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SURVEY

Toward Adaptive Load Shedding Remedial Action Schemes in Modern Electrical Power Systems

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ABSTRACT Modern power grids are becoming more stressed, more complex, and beginning to have a significant integration of energy sources based on power electronics devices, which significantly changes the dynamics of power grids affecting the design and operation of Remedial Action Schemes such as UVLS and UFLS, where the conventional operation philosophy of these schemes is based in operating parameters such as thresholds, amount, and location of the load shedding fixed regardless of the event. Therefore, they are not adaptable to the various conditions of the modern power grids, causing their misoperation. In recent years, a wide variety of adaptive schemes around the world have been proposed as a solid solution with good performance, since its main characteristic is its ability to consider the magnitude of the event in its load shedding, turning them into more selective and with flexibility in their operating parameters. The aim of this article is to review the development of adaptive schemes in UVLS and UFLS over the years, identifying how to approach the design of such adaptable schemes, which operating parameters tend to give them greater flexibility and which have been less explored. Then broken down the methods used to give flexibility to the operating parameters of UVLS and UFLS, and also that other devices such as FACTS and ESS can enhance its operation, with the aim of provide a broad vision of how to give them flexibility to these parameters and which of them are identified as an opportunity to improve the performance of the adaptive schemes. Finally, the review includes some RAS with adaptive approach implemented in real systems which some of them includes load shedding, to show how these schemes have reconfigured their design and operation by giving flexibility to some operating parameters, it is possible to show the need of modern power grids to have adaptive RAS.

INDEX TERMS Special protection scheme, remedial action scheme, adaptive underfrequency load shedding, adaptive undervoltage load shedding, modern power grids.

I. INTRODUCTION

The reliable, safe, and continuous operation of electrical power systems has always been of great relevance and a high level of priority for operators of control centers. The significant increase in electrical demand over the past decades, coupled with inadequate infrastructure, has resulted in systems operating close to their limits. This has gradually made it difficult to achieve compliance with safety, quality, and performance objectives. Moreover, the integration of renewable energy sources and the installation of power reactive control devices both based in power electronics, have improved operational aspects in modern power grids, giving greater flexibility in their operation. However, they have also significantly affected in the performance of the power grids making it susceptible to loss of stability, causing partial or

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total blackouts during certain events. In this way, the design and proper selection of protection schemes have become essential for the control and operation of power systems, helping to improve network reliability, mitigating the spread of disturbances and, in general, avoiding loss of stability and blackouts [1], [2], [3].

The operating conditions of the electrical power system can be perturbed at every moment. Perturbances can be categorized as large and small. The small perturbances as load variations can request continuous control actions, such as the action of transformers with tap changers or the action of the primary and secondary frequency controls and, even, the participation of the operators of the control center is allowed, as long as the dynamics of the event allows [4]. Moreover, for large and critical perturbations, Special Protection Schemes (SPS) or Remedial Action Schemes (RAS) are introduced, they are used to maintain reliable power system operation, even when operates in critical conditions [5]. Conventionally, the design of these protection schemes is based on multiple offline studies (event-based), where critical contingencies are identified, and corrective actions are evaluated that may be but are not limited to load or generation shedding and controlled separation of the system, hoping that such actions will lead the system to an acceptable and safe operating point [4], [6].

The RAS, as we will call this type of protection scheme from now on, have been well accepted and widely used for many years in the electrical industry as they are considered an affordable option since one of its great strengths is that its operation is based on the controlled manipulation of the elements that the electrical network already has installed and because of their fast implementation can replace or postpone works of high cost, or operate preventively while they are completed.

The growth of electrical systems, and the high level of renewable energies, has raised questions whether the design philosophy of conventional RAS is still sufficiently safe and reliable for modern power grids, which has led to various research gaps related to RAS; for example, there is a large field of study in online contingency analysis, since the large number of elements connected to the network and their various conditions makes the calculation of all contingencies very complicated and practically impossible. Therefore, the relevance of using probabilistic methods in this area to select contingencies [7]. Having a broad view of the state of the power grid has been vital in recent years. Therefore, Phasor Measurement Units (PMU) have become essential elements in a power system, achieving greater accuracy in monitoring and leading to centralized protection approaches such as Wide-area Event Identification (WAEI) and Wide-area Monitoring Protection and Control (WAMPAC) [8]. With the above mentioned, the development of adaptive RAS that falls into the category of response-based schemes has become relevant. The adaptative RAS evaluates online the response of some variables of great interest in the network [9]. In addition, estimates online the stability with multiple advanced tools, with which it is possible for the RAS to adapt to the network conditions and evaluate its current state in real time. The design philosophy of these adaptive schemes can consider a network changes and variable renewable generation in the remedial actions, as shown in Fig.1.

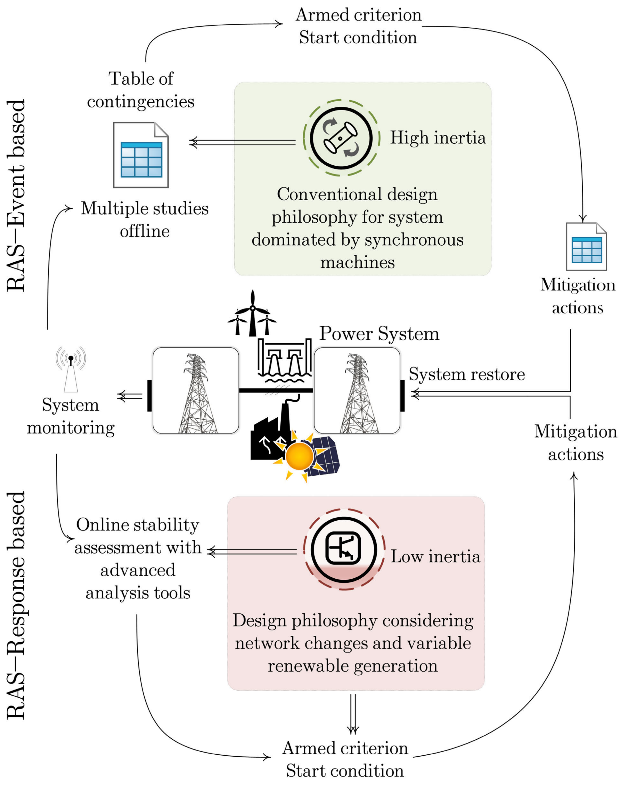


FIGURE 1. Design philosophy of an RAS-Event based and RAS-Response based.

The adaptive RAS has been of great interest, that even its design and implementation has been performed in real systems obtaining great results [10], [11]. In this way, some tools have been designed for the online evaluation, such as the power system status voltage stability indices [12]. There are other adaptive RAS, focused on mitigating transient stability problems, evaluating the stability of synchronous machines online or by evaluating oscillation parameters using signal modeling techniques, such as the Prony algorithm [10]. One of the main approaches has been to incorporate the effect of renewable energy integration into adaptive RAS, where the aim has been to incorporate detailed wind and photovoltaic farms models into protection schemes. In addition, conventional optimization techniques have also been used as heuristic techniques to get optimal remedial actions [13].

Great emphasis has been given to the need for new adjustments in the conventional protection philosophy, as it is well established for systems that have as their main source of generation conventional synchronous machines, and although protection schemes operate reliably in these systems. However, this is not the case when high levels of renewable penetration occur, because the conventional approach loses reliability [14]. Therefore, the transition to adaptive RAS has become important. For example, conventional Under Frequency Load Shedding Schemes (UFLS) shed more power when operated in a system with renewable sources, because this energy sources are based on power electronics devices and do not make any inertia contribution to the electrical network and, UFLS schemes observe deeper frequency deviations, activating more shedding stages. Also, in light demand scenarios, a system with renewable penetration may present more frequency deviations behaving as a maximum demand system and, activating more load shedding stages than necessary [15]. Designers of UFLS have deemed it imperative to consider a greater number of operational points during the scheme's design. There has been notable attention given to adaptive UFLS [16]. The conventional design philosophy is to make the RAS on a base case (the most extreme event), covering several scenarios where in many of them the amount of load shedding is not proportional to the magnitude of the event, disconnecting quantities of power inaccurate. The time interval from which they are designed until the moment of their possible activation can be considerably large and, therefore, the conditions for which it was designed are no longer the same, decreasing its effectiveness and validity, even more if that current power systems present considerable changes in less time, because of the variable nature of renewable generation sources that have been incorporated into electricity networks in recent years.

During the last few years, the need to migrate to adaptable schemes has become clear, and has caused a great development in the design of adaptive load shedding because of its reliability and efficiency, especially when performed in a controlled and strategic manner. However, there is no clear and orderly idea of where to focus the study and development of these schemes, which operating parameters of the load shedding can be provided flexibility, and from which methods, in a few words how to approach adaptive schemes for a modern power grids. In this way, a review was made of the low voltage and low frequency load shedding and present the following contributions:

- The significance of RAS schemes in power grids, with emphasis on experiences in the electrical industry.
- A comprehensive compilation of RAS schemes that have undergone reconfiguration towards an adaptive approach in diverse regions of the globe.
- The chronological presentation of the evolution of UVLS and UFLS, encompassing their design and operation from the conventional operating philosophy to modern adaptive schemes, has been included.
- A classification of the different design approaches of the UVLS and UFSL schemes is presented.
- Classification of operating parameters of UVLS and UFLS which are typically given flexibility during their design and operation of modern power grids, and in addition, a review of the methods used to give flexibility to these operating parameters.
- A set of UFLS coordinated with flexible AC transmission systems and energy storage system technology to boost the performance of these schemes.

Therefore, this paper is arranged as follows. Section II describes a general description of the RAS, costs a typical control actions used in the electrical industry in the last decades and the impact of the renewable energy in the studies for the RAS design, Section III show some reconfiguration of RAS using adaptive RAS approach around the world, Section IV, presents multiple UVLS and UFLS with their classifications and characteristics, and finally in Section V the trend of the collected schemes is described.

II. REMEDIAL ACTION SCHEMES

The North American Electric Reliability Corporation defines an RAS as an ''automatic protection scheme which detects abnormal or predetermined conditions of the system and takes corrective measures which may include, but are not limited to, reducing or shed load, reducing or shed generation, and amend the topology to ensure system reliability'' [17]. While conventional protection schemes are strictly designed to isolate faults and protect specific elements (transmission lines, transformers, buses, generators, etc.), the RAS are used to protect the system or part of it and require multiple monitoring devices distributed selectively on the power grid, as well as robust communication centers [18]. In this regard, the main objectives of a RAS are:

- Maintain the overall stability of the power system during critical events.
- Maintain in acceptable ranges the electrical variables of the system, such as voltages in the buses, currents and power flows across the links and maintain constant the frequency of the system.
- Avoid cascading events that cause blackouts.

A. CLASSIFICATION OF RAS

The algorithm of deciding and corrective actions of the RAS are performed on controllers that can process the information of the monitoring devices. RAS is classified by the type of structure in the controller algorithm, how the remedial protection decision-making process was designed [5], [17], [19];

- Event-based: a table of contingencies is developed previously studied with their corresponding actions, so that the RAS takes action immediately.
- Response-based: it comprises supervise the response of the system to the contingency, monitoring the frequency and voltage drop or other variables of interest, and then deciding on the action to be taken.

