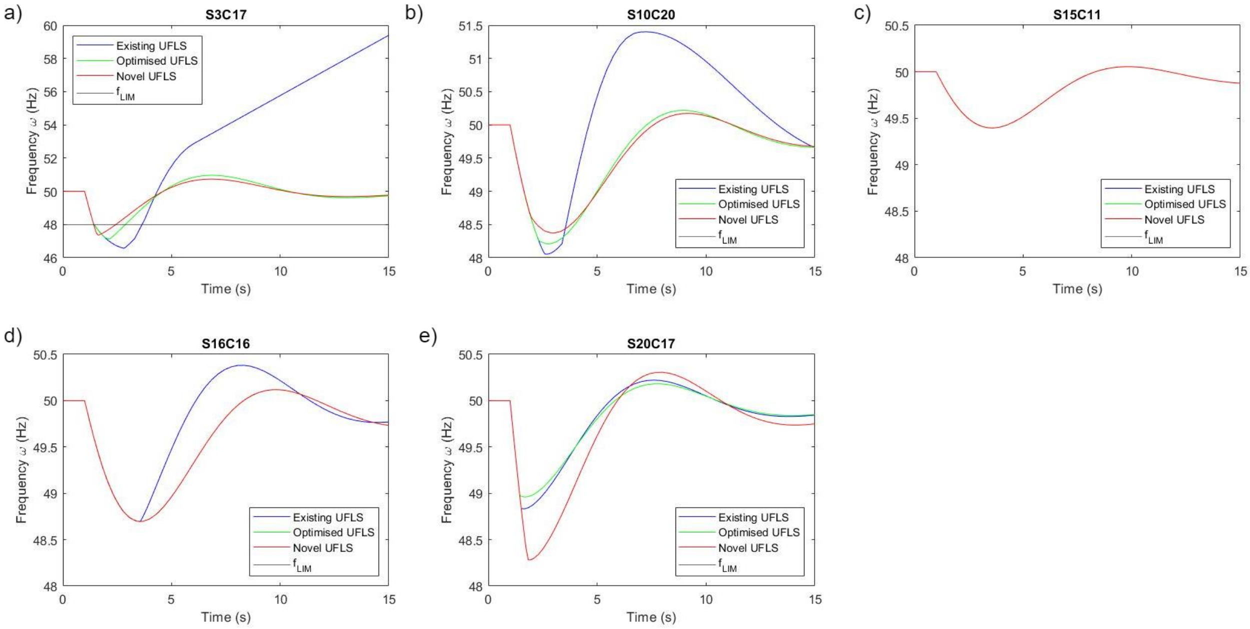

Figure 12. Comparison of the three different UFLS scheme configurations

Table 12 and Figure 12 compare the frequency response of the representative scenarios used to design the M-based scheme. It can be appreciated that the best performance is provided by the novel and the optimized UFLS schemes. In a) outage of S3C17, the existing scheme disconnects an excessive amount of load, greater than the lost generation, and therefore the power system transforms an initial underfrequency situation into an overfrequency problem where the power balance is upset by overshedding. Whereas the other two schemes show a good response. It should be noted that the proposed scheme was able to detect the severity of the contingency (loss of more than 50% of the total generation) and shed load rapidly, causing the frequency to remain less time below $f_{LIM} = 48Hz$. Again, in b) outage of S10C20, the current UFLS scheme activates extra UFLS stages, causing the maximum frequency peak to be higher compared to the other designs. Both in the optimized and the novel scheme, by tripping only one stage and with the help of the spinning reserve, the power system returns the power mismatch to zero.

In the third scenario, c) outage of S15C11, as the power loss is very small (7.64%), no load shedding step is activated. The primary frequency control alone contains frequency variations. This also applies to scenario d), but contrary to the previous case, the existing scheme, unnecessarily, triggers one UFLS step. Furthermore, it should be highlighted that, in the remaining scenario, a) outage of S20C17, the highest minimum frequency peak occurs with the novel setting. This happens because it lets the frequency drop close to f_{LIM} to decrease frequency overshoots and load-shedding.

Finally, the dynamic frequency response of the La Palma power system to the 164 possible contingency scenarios is simulated (see Figure 13). Again, there is an improvement in the overall response of the novel and the optimized schemes over the current shedding practices, since in both cases the minimum and maximum peak values remain within the acceptable range and no frequency overshoot occurs. It is clearly seen that the proposed system, as well as the optimized, significantly improves the frequency response of the existing scheme and in all cases prevents the response from becoming unstable.

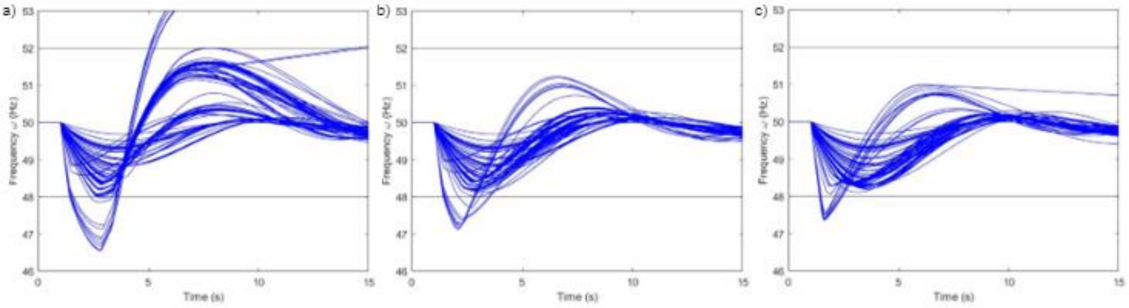

Figure 13. Overall response of the different UFLS scheme configurations. a) existing UFLS scheme, b) optimized conventional UFLS scheme and c) novel UFLS scheme