During the conventional design of the RAS (event-based) it is important to select some aspects of operation for the RAS, which are considered of great relevance for its correct operation, and it is important to mention that once selected

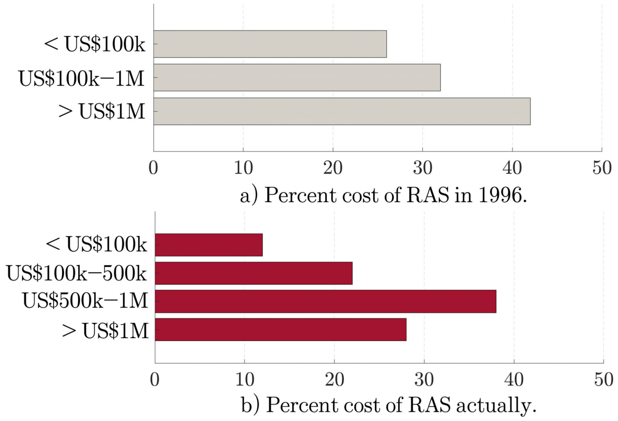


FIGURE 2. Estimated Cost of RAS in 1996 (Fig.a) and at the present day (Fig.b).

during the design stage, these operation aspects remain fixed, which are the following [19];

- Armed criterion: The critical operating point of the system for which the scheme prepares for a possible operation.
- Start condition: Contingency that initiates the control action if the scheme is armed, if the contingency occurs during critical operating point.
- Control actions: Control action required to overcome the effect of contingency on the system.
- Time required or allowed: Maximum time allowed to complete the control action, where delays by communication protocols and switching open time are considered.

B. TYPICAL CONTROL ACTIONS OF AN RAS

The propagation of a disturbance involves various phenomena, such as congestion, transient instability, voltage instability, frequency instability, small signal instability, and the action used to mitigate these phenomena can vary considerably, some of them are shown below [19], [20];

- Automatic generation shedding.
- Congestion load shedding.
- Under frequency load shedding.
- Under voltage load shedding.
- Change of the system topology.
- Out of step tripping (OSS).
- Power system stabilizer control.
- Controlled separation of the system.
- Set point changes in FACTS devices.
- Turbine valve control.
- Set point changes in HVDC systems.
- Automatic Generation Control Actions (AGC).
- Fast control to photovoltaic plants.
- Fast control to wind turbine plants.
- Fast control to energy storage systems.

It is important to mention that, in many cases, the selection of the type of remedial action used is at the discretion of the engineers designing the RAS.

TABLE 1. Percentages of most common RAS types in 1996 [21].

Type of RAS	Percentage
Generator Rejection	21.6%
Load Rejection	10.8%
Underfrequency Load Shedding	8.2%
System Separation	6.3%
Turbine Valve Control	6.3%
Load & Generation Rejection	4.5%
Stabilizers	4.5%
HVDC Controls	3.6%
Out-of-Step Relaying	2.7%
Discrete Excitation Control	1.8%
Dynamic Braking	1.8%
Generator Runback	1.8%
Var Compensation	1.8%
Combination of Schemes	11.7%
Others	12.6%

C. INDUSTRY EXPERIENCE WITH THE RAS

For decades, the design and implementation of RAS has had great relevance in the electrical industry and, therefore, in 1996 an article was reported by the CIGRE/IEEE collecting information from about 111 RAS around the world, obtaining valuable information related to performance, design considerations, cost, reliability and testing [21]. However, the growth of power grids and their stringent performance requirements increased the complexity of these protection schemes, causing the IEEE PES Power System Relaying Committee to publish a new compilation in 2010, updating information with the collaboration of CIGRE and EPRI [20].

The information collected in both reports indicated that the performance evaluation of the RAS operation is based on accounting in a time interval the satisfactory operations, unsatisfactory operations, operating failures, unnecessary operations and the total percentage of time in which the RAS is armed. Both reports concluded that these types of schemes act infrequently, since the surveys indicate they operate once a year, every two years and every 5 years on average; however, the most frequently presented is every year and, despite this, when their action is required they must operate satisfactorily, since the estimated costs of failure of a RAS range from US $10,000 to US $500,000. The estimated costs of designing and implementing an RAS in the 1996 report range from US $100,000 to US $1,000,000; however, as part of this research work, a survey of around 50 RAS was conducted, in which took part during its design and implementation. In this regard, a cost estimate was made and compared with the cost estimate made in 1996, as shown in Fig.2, where the aspects that affect the final price are the size of the scheme and the number of devices involved.

Regarding to the most used remedial actions, the surveys showed similar results. Table 1 shows the results of the actions most used in the 1996 survey, where the generator rejection is the most used with a percentage of 21.6%, followed by actions associated with load shedding (load rejection and under frequency load shedding) with 20%. In the 2010 report, a classification of remedial actions was made by category, in order to clearly account for the actions

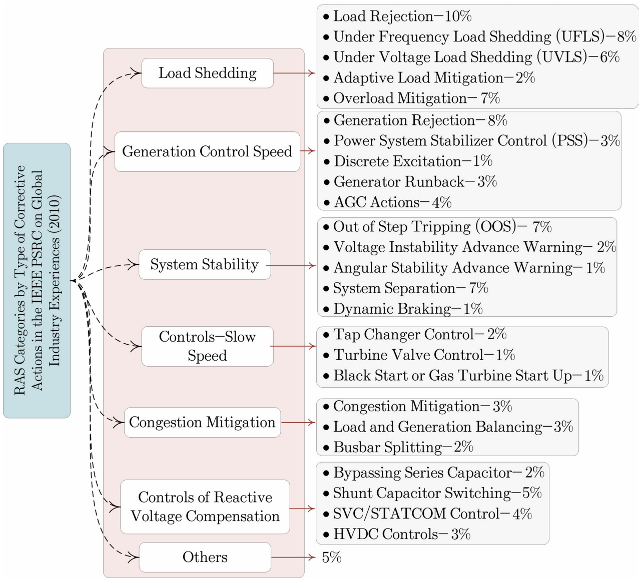


FIGURE 3. RAS Categories by type of corrective actions in the IEEE PSRC on global industry experiences in 2010 (298 entries) [20].

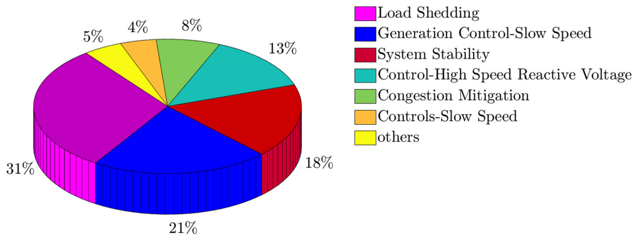


FIGURE 4. Percentage of most corrective actions in the IEEE PSCR on global experience in 2010.

associated with load shedding, stability, generation control, etc. This was done to show which ones have the highest trend, as shown in the Fig. 3. In this sense, Fig. 4 shows that the most used remedial actions (of the 298 actions collected for this survey) are associated with the load shedding. Therefore, it can be concluded that they have had a greater tendency in their use in relation to the results obtained from the 1996 survey, since at that time, the generator rejection had a slightly higher percentage.

D. THE IMPACT OF THE RENEWABLE ENERGY IN THE STUDIES FOR THE RAS DESIGN

The design of the RAS schemes is founded on comprehensive long-term planning studies that consider future operating conditions for a specified time horizon. These studies consider distinct load demands, including minimum demand, middle demand, middle night demand, and maximum demand, throughout different seasons of the year, such as summer, spring, fall, and winter. In systems that are dominated by synchronous machines, it was possible to assume constant system inertia under various load demand scenarios. The helpful function of the inertial response of synchronous machines in supporting the system to withstand transients during specific events was considered. However, the dynamic frequency response of a system is different when the system operates with a high percentage of renewable energy generation. For example, Fig. 5 compares the frequency response of a system dominated by conventional generation (blue line) and a system with a percentage of renewable energy (red line) for the same demand conditions. Firstly, the differences between the two scenarios are clear to observe. The frequency response of a system with renewable energy generation presents a higher ROCOF, a lower Nadir frequency and, in addition, the lack of spinning reserves to overcome the power imbalances. In contrast, the frequency response of a system dominated by conventional generation has greater spinning reserves, presents lower ROCOF and, in addition, higher Nadir frequency. Therefore, this difference between the dynamic responses of both systems directly impacts the design of the RAS schemes, and it becomes indispensable to consider various load demands with conventional generation and, in addition, with a percentage of renewable energy. Consequently, this involves an increase in the number of scenarios that have to be evaluated during the design of the scheme.

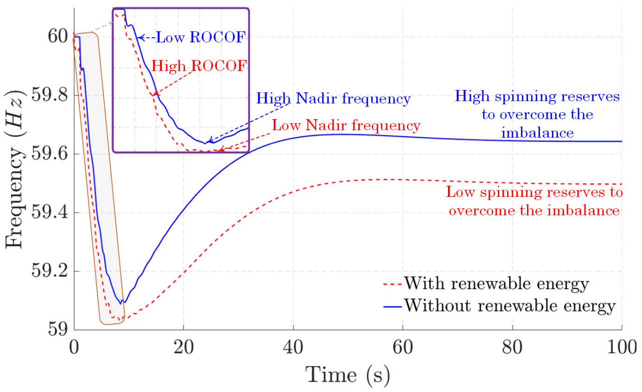
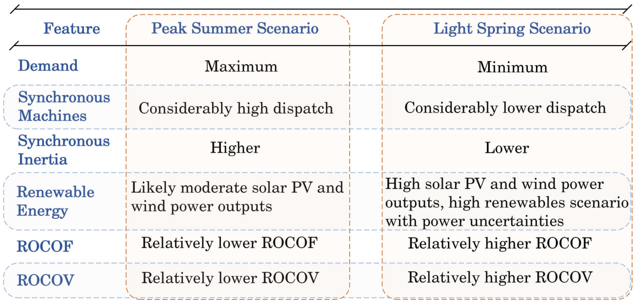


FIGURE 5. Frequency response with RES.

With the above, the Fig. 6 shows an example of the comparison of two study case scenarios between different seasons, describing the differences that exist between them, from the type of generation, demand and some other differences associated with system dynamics for both scenarios. In this sense, the adaptive RAS schemes become relevant, which can adapt to the conditions of generation of the system, to adjust adaptively when changes are presented in the system as a high percentage of renewable energy. Therefore, it has been sought to promote this type of philosophy of operation of RAS schemes in real power grids, giving good performance, and leading to the reconfiguration of RAS in different parts of the world towards adaptive approaches.

III. RECONFIGURATION OF RAS IN THE WORLD TOWARDS AN ADAPTIVE APPROACH

The behaviour of power grids has become more complex and unpredictable, so maintaining stable operation in modern electrical power systems has become a challenge. The conventional operating philosophy of the RAS has changed



Feature	Peak Summer Scenario	Light Spring Scenario
Demand	Maximum	Minimum
Synchronous Machines	Considerably high dispatch	Considerably lower dispatch
Synchronous Inertia	Higher	Lower
Renewable Energy	Likely moderate solar PV and wind power outputs	High solar PV and wind power outputs, high renewables scenario with power uncertainties
ROCOF	Relatively lower ROCOF	Relatively higher ROCOF
ROCOV	Relatively lower ROCOV	Relatively higher ROCOV

FIGURE 6. Example comparision of study case scenarios [15].

in relation to the needs presented by power grids over the years and, in addition to the technological advances that have accurred regarding the monitoring and information processing of these systems. Some RAS that have been operating around the world have undergone important modifications, which are oriented to adaptive RAS approach to continuously monitoring the behavior of the grid. Therefore, to highlight the importance of adaptive RAS in modern power grids, this section describes the problems that have arisen in some real systems and the reconfiguration that have had their respective RAS, where it will be possible to show that their new designs present an adaptive philosophy, making more valuable the study of this type of approaches.