Moreover, although the optimized UFLS scheme already offers a significant improvement, the M-based scheme further reduces the number of activated relays and, consequently the load shed. Table 13 and Figure 14 provide a detailed comparison of the three designs. Here it can be observed that the novel UFLS scheme reduces approximately 63% of the disconnected load compared to the existing scheme and 20% with respect to the optimized UFLS. This is a remarkable enhancement, as fewer consumers are disconnected from the grid while the integrity of the power system is preserved. Note however that this is also due to the fact that the novel scheme has joined steps, which has not been considered in case of the optimized UFLS scheme.

	UFLS performance		
Case	Total shed (MW)	Nº Relays	ΣΔωmin (Hz)
Existing	461.70	255	206.67
Optimised	213.36	121	200.02
Novel	169.98	94	200.35

Table 13. Performance of the different UFLS scheme designs

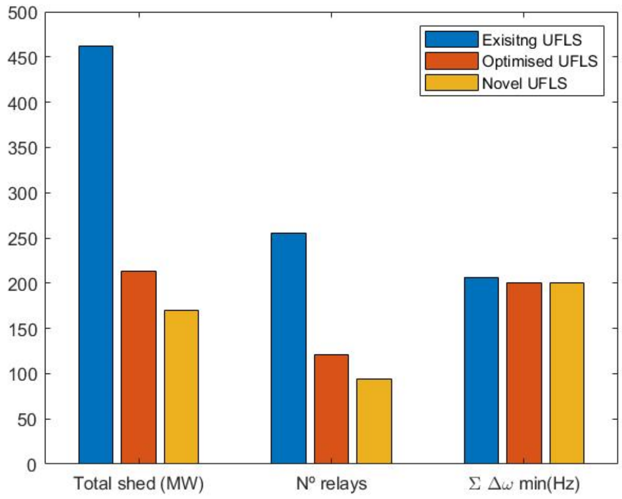

Figure 14. Comparison of the performance of the original, the optimized and the novel UFLS scheme

It might be striking that, despite having lower minimum frequency peaks, the total sum of the minimum frequency is almost equal in the novel UFLS and in the optimized scheme. This happens because the amount of load-shedding is reduced in the proposed scheme. If the disturbance is not considered to be very severe, the UFLS leaves the system to recover exclusively with its spinning reserve, and this may result in higher minimum values in those scenarios in which load-shedding is avoided or delayed. Whereas in the current UFLS scheme, frequency variations are smaller for less severe outages, but they are larger in the case of large outages. In general, these differences are compensated and result in approximately the same minimum cumulative frequency deviations.

3.5 SENSITIVITY ANALYSIS

A sensitivity study will be carried out to study the effectiveness of the frequency margin threshold. Thus, the impact of varying the design parameter f_{LIM}, the inclusion of RES in the generation mix and the response under consecutive generator outages, for which the UFLS scheme was not designed, will be analyzed.

3.5.1 VARIATION OF F_{LIM}

The novel UFLS scheme lets the frequency drop close to f_{LIM} to decrease frequency overshoots. This occurs when the violation is not expected to happen soon, i.e. the RoCoF is moderate. In this project the frequency-stability limit has been set to 48.0Hz, while REE (2005) recommends that frequency should not drop under 47.5Hz. Therefore, in this section it is intended to study the effect of the choice of f_{LIM} on the power system. Figure 15 shows the different frequency responses resulting from varying this constraint between 47.5Hz and 48.2Hz for the outage of generator G19 for dispatch scenario 8. The overall performance of the La Palma power system for the different f_{LIM} values and the designed parameters can be found in APPENDIX III:.

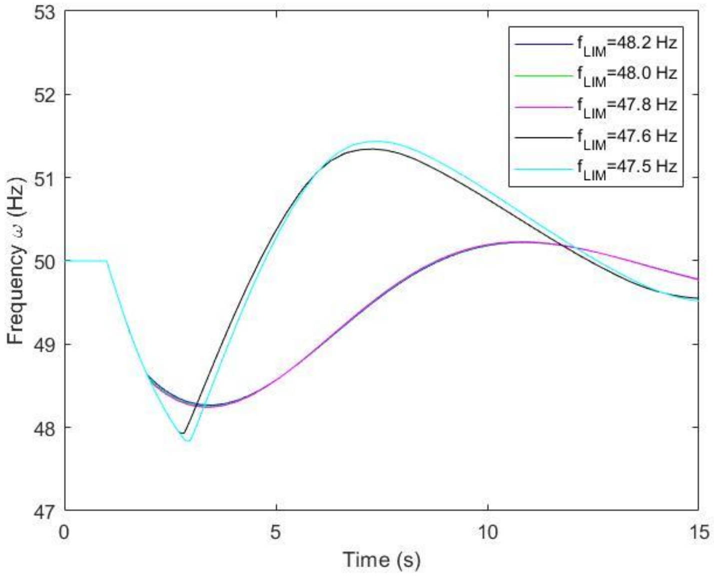

Figure 15. Effect of varying f_{LIM} on the novel UFLS scheme (dispatch scenario 8, outage of G19)

It can be observed that the more conservative f_{LIM} is, the faster the system take actions in the event of a contingency. In principle, this may seem to be an advantage as it avoids compromising the integrity of the system. However, it can happen that the UFLS scheme triggers load shedding steps even though the power system could have recovered naturally, causing possible overshoots. Thus, it can be argued that an extremely conservative approach can turn the problem of underfrequency into one of overfrequency, since unnecessary load shedding rise. On the other hand, the closer f_{LIM} gets to 47.5Hz, the more time the system takes to cope with the frequency decay. It has been observed that depending on the severity of the contingency, two different situations may arise. If the power loss is moderate, there may be no load shedding and the power balance is restored by means of the available spinning reserve, leading to a reduction of the disconnected load. However, in the event of larger outages, by delaying the UFLS scheme intervention and letting the frequency drop close to 47.5Hz, it can result in a larger frequency deviation, causing the power system to shed an excessive amount of load to arrest frequency instability. Indeed, this occurs in Figure 15 for $f_{LIM} = 47.5Hz$ and $f_{LIM} = 47.6Hz$, where more load-shedding steps are activated compared to more conservative f_{LIM} values.

For all these reasons, it can be concluded that the more restrictive f_{LIM} is, the earlier the novel UFLS scheme will intervene, the larger the safety margin will be, but, however, the greater the possibility of overshedding will be. Whereas the lower f_{LIM} is, the higher is the chance that the system will become unstable and severe minimum frequency peaks will appear. Consequently, special attention should be paid when setting f_{LIM}. The optimal value will depend on the power system and the available spinning reserves.

3.5.2 IMPACT OF RES GENERATION

With the increasing penetration of renewables in the energy mix, the inertia of power systems is expected to decrease significantly since RES generation is usually decoupled generation. Moreover, due to the fluctuating nature of renewables, inertia is expected to vary with time (Rudez, Sodin, & Mihalic, 2021). Hence, for the same generation-demand conditions, the power system will present lower underfrequency values and faster frequency decays.

Consequently, it is of great interest to analyze the dynamic response of the proposed UFLS model to inertia variations. For this purpose, the novel UFLS scheme presented in 3.3 will again be applied to the La Palma power system, but now, including the contribution of RES to the total generation (see APPENDIX II:).

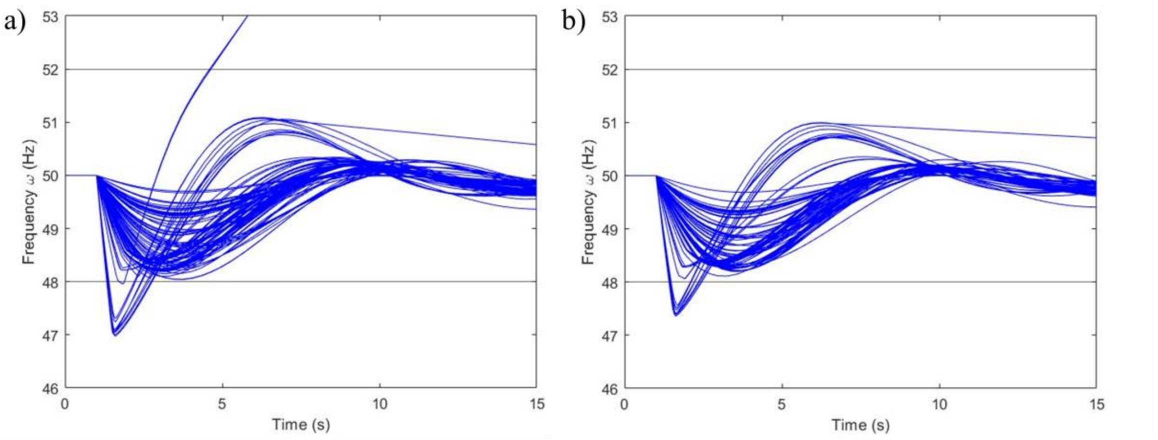

Figure 16. Overall response of the novel UFLS scheme (a) with RES (b) without RES

Figure 16 illustrates the response of the La Palma power system to all possible contingencies. The power system is clearly affected by the penetration of RES in terms of frequency. It should be noted that the most significant differences that Figure 16(a) shows with respect to the simulation without decoupled power generation, Figure 16 (b), occur during the transient; while during the steady-state they present a similar performance, since the equivalent inertia does not affect the final steady-state frequency value (see equation (4)). With decreasing inertia, the RoCoF increases, the minimum frequency peaks are higher, and the power system becomes more oscillating. Nevertheless, although the frequency response worsens, the frequency never drops below 48Hz for more than 2s.

Besides, Figure 17 and Table 14 compare the performance of the three UFLS schemes. There is an overall increase of the load shed. In the case of the M-based scheme, it is essentially caused by two reasons, firstly, for applying the UFLS design that neglects RES. A higher RoCoF leads to smaller $M(t)$ and, consequently, if the UFLS scheme is not adjusted, further load-shedding steps will be activated. Secondly, the rise in the number of active relays is caused by the decline in inertia as well as a by the reduction of available spinning reserve.