A. RAS IN CANADA

Canada's Hydro-Quebec power grid presents serious problems of voltage stability, as its most important generation zones are heavily charged to the north and the densest load zones to the south (Montreal), being connected through long transmission lines. The design of a load shedding RAS in the Montreal area was reported in 2004 to mitigate this problem [22]. The scheme comprised taking measurements with PMU in five substations distributed in the Montreal area and calculating an average voltage of the area. In addition, the RAS comprised three voltage thresholds, and each threshold was programmed to disconnect different power levels; the first and second threshold had fixed values and the third was closed-loop scheme, where the amount of load it disconnected was adaptive and proportional to the error between the average Montreal voltage and its threshold.

In 2017, a new project of RAS with the same purpose and in the same area was started; however, it sought to take advantage of the resources of the Synchronous Compensators (CS) and the Static Compensators of Vars (SVC) distributed along the network [23]. In this regard, the new RAS consisted of temporarily changing the voltage references of the compensators in a coordinated manner at the instant that an abrupt drop of the average voltage of the Montreal area was detected. The 2017 report recounts the pilot tests and, for 2019, reports on control logics used in substation devices, as well as the structure of communication systems and, it was emphasized that the scheme was about to be officially launched [24].

B. RAS IN COLOMBIA

Between Colombia and Ecuador, there is a link compiled four transmission lines. The link transmitted large amounts of power bidirectionally between the two countries and therefore had a RAS monitoring the power levels of the link and the status of the transmission lines (event-based) [10]. However, this RAS was no longer so efficient as of 2016, when a large capacity generation plant was installed in Ecuador. The generation plant in Ecuador had a loss of synchronism and was isolated from the Ecuadorian network, causing Colombia to have to transmit more power to Ecuador through the link and unassembled electromechanical oscillations were present, causing the loss of synchronism between the two nations. In 2020 a redesign of the RAS was reported to increase security between both countries. New functions were incorporated into the new RAS, such as loss-of-synchronism detection logic, to discern between power oscillations and short-circuit oscillations. An angular difference monitoring logic, which monitors the power levels in the link and the stress of it was also added. Finally, a logic for monitoring power oscillations through a modified version of the Prony's algorithm, which identifies the oscillation parameters of power and frequency signals, estimating whether the oscillations are damped. By activating any of these logics, the RAS performs a controlled separation of the link, and since its installation, the ability to safely transfer the link has been increased.

C. RAS IN GEORGIA

The Republic of Georgia has small geographical areas and interconnections with neighboring countries (Russia and Turkey). For many years, its electricity network has experienced several blackouts (14 in 2014, 2 in 2015, 9 in 2016 and 10 in 2017) despite having its own RAS. In 2018, their protection scheme was reported to have been updated, requiring extensive offline studies [25]. The new RAS designed has a combined structure based on event and response as it monitors contingencies and, also, the load disconnected at one end of the system is adaptive and proportional to the flow of power in the most important link of the country's power network. The new RAS has an adjustment of the power references of the interconnected HVDC to Turkey, where the reference change is also made according to the power flow in the most important link of the system. Finally, the new scheme reduced blackouts, since in 2018 only two were registered.

D. RAS IN TAIWAN

Kinmen is an island in Taiwan with a tiny network operating in island mode and is very susceptible to contingencies causing power imbalances. Starting in 2010, it was observed that during some events, the installed RAS shed load when the system had sufficient spinning reserves to maintain stability and cope with the power imbalance. More coordination between the RAS and conventional protection schemes was needed [26]. In 2020, a system study was reported that led to a reconfiguration of the RAS, in which it was determined that the amount of load shedding would be adaptive and, based on the percentage of the power of the generators leaving operation and the total generation surplus. In addition, the reset was done to coordinate conventional protections.

E. RAS IN URUGUAY

Uruguay's power grid is interconnected with Brazil (via an HVDC link) and Argentina is the largest importer of power. The country's system had a restricted RAS with few operating conditions and little flexibility with respect to the growing needs for system expansion, and it was not very efficient, since minor changes in the network, even if they were for maintenance, caused congestion on critical system links.

The reconfiguration of the Uruguay's RAS was reported in 2015 [27]. Its algorithm comprises of several remedial action modules; there are two load shedding modules, one to avoid overloading the elements and another to balance the system when disconnected from Argentina and also, the amount of shedding is adaptive and dependent on the monitored power flow in some specific equipment of the system. The third module is responsible for performing a power adjustment in the HVDC interconnected to Brazil, taking as reference the power flow of some important links. Finally, the fourth module includes auxiliary reactive compesation actions to mitigate the over voltages present when performing the load sheddings.

F. RAS IN CENTRO AMÉRICA

Mexico has been an exporter of large amounts of power to the Central American grid; however, it could not interconnect during certain periods of the day, when the system was more susceptible to lose stability and thus, to present undamped electromechanical oscillations. In 2012, an RAS was installed in the area, which monitors with PMU a link from El Salvador [11]. The RAS computes the modal information of the power and frequency signals of the link using the Prony method, and when it detects unstable oscillations, it performs a controlled separation of the system. With the new RAS, the interconnection of Mexico with Central America has no time constraints, providing a more stable system with additional energy resources. The RAS operated for the first time on 28 July 2012 successfully, detecting a power oscillation of 0.22 Hz.

G. RAS IN PEREÚ

In recent years, there has been a significant expansion of electricity demand in southern Peru, causing congestion of some important links during certain events. In this regard, in 2017, the installation of an RAS that monitors via PMU a 400 km link at both ends was reported [28]. The RAS continuously computes the angular separation of the link, so that when the safety threshold is exceeded, it performs a load shedding. The safety thresholds used are predefined and fixed, as are the power levels for load shedding.

H. RAS IN PANAMA

Panama's power grid is a longitudinal system that presents problems of voltage collapse. Its largest generation plants and the rest of the Central American grid are in the country's west, while the densest load zone made up by Panama City and the Panama Canal is in the east. There are large amounts of power flow from west to east and the system does not have sufficient transmission infrastructure. Therefore, it is a system that operates close to its power transfer limits, and is susceptible to voltage collapse during certain contingencies. From 2021, the design of an RAS to avoid voltage collapse using load shedding was proposed [29]. The RAS proposed has an event-based approach; however, the amount of load shedding is adaptive. In the design of the RAS, power transfer thresholds were established from previous studies, where various scenarios of generation and load demand were considered. The amount of load shedding is adaptive and depends on the amount of power that is transmitted on the most important transmission lines. With implementing the RAS, power transfer limits were increased. The possibility of incorporating real-time Power-Voltage (PV) curves analysis into the RAS is currently being evaluated.

I. RAS IN CHINA

China possesses an extensive power grid, where the operational state varies across its diverse regions. China has made significant progress in smart grid technology, with the development and implementation of a new generation of dispatch systems, as well as the operation and control of its UHV (Ultra High Voltage) systems and smart grids. The development of the latest EMS (Energy Management System) generation was started by the State Grid Corporation of China (SGCC) in 2004. In 2009, the first prototype was developed and named the Smart Grid Dispatching and Control System (D-5000). The primary operations encompassed real-time control and early warning, scheduling, security checking, and dispatch operation management. Additionally, a cybersecurity defense mechanism was deployed to safeguard against potential threats. The real-time control and early warning system have been implemented to coordinate a vast network of AG and AVC controls. The controls have been specifically designed to ease the regulation of both active and reactive power. Multi-zone and multi-objective optimization techniques are employed by them. The AVC technology is used for hierarchical control to perform the adaptive division of zones in the Chinese electrical grid. China's monitoring system, which is integrated with 3000 PMUs, is now the largest. One of the main functions of this monitoring system is to perform a small perturbance stability analysis online, to evaluate the low frequency oscillations of the power grid [30].

The aforementioned schemes provide evidence of the necessity and feasibility of implementing RAS with adaptive approaches in actual power grids. Despite the significant challenge posed by the adaptive design philosophy, the design of these protection schemes is critical, given the operation and dynamics of modern electrical networks. Within this context, Section IV examines a range of design methodologies for UVLS and UFLS schemes, encompassing both traditional and adaptive approaches.

IV. UNDERVOLTAGE AND UNDERFREQUENCY LOAD SHEDDING

Conventional UVLS and UFLS are RAS that have taken a important role in the security of power grids, since there are considered an economical and very efficient alternative, especially if performed in a controlled and selective mode. However, their operation has been exposed as they are inflexible and do not consider changes in the power grid. In this regard, its design and operation methodologies have evolved significantly, where an adaptive approach has been sought, resulting in a more selective load shedding, reducing the amount of shed and simultaneously overcoming the complex problems presented by modern power grids. With the above mentioned, this section describes the role of UVLS and UFLS in the security of electrical networks, and how their conventional design philosophies have been restructured resulting in adaptive load shedding, using certain power system analysis tools in real-time.

A. DESIGN OF AN UNDER VOLTAGE LOAD SHEDDING

The expansion of power grids has resulted in stressed systems with more complex dynamics, where voltage stability or voltage collapse has become a major issue. The voltage instability refers to the ability of a system to reach stable constant voltages in steady-state condition and, after a disturbance, where the reactive power reserves are vital [31]. Voltage stability can be lost because of generation unit outages and dynamic load behavior. There are several actions to mitigate voltage stability; however, Under Voltage Load Shedding (UVL) is one of the most reliable remedial actions because of its immediate effect on system behavior, and in addition, it is important to emphasize that are considered as a last resort. The operating philosophy of conventional UVLS is that if a disturbance causes the system voltage to drop below a certain predetermined voltage threshold, a predefined amount of load will be shed from the system, to return the power grid voltage to its stability limit [32].

In 1992, the general concepts of a load shedding to mitigate voltage collapse were reported [33]. The conventional UVLS are based on rules of the type:

$$\text{if } V \leq V^{vth} \text{ for } \tau \text{seconds, shed } \Delta \text{P MW}.$$

The following features of the UVLS have become the major focus of interest during their design:

1) Amount of power to load shedding (ΔP).
2) Location of the load shedding.
3) Load shedding delay (τ).
4) Voltage thresholds (V^{vth}).

In the evolution of the UVLS, various approaches and a broad classification were developed [34]:

- **Centralized:** It has Under Voltage (UV) relays installed distributed in important buses in certain areas of the electrical network. All information is processed in a control center and trigger signals are transmitted to loads in different geographical areas.
- **Decentralized:** The UV relay monitors locally and if the voltage drop below the threshold, the trigger signal is sent.
- **Static:** The amount of power of the load shedding is predetermined and fixed at each stage.
- **Dynamic:** A dynamic or adaptive scheme does not shed a predetermined amount of power. The amount depends on the magnitude of the disturbance and the dynamic behavior of the system at each stage.
- **Closed loop:** The scheme operates several times and the action of each stage depends on the measured result of the previous action.
- **Open loop:** Its control actions are based on multiple offline studies and considering predetermined scenarios (the most critical ones). The actions of these schemes are fixed.
- **Based on algorithms of decision:** This type of schemes can evaluate the system stability online and detect short-term and long-term voltage collapse. Some of them use quasi-stationary simulation techniques.
- **Based on rules:** This scheme uses starting conditions of the type:

$$\text{if } V \leq V^{vth} \text{ for} \tau \text{seconds, shed} \Delta \text{P MW}.$$

- **Response-based:** These schemes monitor some variables of interest and evaluate online with various analytical tools the evolution and stability of the system
- **Event-based:** This scheme is based on the identification of predetermined conditions defined by multiple offline studies. In addition, the operating conditions are inflexible to network changes.

Independently of the classification of UVLS described above, they all have common design aspects, such as amount of load shedding, the load shedding location, the load shedding delay, and the voltage thresholds. Accordingly, a description of various collected works focused on each of the design features of these load shedding schemes is presented in order to show the most relevant areas in these schemes and how they have been addressed in recent years.

1) AMOUNT OF LOAD SHEDDING

The amount of load shedding is an important factor; on the one hand, less load shedding than necessary will not

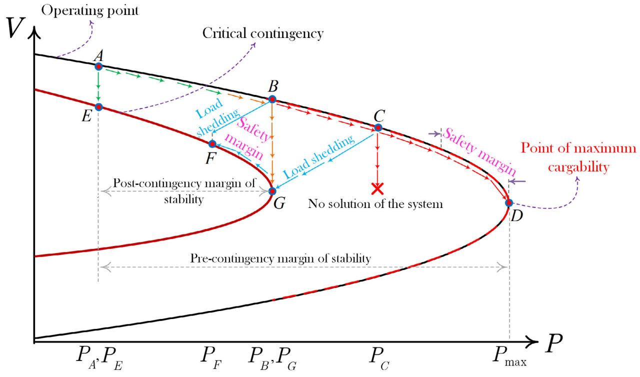


FIGURE 7. **Power-Voltage (PV) characteristic curves.**

mitigate the problem and too much load shedding can lead to an over frequency condition. Conventionally, this value can be computed in different ways, for example tracing offline power-voltage (PV) characteristic curves (as shown in Fig. 7) and, getting the maximum power transfer points for various scenarios, tested by multiple dynamic simulations [35]. Typically, the selection of the amount of load shedding is previously performed based on offline studies, since some electrical phenomena are so fast, and then, the calculation time to determine the amount of power, delays in communication protocols and breaker opening time become crucial and severely affect the performance of the protection scheme. However, when the amount of shed is computed by offline studies, the amount of power is fixed and for a set of scenarios with similar conditions, which results in an inaccurate amount of power to shed.

The amount of power to shed can be a dynamic value that depends on the magnitude of the event. For example, in [36] a rule-based UVLS is presented, where one of its stages uses a closed-loop control where the amount of shed is adaptive and proportional to the measured voltage deviation regarding the voltage threshold of its corresponding stage. In [37], a two-stage response-based UVLS with a data-driven approach is proposed. This scheme uses a scalable Gaussian process (SGP) model to estimate the amount of power in the shedding load. In relation to the location of the load shedding, it uses the transient voltage violation index (TVSI) to evaluate the most critical loads. Due to the continuous growth of load demand and to affect the consumer as little as possible, to maintain a continuous electricity supply, the computation of the amount of power has become an optimization problem with multiple objectives. In this sense, the techniques based on heuristic methods have been of great impact and a widely used tool to solve this problem, because of its reliability and its outstanding performance [38]. For example, in [39] first a detection of critical scenarios is performed by quasi-stationary simulations, and then it is sought to minimize the amount of load shedding through a Genetic Algorithm (GA). In [40], a Particle Swarm Optimization (PSO) is used to compute and reduce the amount of shed. Similarly, to compute the amount of shed in [41] an AG based technique was used, and implemented in the Hydro-Quebec system; however, this approach does not consider the load behavior, and only some predefined scenarios are considered. In [42] propose an optimal load shedding in real time based on two modes; the first mode performs an offline Artificial Neural Network (ANN) to compute the amount of load shedding to maintain voltage stability and then, the trained neural network is used in the second mode to reduce the amount of load shedding and identify the optimal location of the load shedding through online IDPSO, where the effect of demand response, critical loads and voltage dependence of the load, are taken in account in the load shedding. In [43], the design of a UVLS based on a multi-objective optimization model is proposed, which seeks to maximize the Voltage Stability Margin (VSM) of the system with the minimum amount of load shedding, and also improve the dynamic behavior of the voltage during the load shedding. Therefore, to solve this problem, they use a multi-objective Fuzzy based Theta Gravitational Search Algorithm (MF-TGSA). Finally, the locations of disconnections are identified with a Q-V sensitivities analysis. The authors of [44] presented a stochastic optimal approach that targets the avoidance of voltage collapse by incorporating correlated uncertainties of wind power and load, described through a correlation matrix. Regarding the UVLS scheme, it is incorporated into a stage known as wait-and-see, where the load shedding amount is calculated through linear programming, and the position of loads is determined based on electric distances (ED). Multiple techniques have been used to solve the optimization problem, such as artificial neural network [45], ant colony [46], firefly algorithm [47] and fuzzy logical control [48], where many of them present either good accuracy or good convergence times and, therefore, it has been sought to combine their characteristics giving rise to hybrid optimization methods to obtain better performance, such as, AG-PSO [49], linear programming (PL)-PSO [50], discrete PSO [51], etc.

2) LOCATION OF THE LOAD SHEDDING

Load-shedding location is a very important design aspect and, sometimes, the magnitude of the voltage in a bus is not sufficient to determine the weakest bus in the grid (load shedding bus) especially for modern power grids that present complex dynamics with non-linear loads and renewable sources. One way of identify the load-shedding location is to compute the dV/dQ sensitivities of each bus, and to order them ascending, with the bus with highest sensitivity being the optimal load-shedding location [52]. The utilization of tangent vector (TV) in the continuation power flow methods, as described in [53], can be employed for tracing PV curves and determining the load shedding buses in a microgrid. The most critical buses in the system are the most sensitive to load variations. Conversely, the power allocation for load shedding is categorized as low, medium, and high priority, with TV magnitude as the determining

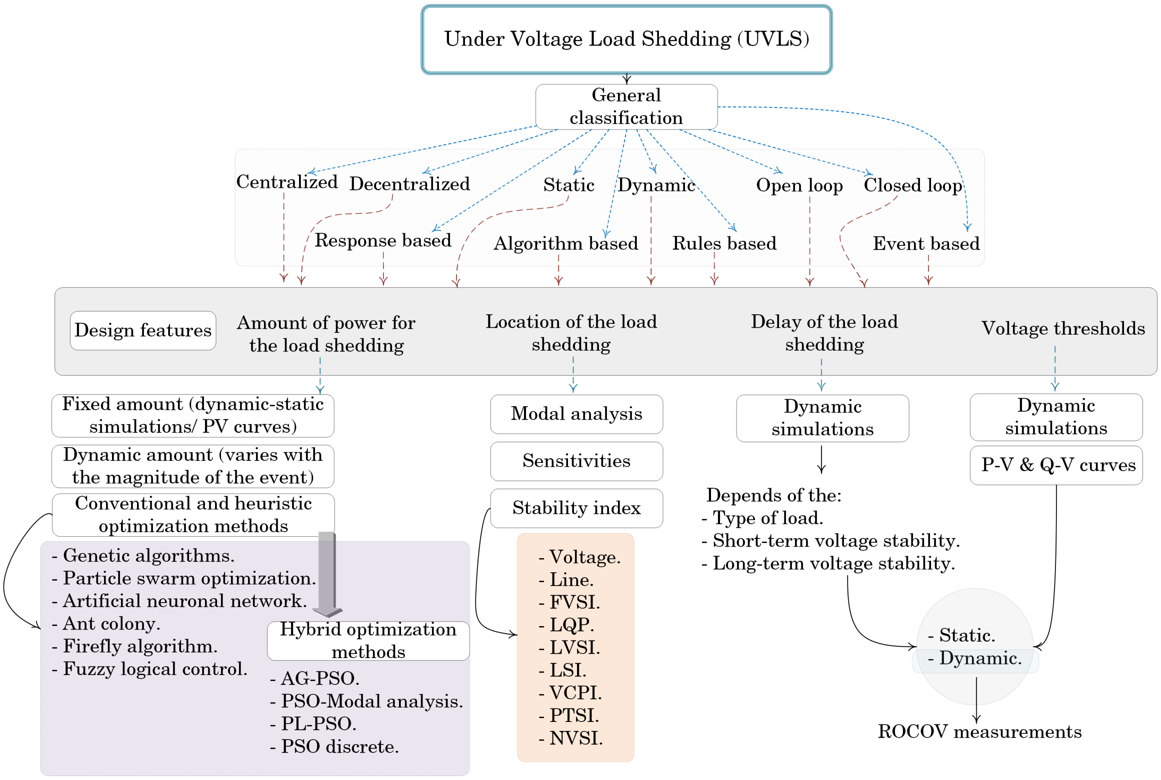


FIGURE 8. Flowchart of different types of UVLS schemes and the various ways to approach their operational parameters.

factor. Another method is to perform modal analysis to the power flow Jacobian matrix at the maximum power transfer point and compute the participation factors associated with the unstable eigenvalue [54], [55]. Furthermore, in [56] an RAS is proposed to prevent mid-term and long-term voltage instabilities, where several Voltage Control Areas (VCA) are considered. The proposed scheme uses all available nearby elements to improve stability. In this sense, the scheme has three voltage thresholds (alert, critical, and emergency status), where in relation to the UVLS stage, if the control area falls below these thresholds, a predefined amount of load is shed; however, the location of the disconnection is identified by the concept of electrical distances.

Reference [57] seeks to increase loadability margin and therefore proposes a closed-loop UVLS that uses loadability margin sensitivities to compute the amount of load shedding and then performs a ranking based on the decreasing sensitivities to identify the load-shedding location. A response-based UVLS is proposed in [58], which uses a data-driven approach. The scheme utilizes a weighted kernel extreme learning machine (WKELM) to effectively identify the most crucial load busses using the TVSI index, thereby minimizing load busses during load shedding. A system that integrates PV generation is analyzed in [59], where the optimal location for load shedding is identified using the voltage collapse proximity indicator (VCPI). A wide variety of indices have been proposed in the literature to help identify the best load-shedding location, such as voltage and line index [60], fast voltage stability index (FVSI) [61], line stability index (LSI) [62], line stability factor (LQP) [63], line voltage stability index (LVSI) [64], voltage collapse prediction index (VCPI) [12], power transfer stability index (PTSI) [65], new voltage stability index (NVSI) [66], among others. However, most of these indices are static as many are based on the power flow model and, therefore, do not provide information on system dynamics. In this regard, in [67], a novel UVLS design is recommended, it proposes the new index Dynamic Voltage Active Power Sensitivity (DVPS), based on dynamic voltage curve sensitivity analysis, which verify the minimum amount of load shedding and to identify the load-shedding location considering the load dynamic model.

3) DELAY IN THE LOAD SHEDDING

The main motivation for performing a delaying load shedding is to avoid an inappropriate disconnection for a fault that would normally be cleared and ensure that the system is becoming unstable by voltage before the disconnection.

The time delay required to execute a load shedding function is contingent upon the type of voltage collapse observed. In the event of a long-term voltage collapse, the time delay may be adjusted to fall within the range of 3 to 10 seconds, while accounting for the specific system's characteristics. Conversely, in the event of a momentary voltage collapse, load shedding can be fine-tuned from 150 ms to 360 ms, and may need to be triggered immediately, as the system may not recover [29]. This UVLS operating parameter is vital and must be coordinated with the generator voltage ride-through capability and other protections and control schemes [68]. Efforts have been directed towards providing greater flexibility in the delay of load shedding, owing to the strong connection between voltage stability and load behavior, and because usually, this delay is fixed for all scenarios. For example, an UVLS that considers the effect of non-linear loads (induction motors) was designed in [69] to cover short-term voltage stability. The protection scheme is based on wide area measurements, where it monitors if the field current of some generators exceeds their over-excitation limit for a certain time and, if this is met, a signal is sent to reduce the shedding time, making the delay adaptable and dependent on the conditions of the system. An adaptive time delay technique for load shedding is proposed by the authors in [70]. A rule-based scheme is used where voltage thresholds are fixed, the amount of load shedding is predefined, and offline non-critical loads are selected. An adaptive time delay, which depends on the local rate of change of voltage (ROCOV) measurements, is proposed. In case of a high ROCOV detection, the time delay is lessened to speed up the load shedding process. On the contrary, the detection of an insignificant ROCOV results in an increase in the delay of shedding load.