Despite the shortcomings of the proposed scheme, its overall response is good. Even though it disconnects unnecessary load in two incidents, it still minimizes the amount of load to be shed. Indeed, Figure 17 reveals that the performance of the novel UFLS scheme with DPG is in line with the response it exhibited during contingencies without DPG (see Figure 14).

Finally, it can be concluded that DPG should not be neglected when designing the novel UFLS scheme, because by doing this, the system would be tuned with less oscillating and severe representative scenarios in terms of frequency. In addition, it should be noted that, besides considering DPG, time delays should be adjusted at each stage, since with renewables the frequency response is slower and, therefore, the system needs more time to recover. If this condition is not taken into account, it could lead to overshedding, as occurs in Figure 16, where a constant and equal time delay for all stages was assumed.

	UFLS performance		
Case	Total shed (MW)	Nº Relays	ΣΔωmin (Hz)
Existing	526.61	295	223.43
Optimised	293.31	170	227.41
Novel	224.36	122	210.21

Table 14. Performance of the different UFLS scheme designs with DPG

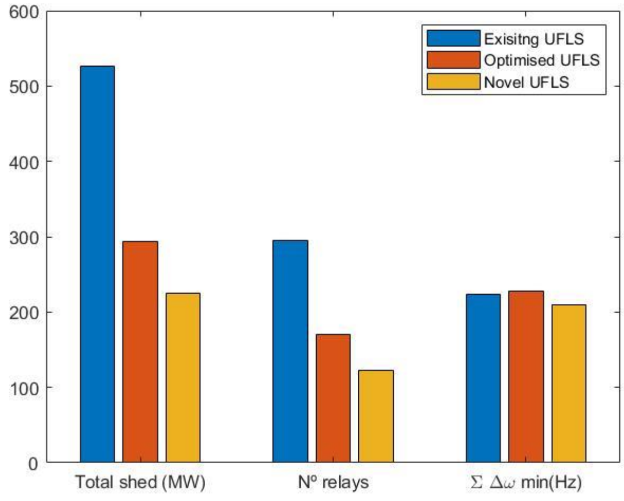

Figure 17. Comparison of the performance of the original, the optimized and the novel UFLS scheme with RES

3.5.3 CONSECUTIVE GENERATOR TRIPPING

Very often, the outage of a generating unit can lead to the loss of other generators and in the worst-case scenario, if frequency deviations are not maintained within ± 2.5 Hz/s range (Egido, Sigrist, Lobato, Rouco, & Barrado, 2015), it can lead to a cascading power failure, which would consequently result in a system blackout. Thus, it is important to minimise the risk of this phenomenon from arising, since it could have a major impact on the grind and drastic economic consequences (Brown-Cohen, 2010). The consecutive generator tripping is a common event in small isolated power systems, due to their weak meshed grid, limited spinning reserve, lack of interconnection and reduced inertia. In fact, in the province of Santa Cruz de Tenerife (Canary Islands) between 2002 and 2020 there were up to 8 blackouts, and in some cases they even occurred within less than a year apart (Millet, 2019). It is therefore interesting to evaluate whether the proposed model is able to cope with several outages or, on the contrary, becomes unstable.

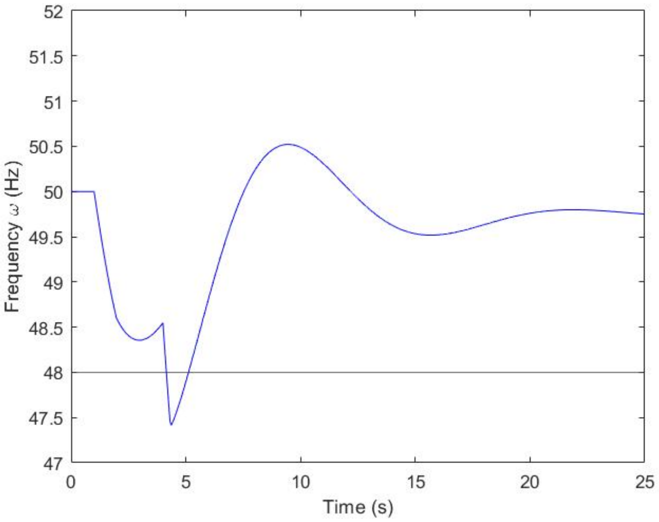

Figure 18. Consecutive outages of generating units G19 and G16

Figure 18. Consecutive outages of generating units G19 and G16Figure 18 shows the response of the La Palma power system to two consecutive outages. Initially, the power system is in equilibrium, maintaining a power demand and generation of 30.69 MW (dispatch scenario 9), when at $t=1s$ group G19 is lost (i.e. 21.60% of total generation). This

causes the load shedding system to activate the first load-shedding step and frequency starts to recover, until at *t* = *4s* generator G16 (i.e. 16.03% of total demand) is tripped. Note that not only a 16.03% of the generation dispatch is lost, but also the contribution of G16 to the primary frequency control to overcome the first outage is lost. In response to the second perturbation, the remaining groups increase their generation to arrest the frequency decay, however, it is insufficient. Therefore, the UFLS scheme activates the remaining steps and stabilizes the frequency in steady sate.

For this particular case, where a moderate scenario with a loss of 37.63% of total generation is simulated, the novel UFLS scheme offers a good response to consecutive generator tripping. Nonetheless, for O&C scenarios with large outages, the designed model cannot cope with the additional loss, resulting in an underfrequency problem. An example of this problem is illustrated in Figure 19 (a), where the outage of generator G17 and G19, respectively, for generation dispatch 21 (a total loss of more than 55.45% of the generation) is simulated.