4) VOLTAGE THRESHOLDS

Typically, voltage thresholds are defined from power-voltage (PV) and reactive-voltage (QV) characteristics curves or by multiple offline simulations; however, conventionally, it is a fixed value where the magnitude of the event is not considered. Ways have also been sought to give flexibility to this threshold. For example, in [71] a two-level UVLS is designed; the first level is based on rules with fixed thresholds and of the second level has a wide area monitor the state of the system, this level performs an online sensitivity study and, when detecting a sign change, identifies a system evolution to voltage instability, selecting as a threshold the value of the voltage being measured at that moment, preventing the system from further degrading to the initial threshold. An adaptive voltage threshold has been incorporated into the UVLS technique proposed by the authors of [72]. The determination of these thresholds is contingent upon the local measurement of the ROCOV. When a large ROCOV is detected, the voltage threshold increases, which prevents voltage drop and results in faster load shedding. In the event of a small ROCOV, load shedding becomes unnecessary, thus requiring a lower voltage threshold. From the above, Fig. 8 shows a general classification of the different types of UVLS, besides the most relevant characteristics during the design of these schemes, which were described above. Finally, it also shows the different approaches with which each of these design features is addressed.

TABLE 2. **Western interconnection of USA UFLS program settings [15].**

Frequency Set point	Coordinated Plan	NWPP Sub-Area	Southern Island Sub-Area
59.6 Hz	-	-	0.07%
59.5 Hz	-	-	4.0%
59.3 Hz	-	5.6%	-
59.2 Hz	-	5.6%	-
59.1 Hz	5.3%	-	2.8%
59.0 Hz	-	5.6%	-
58.9 Hz	5.9%	-	6.5%
58.8 Hz	-	5.6%	-
58.7 Hz	6.5%	-	7.4%
58.6 Hz	-	5.6%	-
58.5 Hz	6.7%	-	7.4%
58.3 Hz	6.7%	-	7.3%
Total % Shed	31.1%	28%	35.4%%

B. DESIGN OF AN UNDER FREQUENCY LOAD SHEDDING

The outages of generating units lead to significant power imbalances. Sometimes primary and secondary frequency controls do not respond quickly and efficiently. In these cases, UFLS can be used as an emergency protection scheme and fall under the category of RAS schemes used to prevent large-scale blackouts. UFLS aims to minimize frequency deviations during abnormal situations. The premise of an UFLS is that a strategic and controlled load disconnection can avoid an uncontrolled disconnection of generation units. The operation of UFLS is based on shedding a predefined amount of power (which varies according to consumption users) when the system frequency exceeds a threshold. If, at this point, the frequency continues to fall to lower values, the following frequency threshold is activated, and the predefined power percentage is shed, and so on, until the frequency recovers or UFLS stages are completed. This is the conventional method of an UFLS, and it is essential to note that its predefined operating parameters, i.e., the frequency thresholds and the amount of power to load shedding, make UFLS susceptible to excessive or inappropriate load disconnections, especially in modern power systems, where the uncertainties of wind and photovoltaic power play an important role, as their inherent variability strongly impacts in the frequency stability, as well as the null inertia. In this sense, three categories of UFLS have been identified; conventional, semi-adaptive, and adaptive. In the last two categories, the aim is to overcome the limitations of conventional UFLS by reducing inappropriate disconnections and designing them adaptable to changes in the electrical grid. Therefore, this section will show the design structure of the different categories of UFLS, relevant works in this area, approaches studied and the areas of opportunity within the UFLS design.

1) CONVENTIONAL UFLS

Several methods have been proposed to design conventional UFLS; however, there is no generalized method to design these schemes. The design approaches are typically based on the experience of the designers and the robustness of the power grid, and even follow typical design criteria on the number of stages, step size, frequency thresholds, and the amount of power to load shedding [73]. Most conventional UFLS have an experimental approach in which a trial-and-error process is used, and the best scheme within a set of candidate UFLS is selected. With the above, Table 2 shows the settings of the UFLS programs that are configured in the Western Interconnection. In this sense, in 1968, a conventional process to develop a UFLS was presented, which has been taken as a reference for a long time [74]. The methodology is divided into three steps.

1) **Level of overload:** It is the level of protection provided to the system, the degree of maximum overload to cover, and is considered the most critical overload scenario. The selection of this parameter is very relevant; it directly influences the amount of power for the load shedding and computes as follows:

$$\mathrm{L} = \frac{\mathrm{Total}_{\mathrm{Load}} - \mathrm{Total}_{\mathrm{Gen}}}{\mathrm{Total}_{\mathrm{Gen}}}$$

2) **Amount of load to shed (LD):**

$$\mathrm{LD} = \frac{\frac{\mathrm{L}}{1+\mathrm{L}} - d\left(1 - \frac{f}{f_n}\right)}{1 - d\left(\frac{f}{f_n}\right)}$$

where:
L = Level of overload.
d = Load reduction factor.
f = Minimum permitted frequency.
f_n = Nominal frequency.
The load reduction factor (d) is the percentage change in load due to the percentage change in frequency (frequency dependent load). Typically, d is assumed to be 2% (it can range from 1.27% to 7.8%) by 1% in frequency reduction.

3) **Number of stages of shed:** The amount of power to the load shedding is performed in stages to avoid disconnecting large amounts of power when the system presents small disturbances; therefore, in the early stages, the magnitude of the shed is lower, while in the later stages, the magnitude of the shed is large. The number of stages is preset, and the more stages used, the load shedding will be more accurate. However, a large number of stages complicates its coordination (typically, the number of stages is between 3 to 6).

The aforementioned process performs the design of the UFLS on the most critical hypothetical scenario. It coordinates each load shedding stage from frequency response curves that only consider the response of the load characteristic and the equivalent inertia of the system, omitting the response of the governor controls. This approach was designed considering a system dominated by synchronous machines and loses accuracy when applied to a system with renewable integration and, even more, when not considering the response of governors. In this respect, a similar methodology is presented in [75]; however, they propose a methodology for the calculation of the frequency thresholds. It is clear that, the calculation of the amount of power, the number of stages, the frequency thresholds, and the percentage of shed in each stage are decisive for the design of a UFLS [76]. However, the design of conventional UFLS has the disadvantage of the lack of adaptability to network conditions and the magnitude of the event, as its design is performed on a given scenario and, therefore, its operating parameters are constant and predetermined, causing more load to be disconnected in scenarios that are not required.

2) SEMI-ADAPTIVE UFLS

The characteristics of conventional UFLS do not meet the needs of the modern power grids, which are constantly changing especially with high levels of renewable penetration, which gradually affects the frequency of electrical networks, leading to the development of schemes that seek to provide greater flexibility to the design parameters, for example, in [77] a semi-adaptive scheme was proposed, which performs a sweep of the rate of change of the frequency (ROCOF) with respect to the frequency of the system, different amounts of load shedding (LS) and different time delays in the load shedding (TD), obtaining characteristic curves (ROCOF-f-LS-TD), these curves are loaded to the UFLS and it is enough to monitor the ROCOF of the system; however, despite the flexibility of the operating parameters. The methodology is designed offline and they are not fully adaptive. Furthermore, in [78] a semi-adaptive UFLS was proposed based on a linear system frequency response (SFR) model, where it computes the amount of load to be shed by measuring the initial slope of the frequency deviation when an island mode is presented. From this information, the first stage of load shedding is configured adaptively, while the following stages are predefined.

3) ADAPTIVE UFLS

On the other hand, the design of adaptive UFLS has become an emerging area which seeks to give greater flexibility to the operating parameters of these schemes, so that its operation is adapted to the behavior of the modern electrical networks. The first generation of UFLS was based in the online estimation of the magnitude of the disturbance, through the swing equation from the synchronous machine, as shown in (1). In [79], an UFLS is proposed which estimates online the power imbalance using the swing equation and taking measurements at the output of synchronous machines in the area. Then, the estimated amount of imbalance is distributed between each stage of shed, then the fault location is performed by monitoring the ROCOF, where the bus with the highest ROCOF is to the fault and, therefore, where the shed of load is performed. Similarly, in [80] the online power imbalance is estimated from the swing equation; however, it uses optimization techniques to reduce the frequency deviation with the minimum amount of load shedding. Moreover, in relation with the online estimated power imbalance when considering electrical power networks with considerable geographical dimensions and multiple synchronous machines distributed in different areas, the problem becomes more complex because during a disturbance, occur a frequency variations between machines located in different areas of the system, even more if there are inter-area oscillations, as shown in (2). To overcome this problem, the center of inertia (COI) is usually used in adaptive UFLS schemes for the power imbalance estimation stage, as shown in (3) and (4) [81].

$$\frac{2H_i}{f_n}\frac{df_i}{dt} = P_{m_i} - P_{e_i} = \Delta P_i \tag{1}$$

$$\Delta P = \sum_{i=1}^{N} \Delta P_i = \frac{2\sum_{i=1}^{N} H_i}{f_n}\frac{df_{COI}}{dt} \tag{2}$$

$$f_{COI} = \frac{\sum_{i=1}^{N} H_i f_i}{\sum_{i=1}^{N} H_i} \tag{3}$$

or in function of δ

$$\delta_{COI} = \frac{\sum_{i=1}^{N} H_i \delta_i}{\sum_{i=1}^{N} H_i} \tag{4}$$

In [82], the UFLS estimates the COI of each area, which calculates the power imbalance by areas and simultaneously detects the most vulnerable areas, then distributes the amount of shed among the most vulnerable areas. Finally, it calculates the stability indices FVSI to identify an optimal location of the load shedding and simultaneously avoid voltage stability problems. Similarly, a two-stage scheme is proposed in [83]; the first stage calculates the power imbalance using the COI and, the second stage, using Lagrange Multipliers to identify the optimal load shedding location. Furthermore, the adaptive UFLS schemes seek to have visibility of frequency dynamics in different areas of the power system. In this sense, thanks to recent advances in the Phasor Measurement Units (PMUs), they have allowed an accurate monitoring of power systems, giving rise to the concept Wide-Area Monitoring, Protection and Control (WAMPAC), widely used in adaptive UFLS, as shown in Fig. 9 [84]. In this regard, the efficiency of adaptive approaches is highly dependent on the system observability provided by existing PMUs, it is critical the nearest an optimal distribution of measurements in the system, to know uncertainties in measurements, avoid communication network failures and false data injection by cyber attacks [85]. From the above, reference [86] describes how a false injection of data can affect the frequency measurements and power flow measurement and cause a failed operation of a UFLS and, consequently, a blackout. In this sense, [86] proposed a data classification method to make an reliable estimate states of the power system and, then, use a dynamic power flow analysis to compute the power imbalance and only shed the load in one stage. Finally, the amount of load shedding is distributed depending on the voltage dips at the load buses. In [87] they propose a new data-driven approach to estimate the nadir frequency from a rolling first-degree polynomial function, considering time delays and measurements uncertainty. For the estimation of the imbalance they use an approach associated with the swing equation; however, within the formulation they perform a comparison between a system database and the current conditions of the system under study and, in addition, they introduce the frequency estimation stage in this calculation. The UFLS problem is tackled as a Markov decision process (MDP) in a data-driven load shedding strategy proposed by the authors of reference [88]. The algorithm is based on a dueling deep Q-learning (DQL) to determine the best UFLS scheme according to the condition of the system. In addition, it considers the priority of loads through a load shedding contribution indicator (LSCI).

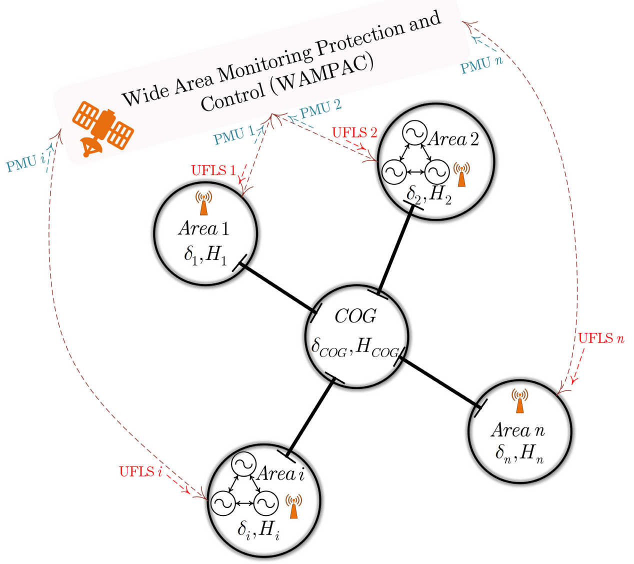


FIGURE 9. Concept of the center of inertia with WAMPAC in a UFLS scheme [81].

Nevertheless, the conventional, semi-adaptive and adaptive schemes mentioned above assume only systems with synchronous machines, and assume constant the equivalent inertia of the system; however, when a generation unit is disconnected, the equivalent inertia of the system changes and also, when considering scenarios with high levels of renewable penetration, the inertia of the system is highly variable and uncertain in nature, jeopardizing the accuracy of power imbalance estimation, and disconnecting inadequate amounts of power. In this regard, in [89] it is considered an electrical network with wind generators with virtual controls, where the scheme makes a correction when calculating the COI, considering the power variations in wind farms. Similarly, in [90] a correction in the COI is used considering power variations in wind farms. However, the UFLS calculates online sensitivities to detect critical buses for voltage instability and perform load shedding optimally. In [91] the COI principle is used to estimate the power imbalance, from ROCOF measurements on each machine and their respective inertia constants, and not estimate the equivalent inertia of the system; however, the photovoltaic park models are integrated to consider their power variations due to their intermittent nature, in order to calculate more accurately the voltage stability indices (VSI) from Thevenin equivalents at each load bus, to detect more accurately the proper location of the load shedding. The aforementioned schemes are primarily centralized, meaning that they obtain readings from remote locations and transmit the data to a central control center where the COI calculation is typically performed. The authors of [92] proposed a decentralized UFLS system, comprising multiple UFLS distributed throughout the system, each equipped with an inertial estimator for calculating the corresponding center of inertia (COI). By providing continuous inertia estimation, this system can accommodate high levels of renewable penetration. In this context, it becomes necessary to employ local frequency estimation methods to ensure appropriate UFLS performance. The methods in question are surveyed in the following publications [93], [94], [95].

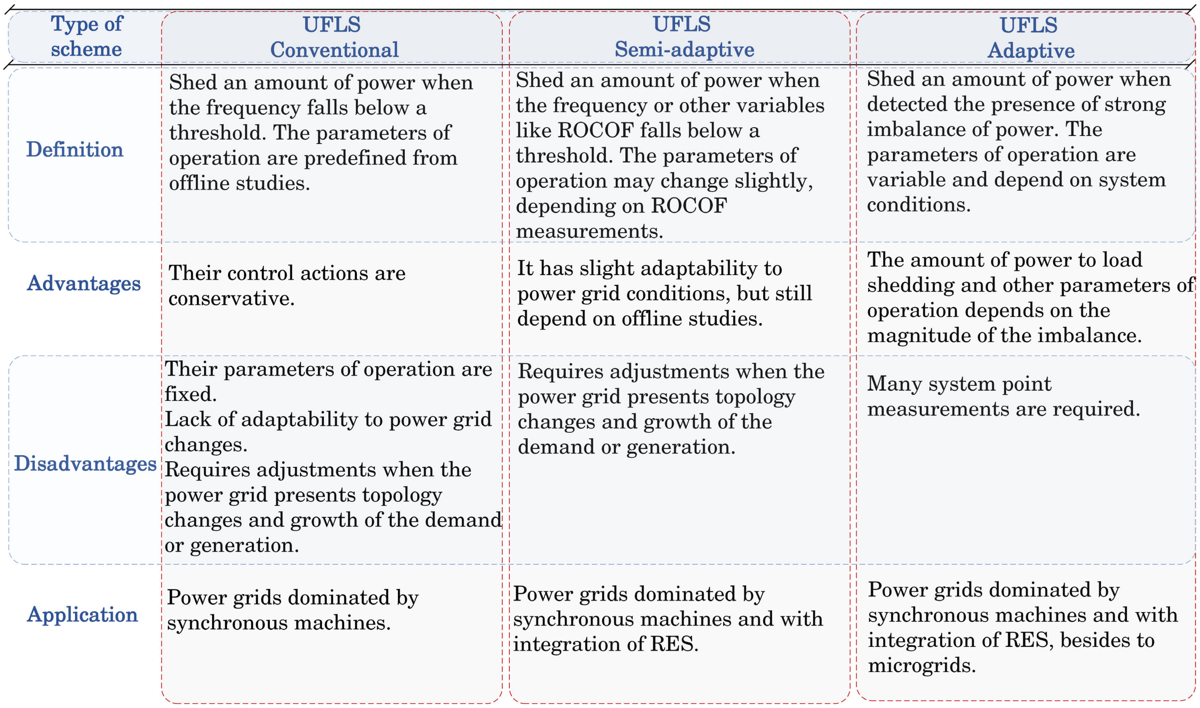
Another research gap within the UFLS has focused on giving flexibility to frequency thresholds. For example, in [96], an UFLS was proposed which dynamically modifies the frequency thresholds in each of the stages, this scheme is based on the idea that the buses closest to a fault have large voltage deviations and are highly recommended to perform a load shedding. In this way, buses with high voltage deviation during a failure modify their frequency threshold to activate quickly. Furthermore, in [97] an UFLS with two frequency thresholds is proposed, the first for small disturbances and the second for large disturbances; both thresholds are adapted continuously monitoring the ROCOF and the spinning reserves of the power grid. To estimate the power imbalance, the UFLS measures the amount of generation power that was tripped and compares it to spinning reserves, and for the location of the load shedding proposes a new voltage stability index (VQS). Similarly, in [98] the same methodology as in [97] is proposed to give flexibility to frequency thresholds, with the difference that they use a completely different voltage stability index (QVSI), however, none of the above proposals consider scenarios with renewable sources. On the other hand, more advanced techniques have been integrated into the adaptive UFLS scheme approach as in [99], which uses a linear programming method to calculate UFLS parameters such as frequency thresholds, amount of power for load shedding and shed delay times, considering uncertainties. Moreover, in [100] the UFLS uses a Markov model to model historical wind speeds, then to minimize the load shedding solves a problem of optimization with PSO and fuzzy optimization. It is possible to emphasize that optimization techniques present excellent results to minimize or maximize functions and find optimal solutions; however, they use very complex mathematical methods, which complicates their integration into real systems and, in addition, as system dimensions increase the convergence times of these methods become more extensive, making them unsuitable for online applications. The authors of reference [101] have proposed a novel flexible approach that is founded entirely on the principles of conventional UFLS. The proposed scheme introduces a novel frequency stability parameter, which acts as a variable in the activation logic and relies on the ROCOF and the fixed frequency drop criterion. The recently introduced parameter functions as an indicator of the severity of frequency deviation. The proposed method is applicable to electrical networks that have a significant percentage of power electronics-based sources. This scheme is a patent [102].

4) UFLS COORDINATED WITH ESS AND FACTS

Despite the attempt to reduce the amount of load shedding from adaptive UFLS schemes, these continue do not shed exact amounts of power, causing massive interruptions in the electrical power supply. Therefore, new resources have been sought within the power system to enhance the performance of adaptive UFLS, helping them to operate only under indispensable conditions and to reduce the percentage of power that is shed. Energy Storage Systems (ESS) have been used in recent years as an active power support during frequency deviations, using a fast frequency response (FFR) feature. For example, in [103] an adaptive UFLS operating in coordination with a Battery Energy Storage System (BESS) is proposed, where the storage device has two functions; the first function is to provide virtual inertia, which will be proportional to the ROCOF measurements and, the second function, is to use the BESS as primary frequency reserve control, to reduce the amount of shed. The authors of [104] proposed a coordinated UFLS with a Battery Energy Storage System (BESS) aimed at enhancing the dynamic stability of the designated feeder, in the event of its disconnection following UFLS operation, leading to its isolation from the rest of the network. By incorporating BESS to provide primary frequency response when significant frequency deviations are detected, the proposed scheme BESS-UFLS, as presented in reference [105], aims to minimize the need for load shedding. Likewise, the authors in [106] presented a proposal that employs optimal power flow (OPF)-driven under frequency load shedding and BESS to minimize the amount of power during the shed in a low-inertia system. The proposal presented in [107] suggests the implementation of a Battery Energy Storage System (BESS) to address power imbalances in a microgrid operating in island mode, consequently avoiding the requirement for Under Frequency Load Shedding (UFLS) operation. The power imbalance is estimated by the scheme using ROCOF measurement, with the BESS control serving as a reference. An adaptive dispatch strategy for a BESS has been proposed in [108], which offers virtual inertia to enable high levels of penetration in a microgrid. The proposed work in [109] introduces a BESS that provides the network with inertial support through virtual inertia. This scheme takes into consideration an equivalent battery model based on data-driven analysis, which includes the annual costs, life expectancy and state of charge. Ultimately, the power angle-based stability index is utilized to assess the impact of virtual inertia on transient stability. However, a disadvantage of these approaches is that ESS has limited energy and therefore it is valuable to

TABLE 3. Adaptive UFLS coordinated with ESS and FACTS.

		Coordination with ESS			Coordination with FACTS		
Year	Ref	ESS	Type of ESS	Objective	SVC	STATCOM	Objective
2015	[110]	✓	BESS	Avoid UFLS	x	x	-
2016	[107]	✓	BESS	Avoid UFLS	x	x	-
2018	[111]	✓	EVs	Reduce ΔP	x	x	-
2019	[114]	✓	BESS	Prolong UFLS	x	✓	Improve the dynamic
2019	[108]	✓	BESS	Improve the dynamic	x	x	-
2020	[104]	✓	BESS	Improve the dynamic	x	x	-
2020	[115]	x	-	-	x	✓	Reduce ΔV
2020	[116]	x	-	-	✓	x	Reduce ΔP
2021	[117]	x	-	-	✓	✓	Reduce ΔP & avoid voltage collapse
2021	[103]	✓	BESS	Reduce ΔP	x	x	-
2021	[105]	✓	BESS	Reduce ΔP	x	x	-
2021	[106]	✓	BESS	Reduce ΔP	x	x	-
2022	[112]	✓	EVs	Sequential EVs restoration	x	x	-
2022	[113]	✓	EVs	Reduce ΔP	x	x	-



Type of scheme	UFLS Conventional	UFLS Semi-adaptive	UFLS Adaptive
Definition	Shed an amount of power when the frequency falls below a threshold. The parameters of operation are predefined from offline studies.	Shed an amount of power when the frequency or other variables like ROCOF falls below a threshold. The parameters of operation may change slightly, depending on ROCOF measurements.	Shed an amount of power when detected the presence of strong imbalance of power. The parameters of operation are variable and depend on system conditions.
Advantages	Their control actions are conservative.	It has slight adaptability to power grid conditions, but still depend on offline studies.	The amount of power to load shedding and other parameters of operation depends on the magnitude of the imbalance.
Disadvantages	Their parameters of operation are fixed. Lack of adaptability to power grid changes. Requires adjustments when the power grid presents topology changes and growth of the demand or generation.	Requires adjustments when the power grid presents topology changes and growth of the demand or generation.	Many system point measurements are required.
Application	Power grids dominated by synchronous machines.	Power grids dominated by synchronous machines and with integration of RES.	Power grids dominated by synchronous machines and with integration of RES, besides to microgrids.