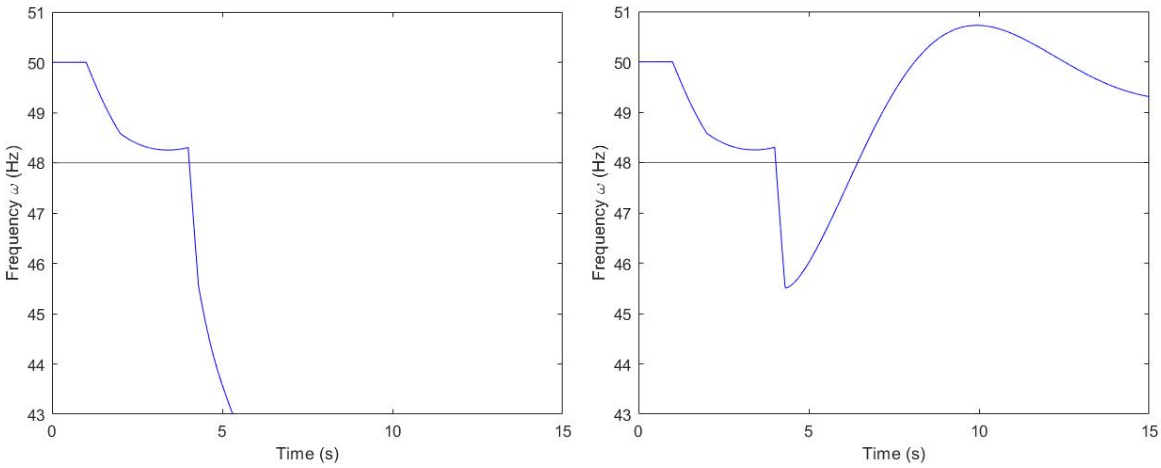

Figure 19. Power system response with the novel UFLS scheme (a) without additional load-shedding steps (b) with 3 additional load-shedding steps

From Figure 19 (a), it can be seen that the power system presents a good performance when the first contingency occurs, but, however, it is not able to restore the power balance during the second outage. Consequently, the frequency response becomes unstable and drops drastically leading to a collapse of the power grid.

It should be noted that the tuning of the novel UFLS scheme was carried out with single outages, thus six load-shedding stages were sufficient to arrest frequency decay, given that the maximum possible power loss amounted to 51.68%. Accordingly, moderate or small consecutive perturbances will generally perform well to the proposed novel UFLS scheme. Nonetheless, when it comes to larger outages, the model becomes ineffective and is not able to arrest frequency decay. Consequently, it could be argued that in order for the novel UFLS scheme to be effective for all possible outage scenarios, the number of the load-shedding steps should be increased. This is shown in Figure 19(b) where, if three additional UFLS steps were activated, the power system would have been able to restore the power balance. However, the restoration may be not effective since frequency fell below 46 Hz.

Chapter 4. CONCLUSION

4.1 CONCLUSIONS

This project has aimed to address one of the main problems faced by small isolated power systems, i.e. frequency stability, an issue that will be even more exacerbated with the increasing penetration of renewables. For this purpose, the work has been focused on a widely used last-resort tool, the UFLS scheme.

In this sense, the main objective has been to improve the conventional static and semi-adaptative UFLS scheme, a current common shedding tool to protect the power system, through the implementation of the frequency stability margin. To do so, the conventional semi-adaptative UFLS scheme has been modified and a design methodology for the new threshold has been developed.

To confirm the feasibility of the novel UFLS scheme, the proposed model has been applied and designed for the La Palma power system. A set of representative O&C scenarios have been simulated to tune the new threshold and, subsequently, the effectiveness of the model has been evaluated for all possible outages.

From the design method followed, it has been seen the importance of choosing the right set of representative scenarios to achieve a robust UFLS scheme. Particularly, it has been found that the initial set of O&C scenarios, a total of four, has not been adequate to arrest frequency decay in case of intermediate power losses, meaning that the chosen contingency events did not provide a good representation of the overall power system. Thus, an additional O&C scenario has been taken to characterize the intermediate O&C scenarios. By increasing the number of representative scenarios, a wider frequency range has been covered and, consequently, an efficient and robust UFLS scheme has been obtained.

Moreover, from the comparison of the performance of the novel UFLS scheme with the existing UFLS scheme and the optimized version of this, it has been seen that, although both the optimized and the novel schemes have exhibited the best performance, the most effective frequency response has been provided by the M-based scheme. It has been proven that the proposed model has been able to further reduce the load to be shed and has presented less severe frequency maximum and minimum peaks. Likewise, it has been observed that it was able to differentiate between critical contingencies and those in which load-shedding could be either delayed or avoided.

Regarding the sensitivity study, it has been seen the importance of choosing the suitable f_{LIM}. It has been inferred that a higher f_{LIM} will result in a larger safety margin and an earlier intervention, but however the risk of frequency overshoot will be increased. Whereas a less conservative frequency constraint will delay load shedding, leading to higher minimum frequency peaks and, consequently, to a greater chance of the frequency response becoming unstable. In addition, the analysis performed has revealed the importance of including RES in the design of the novel UFLS scheme, since otherwise the frequency deviations will greatly increase, and frequency response will worsen during the transient. It has further been observed that by implementing decoupled power generation, is some cases, the frequency response was slower and needed more time to recover naturally, i.e. the design would have required a longer time delay to avoid unnecessary shedding. Finally, from the consecutive generator tripping simulation, it has been found that in order to provide a good performance of the UFLS scheme to successive outages, additional load shedding steps need to be designed. Because, it has been observed that the proposed design was effective for arresting frequency decay in small and moderate consecutive contingencies, but, however, when severe outages were simulated, the UFLS scheme was not capable of overcoming the power imbalance, causing the power system to collapse.