FIGURE 10. Differences between Conventional, Semi-adaptive and Adaptive UFLS.

consider this feature within the scheme. Furthermore, the high levels of renewable penetration lead to a reduction in the equivalent inertia of the system and, therefore, the frequency usually shows deeper deviations, causing UFLS to activate unnecessarily even though the system could overcome the power imbalance and stabilize the frequency. In this sense, in [110] is proposed to incorporate the control of a BESS to support the system when detect a deep deviation of frequency in order to prevent the unnecessary activation of the UFLS. The controls of the BESS use a network parameter identification using a Kalman filter to implement predictive control for active power support without UFLS operation. On the other hand, in [111] is proposed the first attempt to enable Electric Vehicles (EVs) within an adaptive UFLS strategy. The adaptive UFLS achieves full integration from the control center, the charging stations and the terminals of the EVs. In addition, it is a strategy that considers various modes of support of EVs to the power grid, for example, the scheme is able to interrupt or decrease the power charged of EVs during a frequency drop event, to reduce the total load of the system or, on the other hand, it can indicate high capacity EVs to inject active power into the power grid during a deep frequency drop, performing frequency support. Furthermore, in the event of a UFLS operation, a disorganized recharge of EVs could trigger a secondary frequency drop in the system, resulting in a negative impact on frequency stability. In this sense, in [112] a sequential multi-stage load restoration is proposed for EVs during operation of the UFLS.

Finally, another problem arises with the uncertainty of wind power, as its uncertainty amplifies frequency imbalances and seriously compromises the stability of the system. Within this context, the authors in [113] present an optimal UFLS approach that utilizes a non-parametric KDE technique to assess the uncertainties associated with wind power and the stochastic nature of EV commuting. This strategy minimizes the amount of power shed during load shedding.

Frequency stability is a problem involving voltage stability in a certain way, this is due the synchronous machines can inject reactive power to the power grid and, therefore, when occur a frequency drops due to the trip of one or more synchronous machines, there is also a reactive power imbalance in the power grid, causing a deficit of reactive power and, consequently, low voltage profiles. Therefore, in [114] proposes to use a BESS to support critical loads for a certain time, with the aim of prolong the activation of load shedding; however, this UFLS also uses a STATCOM to compensate frequency transients and improve the dynamic response of the power grid. In [115] proposes an adaptive UFLS coordinated with a STATCOM to prevent loss of voltage stability after the load shedding. Similarly, in [116] it proposes an adaptive UFLS which considers the daily variations in load profiles and the type of load, with the aim of minimize the interruption costs during the operation of the load shedding and, therefore, the UFLS involves the model of loads to have a more accurate estimate of the power imbalance; the peculiarity of this adaptive UFLS is that after of the load shedding, intentionally reduces the voltages of some buses from the SVCs distributed along the power grid, with the aim of reduce the active power consumed by the loads on those buses, helping adaptive UFLS to more easily stabilize system frequency. To determine the amount of load shedding, an improved moth flame optimization (IMFO) algorithm was proposed in [117]. In addition, the scheme is coordinated with an SVC and a STATCOM to reduce the amount of load shedding and prevent voltage collapse simultaneously. In this regard, Table 3 shows a comparison of the UFLS coordinated with ESS and FACTS, with the aim of showing the control objectives when using these devices. In relation to the ESS it is observed that its objectives are directly associated to reduce the amount of load shedding and to avoid or prolong the use of load shedding. In contrast, the use of FACTS is often used to prevent voltage instability in the load buses after load shedding and even improve the dynamics of the electrical network during transients that occur in these events. From the above, UFLS schemes coordinated with ESS or FACTS can be included within the classification of adaptive schemes. In this sense, the Fig. 10 shows the general definitions, advantages, disadvantages and application between the conventional, semi-adaptive and adaptive UFLS. Finally, Fig. 11 shows a general diagram of the main characteristics of UFLS, a description of conventional, semi-adaptive UFLS and, in addition, a very general classification of the different approaches of adaptive UFLS, showing some characteristics from which this protection schemes have been given adaptability in recent years, and which have been mentioned throughout this section.

V. TREND OF RAS

The information obtained in the previous sections has been broken down to show the advances in the development of the load shedding schemes focused in UVLS and UFLS. The presented section showcases the trend of the load shedding schemes in modern electrical power systems, which exhibit fast and intricate dynamics due to their extensive dimensions, their operation near their stability limits, and the significant portion of renewable integration that relies on power electronics. For example, Table 4 shows chronologically the trend and the main characteristics of UVLS collected in the previous sections. It is possible to observe that rule-based UVLS predominates, but they are usually combined with other types of schemes, such as closed-loop based (35% of those collected) and event-based (30% of those collected) to give greater robustness and flexibility to this protection scheme. With the help of such combined schemes, it is possible to give some flexibility to some operating parameters of the UVLS. For example, in relation to the amount of load shedding, the conventional UVLS focused on shedding a predefined power amount for each rule. The design is performed offline from static analysis tools to evaluate the voltage stability, such as the P-V curve, then validate these schemes and make the relevant corrections from offline simulations. Due to the economic problems involved in load shedding, it has been considered that an optimization problem should solve, where it has sought to reduce the amount of load shedding and increase the stability margins of the system. Therefore, it has been observed that, in the design stage, metaheuristic approaches were used to solve multi-objective problems and calculate an accurate amount of power to be shed, such as AG, MF-TSGA, PSO, ANN, and IDPSO or schemes based in data-driven approach.

Despite the above, events may occur during operation of the power grid that were not considered during the design of the UVLS and, even given that in most cases the design is based on static approaches, the amount of load shedding may not be sufficiently accurate. In this regard, several of the collected schemes propose an adaptive approach where the scheme estimates online the magnitude of the event and calculates an amount to shed suitable to the conditions of the power grid. Such schemes usually use a PI control in one of their shed disconnection stages, where their philosophy is to measure the voltage deviation at some point in the power grid concerning some predefined voltage threshold.

For conventional UVLS, it was sufficient to associate the load-shedding location to buses with large voltage drops, but due to how complex the voltage stability problem has become, this methodology could be less effective. Therefore, in Table 4, it is shown that the collected UVLS uses various techniques to identify the optimal load-shedding location. The calculation of Q-V sensitivities is the most commonly used, even though some schemes use this tool for adaptive

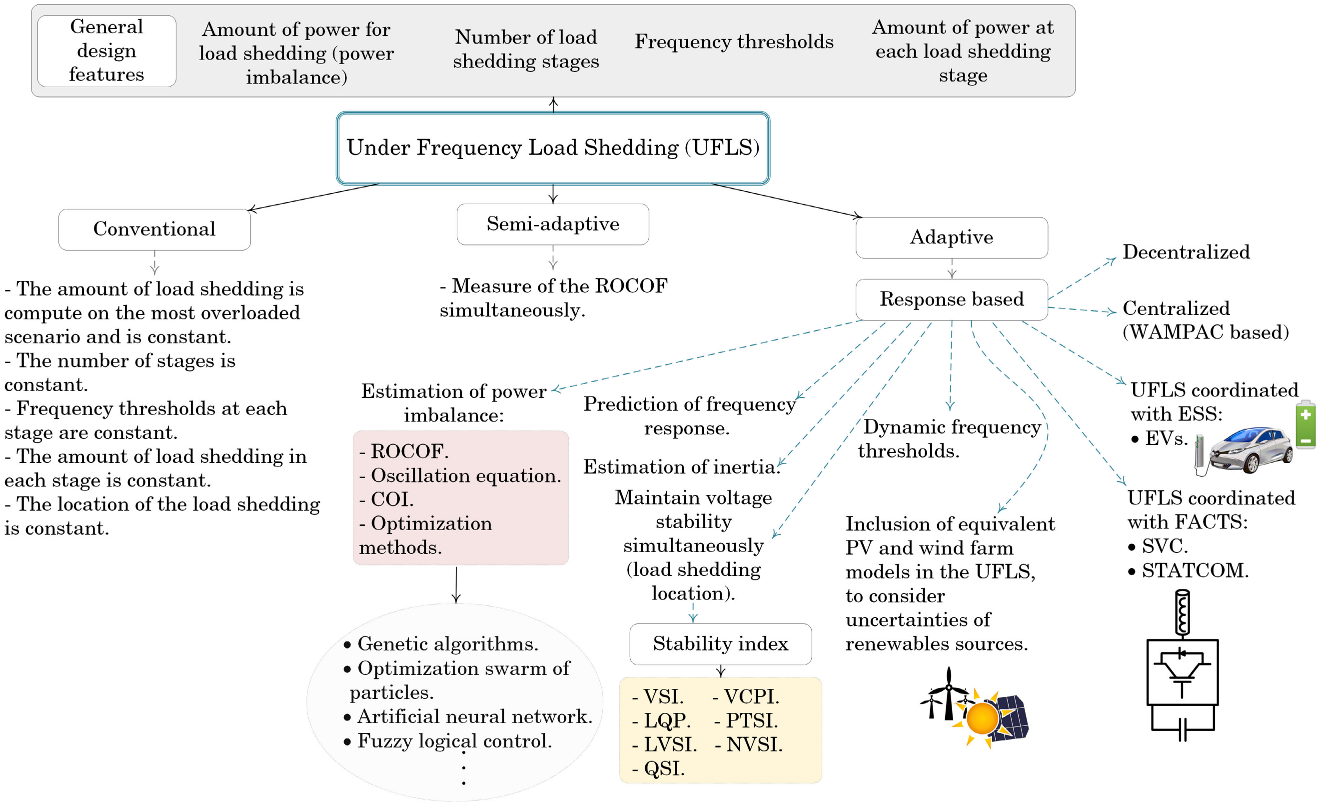


FIGURE 11. Flowchart of different types of UFLS schemes, and their main design and operation features.

TABLE 4. Characteristics of the collected UVSL.