All in all, the results provided in this project have shown an efficient and robust performance of the novel UFLS scheme when applying to single outages. By implementing it, small isolated power systems would be able detect non-critical events and diminish the load to be shed without compromising the power system integrity. Moreover, if the contribution of decoupled power generation were included in the design of the frequency stability margin threshold, the M-based model would have a promising potential to facilitate the increasing penetration RES and diminish its impact on frequency stability.

4.2 FUTURE WORK

Throughout this project, some aspects have been identified that would be interesting to study in detail in future works. Firstly, given the promising results of the new threshold, a more accurate tuning could be carried out, whereby two different approaches are suggested. On the one hand, it would be convenient to enhance the M-based scheme design by means of algorithms to optimize, through a set of representative O&C scenarios, not only the frequency stability margin, but also the other parameters, such as the frequency thresholds and time delays. On the other hand, a further interesting approach would be to apply the tuning methodology presented in this project to all possible O&C scenarios, rather than considering only five representative events. What is more, it would be interesting to include additional load-shedding stages in the UFLS design to be able to effectively cope with consecutive generator outages.

Moreover, one aspect that should be taken into account in future research is the relevance of including decoupled power generation when designing the novel UFLS scheme, given that, by neglecting it, the system would be tuned with less oscillating and severe representative scenarios, in terms of frequency.

Finally, although the contribution of the energy store system (ESS) has been discarded in this project, it would be worthwhile and realistic to evaluate the impact of including ESS such as ultracapacitors (UC) in the power system model, since La Palma is equipped with a 4MW-5s UC.

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Chapter 6. APPENDIX

APPENDIX I: Simulink models

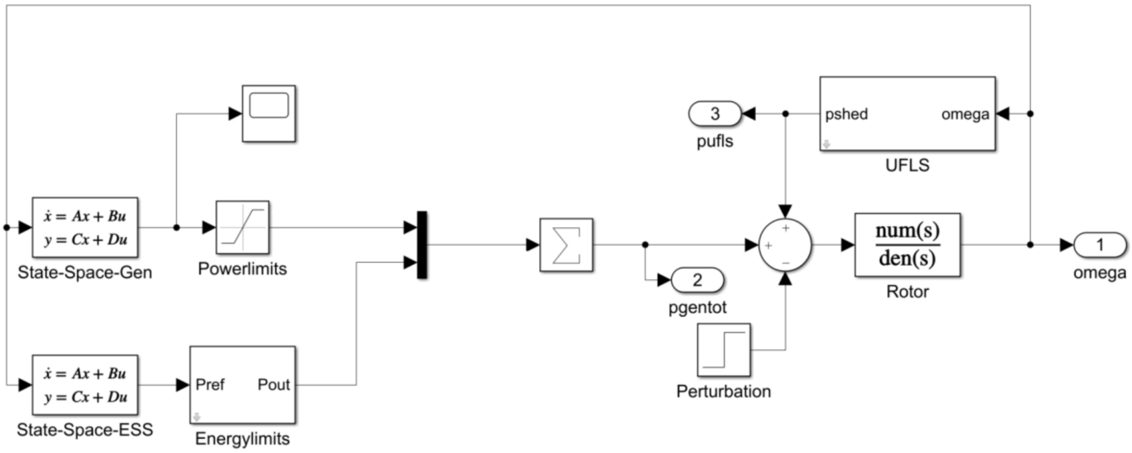

Figure 20. Block diagram of the electrical power system

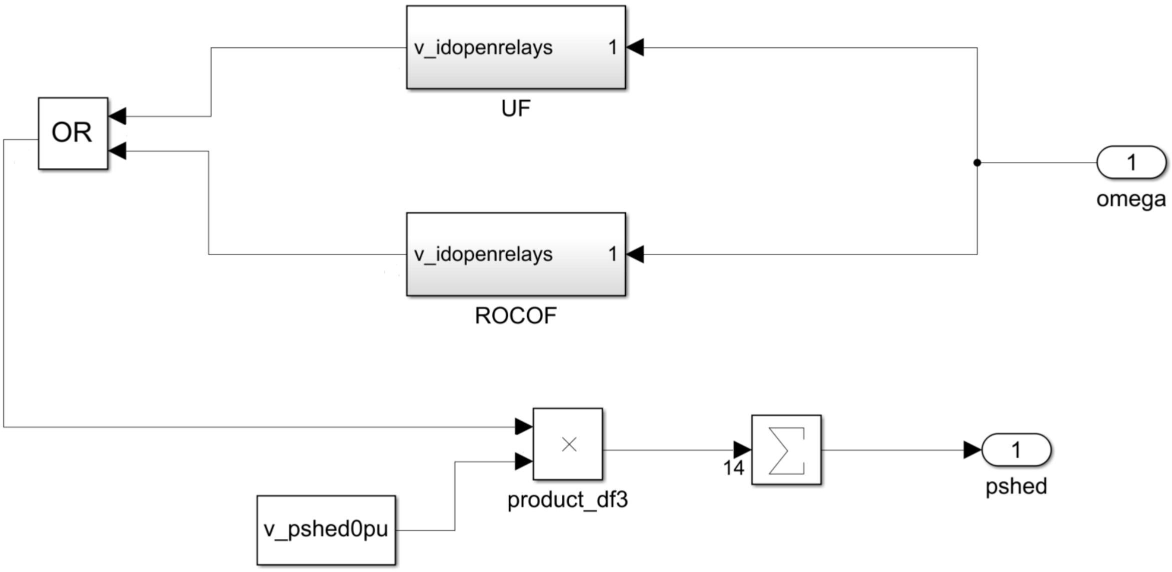

Figure 21. Block diagram of the conventional UFLS scheme

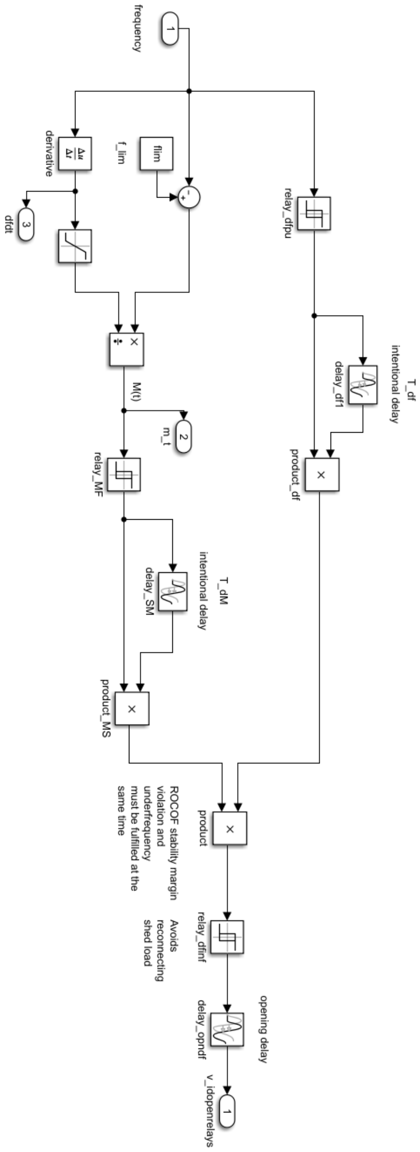

Figure 22. Detailed block diagram of the M-based UFLS scheme

APPENDIX II: The La Palma power system with DPG

S. O. C.	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20	G21	DPG	$P_{G_{tot}} = P_{D_{tot}}$
1	2.35	0.00	0.00	0.00	3.41	3.69	10.41	0.00	0.00	0.00	0.00	2.23	22.09
2	0.00	0.00	0.00	0.00	3.41	4.26	9.26	0.00	0.00	0.00	0.00	2.23	19.16
3	0.00	0.00	0.00	0.00	3.41	3.29	9.55	0.00	0.00	0.00	0.00	2.23	18.48
4	0.00	0.00	0.00	0.00	3.41	3.69	8.96	0.00	0.00	0.00	0.00	2.23	18.29
5	0.00	0.00	0.00	0.00	3.41	3.29	9.35	0.00	0.00	0.00	0.00	2.23	18.28
6	0.00	0.00	0.00	0.00	3.41	3.29	9.61	0.00	0.00	0.00	0.00	2.23	18.54
7	2.35	0.00	0.00	0.00	3.41	3.29	10.02	0.00	0.00	0.00	0.00	2.23	21.30
8	2.53	0.00	0.00	0.00	6.10	5.84	0.00	0.00	6.63	4.00	0.00	2.27	27.37
9	2.35	0.00	0.00	2.82	5.00	4.92	0.00	0.00	6.63	6.70	0.00	2.27	30.69
10	2.41	0.00	0.00	2.82	5.73	5.59	0.00	0.00	6.63	6.70	0.00	2.27	32.15
11	2.46	0.00	0.00	2.82	5.88	5.69	0.00	0.00	6.63	6.70	0.00	2.27	32.45
12	2.49	0.00	0.00	2.82	5.99	5.77	0.00	0.00	6.63	6.70	0.00	2.27	32.67
13	2.58	0.00	0.00	2.82	6.27	5.96	0.00	0.00	6.63	6.70	0.00	2.27	33.23
14	2.40	0.00	0.00	2.82	5.69	5.56	0.00	0.00	6.63	6.70	0.00	2.27	32.07
15	2.35	2.35	0.00	2.82	5.20	5.12	0.00	0.00	6.63	4.00	0.00	2.27	30.74
16	2.35	2.35	0.00	2.82	4.82	4.74	0.00	0.00	6.63	4.00	0.00	2.27	29.98
17	2.35	2.35	0.00	2.82	4.30	4.22	0.00	0.00	6.63	4.00	0.00	2.27	28.94
18	2.35	2.35	0.00	0.00	3.37	3.29	9.21	0.00	6.63	0.00	0.00	2.27	29.47
19	2.35	2.35	0.00	0.00	3.37	3.29	8.68	0.00	6.63	0.00	0.00	2.27	28.94
20	2.35	2.35	0.00	0.00	3.41	3.29	9.35	0.00	6.63	0.00	0.00	2.23	29.61
21	2.35	2.35	0.00	0.00	3.83	3.71	11.38	0.00	6.63	0.00	0.00	2.23	32.48
22	2.35	2.35	0.00	0.00	3.70	3.58	11.38	4.85	6.63	0.00	0.00	2.23	37.07
23	2.35	2.35	0.00	0.00	3.75	3.63	11.38	0.00	6.63	0.00	0.00	2.23	32.32
24	2.35	2.35	0.00	0.00	3.41	3.29	6.63	0.00	6.63	0.00	0.00	2.23	26.89
25	0.00	0.00	0.00	0.00	3.41	3.29	9.16	0.00	0.00	0.00	0.00	2.23	18.09
26	2.35	2.35	0.00	0.00	3.70	3.58	11.38	4.85	6.66	0.00	0.00	2.23	37.10

Table 15. Generation dispatch scenarios of the La Palma power system with decoupled power

Generator	H (s)	K	b1 (s)	b2 (s)	a1 (s)	a2 (s)	Pmin (MW)	Pmax (MW)
G11	1.75	20	1.44	0	18.60	3.98	2.5	4.0
G12	1.75	20	1.44	0	18.60	3.98	2.5	4.0
G13	1.75	20	1.44	0	18.60	3.98	2.5	4.0
G14	1.73	20	1.44	0	18.60	3.98	3.0	4.5
G15	2.16	20	1.32	0	18.40	2.7	3.5	7.0
G16	1.88	20	1.43	0	18.70	3.85	3.5	7.0
G17	2.10	20	1.32	0	18.30	2.71	7.0	12.0
G18	6.50	21.25	0.89	0	5.66	3.48	0.0	22.8
G19	2.10	20	1.32	0	18.30	2.71	7.0	12.0
G20	2.10	20	1.32	0	18.30	2.71	7.0	12.0
G21	2.10	20	1.32	0	18.30	2.71	7.0	12.0
DPG	0.00	0	0.00	0	0.00	0.00	0.0	2.4

Table 16. Parameters of the generator models of the La Palma power system with DPG

APPENDIX III: Overall effect on the La Palma power system by varying f_{LIM}

UFLS relays											
			f_{LIM} (Hz)								
			47.5	**47.6**	**47.8**	**48.0**	***48.2***				
Stage	Substation	ω_{thr} (Hz)	M_{thr} (s)	M_{thr} (s)	M_{thr} (s)	M_{thr} (s)	M_{thr} (s)	$t_{int, F}$ (s)	$t_{int, M}$ (s)	t_{open} (s)	Step size (%)
1	2101	49.0	0.696	0.655	0.870	0.730	0.582	0.1	0.1	0.2	7.1
2	2102	48.8	0.630	0.586	0.480	0.390	0.290	0.1	0.1	0.2	0.6
3	3101	48.8	0.630	0.586	0.480	0.390	0.290	0.1	0.1	0.2	14.5
4	2103	48.6	0.232	0.210	0.170	0.130	0.085	0.1	0.1	0.2	3.6
5	1101	48.6	0.232	0.210	0.170	0.130	0.085	0.1	0.1	0.2	7.3
6	1111	48.4	0.194	0.172	0.129	0.087	0.043	0.1	0.1	0.2	13.6

Table 17. Novel UFLS scheme tuning for different f_{LIM} values

	Novel UFLS performance		
f_{LIM} (Hz)	Total shed (MW)	Nº Relays	ΣΔωmin (Hz)
48.2	207.67	113	197.21
48.0	169.98	94	200.35
47.8	160.97	89	201.63
47.6	127.77	73	213.88
47.5	126.41	72	214.36

Table 18. Effect of varying the design parameter f_{LIM} of the novel UFLS scheme

APPENDIX IV: Alignment of the project with the Sustainable Development Goals (SDGs)

This project is aligned with various SDGs. The main focus of this paper contributes directly to the achievement of Goal 7, which seeks to “Ensure access to affordable, reliable, sustainable and modern energy for all” (United Nations, 2015). It targets that the share of renewable energy should significantly increase in the global energy mix and that the global rate of improvement in energy efficiency should be doubled by 2030. Furthermore, it aims to improve the infrastructure for sustainable energy supply. Hence, this project greatly contributes to its attainment, as the modification of the UFLS scheme facilitates the penetration and exploitation of RES.

In this line, the project is also aligned to Goal 12, “Ensure sustainable consumption and production patterns” (United Nations, 2015). It strives to achieve the efficient use and sustainable management of natural resources by 2030 and moving towards sustainable consumption and production patterns. The latter will be a direct result of the effects of the solution proposed in this project.

In addition, it should be noted that it is highly linked to Goal 13 “Take urgent action to combat climate change and its impacts” (United Nations, 2015). As it has been introduced throughout the different sections, the implementation of the novel UFLS scheme will allow to accelerate and promote the creation of a larger RES infrastructure in small isolated power systems, which would significantly reduce the need to rely on unsustainable energy sources that are highly polluting and dependent on fossil fuels. RES are a clean and inexhaustible resource, as they emit hardly any greenhouse gases, so their pollution levels are minimal.

Finally, it is worth mentioning that it also favours the accomplishment of other goals, but to a lesser extent. These include: Goal 3, “Good health and well-being”; Goal 8, “Decent work and economic growth”, and Goal 9, “Industries, innovation and infrastructures” (United Nations, 2015).