			Amount of power to shed		Location		Delay	Threshold (V_{th})
Year	Ref	Type of scheme	Method	Dynamic	Method	Dynamic	Dynamic	Dynamic
1992	[33]	Rules/Event	Simulations	x	Under voltage	x	x	x
1998	[35]	Rules/Event	PV curves	x	Under voltage	x	x	x
2000	[39]	Closed loop	AG	x	dV/dQ	x	x	x
2004	[22]	Rules/Closed loop	PI Control	✓	dV/dQ	✓	x	x
2007	[36]	Rules/Closed loop	PI Control	✓	dV/dQ	✓	x	x
2008	[57]	Closed loop	Loadability margin	✓	Loadability margin	✓	x	x
2011	[69]	Rules/Closed loop	PI Control	✓	dV/dQ	✓	✓	x
2012	[71]	Rules/Closed loop	PI Control	✓	dV/dQ	✓	x	✓
2015	[43]	Rules/Event	VSM-MF-TSGA	x	dV/dQ	x	x	x
2017	[44]	Rules/Event	Linear-Programming	✓	Electrical distances	✓	x	x
2017	[59]	Closed loop	Power Measurements	✓	VCPI	✓	x	x
2019	[72]	Rules/Event	Predefined	x	Predefined	x	x	✓
2019	[53]	Rules/Event	Tangent vector	✓	Tangent vector	✓	x	x
2020	[56]	Rules/Closed loop	Predefined	✓	Electrical distances	✓	x	x
2020	[55]	Event	PV curves	✓	Modal analysis	✓	x	x
2020	[70]	Rules/Event	Predefined	x	Non-critical load	x	✓	x
2021	[58]	Closed loop	Data-driven (WKELM)	✓	TVSI	✓	x	x
2022	[67]	Event	Index DVPS	x	Index DVPS	x	x	x
2023	[42]	Closed loop	ANN & IDPSO	✓	IDPSO	✓	x	x
2023	[37]	Closed loop	Data-driven (SGP)	✓	TVSI	x	x	x

UVLS. On the other hand, other schemes use modal voltage stability analysis, but these techniques focus on a steady-state model, and the bandwidth of these models usually needs to be improved, at least considering the voltage dependence of the load or inherent intermittency of the renewable sources. Moreover, as the dimensions of the power grid grows, the computational burden to use these methods becomes denser, complicating their real-time implementation. Finally, some of the collected UVLS schemes adapt the voltage thresholds, as well as the load shedding activation delay.

Table 5 shows chronologically the trend and key characteristics of the UFLS collected in this review. Of the UFLS collected, the adaptive UFLS predominate with 76%, then the conventional UFLS with 14% and finally the semi-adaptive UFLS with 10%. This indicates the interest in developing adaptive UFLS. It was observed that the amount of load

TABLE 5. Characteristics of the collected UFLS.

Year	Ref	Type of scheme	Amount of power to shed		Location		Threshold (f)	Inertia	Renewable
			Method	Dynamic	Method	Dynamic	Dynamic	Estimation	
1968	[74]	Conventional	Offline testing	x	Offline testing	x	x	x	x
1988	[75]	Conventional	Offline testing	x	Offline testing	x	x	x	x
1992	[78]	Semi-adaptive	ROCOF	✓	Offline testing	x	x	x	x
2006	[79]	Adaptive	Swing equation	✓	ROCOF	✓	x	x	x
2008	[80]	Adaptive	Swing equation	✓	ROCOF	✓	✓	x	x
2009	[77]	Semi-adaptive	Curves ROCOF-LS	✓	ROCOF	x	x	x	x
2015	[96]	Adaptive	Offline testing	x	Voltage dips	✓	✓	x	x
2017	[89]	Adaptive	COI	✓	dV/dP	✓	x	✓	✓
2017	[90]	Adaptive	COI	✓	ROCOF	✓	x	✓	✓
2018	[97]	Adaptive	Measure Power Out	✓	VQS	✓	✓	x	x
2018	[98]	Adaptive	Measure Power Out	✓	QVSI	✓	✓	x	x
2019	[92]	Adaptive	COI	✓	-	-	x	✓	x
2020	[83]	Adaptive	COI	✓	Lagrange M	✓	x	x	x
2020	[99]	Adaptive	COI LP	✓	Offline testing	x	x	x	x
2020	[101]	Conventional	Offline testing	x	Offline testing	x	x	x	x
2020	[82]	Adaptive	COI	✓	ROCOF-FVSI	✓	x	x	x
2021	[91]	Adaptive	COI	✓	VSI	✓	x	x	✓
2021	[100]	Adaptive	COI PSO-Fuzzy	✓	ROCOF	✓	x	x	✓
2021	[88]	Adaptive	Data-driven (DQL)	✓	LSCI	✓	x	x	x
2022	[86]	Adaptive	Dynamic power flow	✓	Voltage dips	✓	x	x	x
2022	[87]	Adaptive	Data-driven	✓	Not mentioned	x	x	x	x

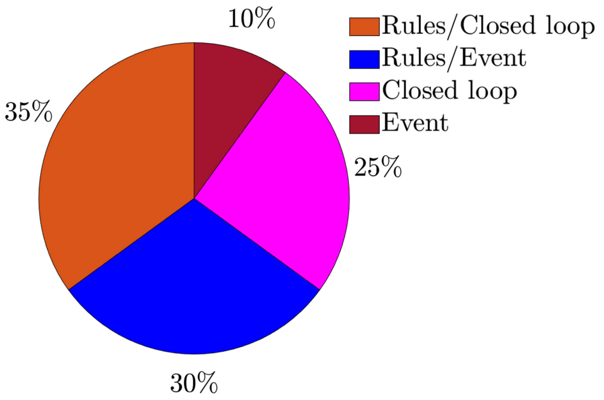


FIGURE 12. Most commonly used types of UVLS.

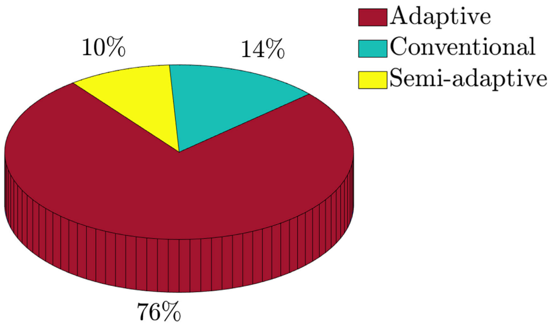


FIGURE 13. Percentage of type of UFLS schemes.

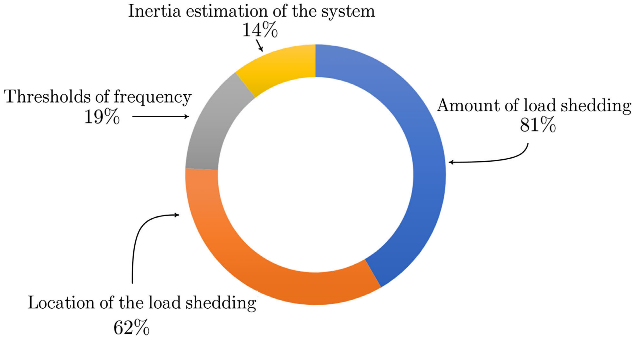


FIGURE 14. Parameters given greater flexibility within adaptive UFLS.

shedding (81%), the location of the load shedding (62%) and the thresholds of frequency (19%) are the operating parameters, in this order, that should give the most flexibility during real-time operation and, in addition, there are some others that make inertia estimation continuously (14%). Regarding the amount of load shedding, most of the schemes estimate the magnitude of the event from the swing equation and the COI concept, but most of these works only consider power grids dominated by synchronous machines. Therefore, consider constant equivalent inertia, which reduces their accuracy, and even more, if it is considered that in modern electrical networks have a greater participation of renewable generation sources based on power electronics. In this sense, the solutions that were observed before this inconvenience were to make corrections within the calculation of the COI, considering the wind profiles in wind power and the generation variations in the photovoltaic parks. In addition, introducing inertia estimation algorithms online was another solution, which has achieved greater precision in estimating the amount of power to shed and, even has used optimization techniques to reduce the amount of power to shed. However, because of precision problems that can occur using the COI, other works have decided to use approaches, such as dynamic power flow and data-driven schemes or even monitor spinning reserves and generation unit outages.

In relation to the load shedding location some works use ROCOF measurement to identify the optimal zones to shed; although, due to the voltage dependence of the load, more recent works have used the calculation of sensitivities and

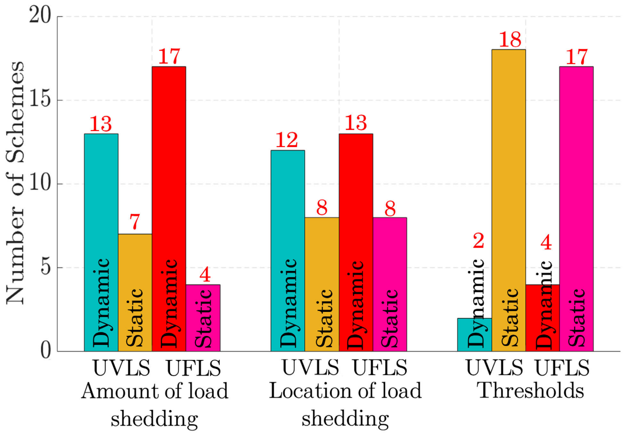


FIGURE 15. **Number of static and dynamic operating characteristics of UVLS and UFLS.**

also different voltage stability indices to identify the optimal disconnection location to simultaneously maintain voltage stability. Moreover, some other UFLS schemes consider it sufficient to monitor the voltage dips at the load buses to identify the load shedding location. In relation to the thresholds of frequency, some works use measurements of the power grid to identify their conditions and decide, and it is necessary to move the frequency thresholds to speed up o delaying the load shedding. In this regard, some works use ROCOF measurements, spinning reserves and other voltage dips. Finally, as described in the previous section, another newly explored trend is to coordinate the operation of UFLS with other elements of the electrical network, such as; BESS, EVs, FACTS etc, with the aim of enhancing the performance of these schemes, reducing the amount of load shedding and improving the dynamics of the modern electrical networks. Even in some scenarios, it has been possible to avoid UFLS activation.

Finally, in Fig 15, the operating characteristics of the UVLS and UFLS collected in tables 4 and 5 were counted, so that it was possible to observe how many schemes made their operating characteristics dynamic (the amount of load shedding, the location of load shedding and their respective thresholds). It is possible to appreciate that, for the amount of power to shed and the location, both the UVLS and the UFLS tend to make dynamic (adaptive) these characteristics in greater percentage. In contrast, the thresholds are functional characteristics that in smaller percentage are dynamic, which makes it an area of research opportunity in which can deepen.

VI. FUTURE WORK

Throughout the review, it was shown that the amount of load shedding and the location are the operating parameters studied extensively to be adaptable, from a wide variety of methods. However, the power grids have numerous restrictions associated with the operational, economic and social aspects, which makes it difficult to give complete freedom to RAS schemes to determine online the amount of load shedding and its location, the decision making that is allowed to RAS schemes is bounded and directly associated with their design studies. There are many reasons why the RAS schemes are not given full decision control, and many have to do with economic and reliability aspects. The decision to shed load or not shed load is very important, and should not be taken simplicity, as this can cause important economic issues for consumers. Consequently, a limitation to implementing fully adaptable RAS schemes is the concern for the reliability of their correct operation.

With the above mentioned, the transition to fully adaptable RAS schemes for real modern power grids should be meticulous and smooth, to give flexibility for some functions of the RAS schemes that have not even been explored so much or have not been given the necessary relevance. For example, adaptability to the voltage and frequency thresholds of the UVLS and UFLS is a safe and reliable beginning for adaptive schemes, as it involves accelerate or delaying the load shedding, depending on the conditions of the power grid and the magnitude of the event, considering the same amount of load to shed and its location, but modifying the instant of the control action. On the other hand, time delay is also a safe and reliable area of opportunity, with which can give adaptability to these protection schemes. In conclusion, thresholds and time delay are opportunity areas that have not been extensively addressed, and that have a high value if want to make a smooth transition to adaptive RAS schemes, consequently, it is considered an important research area that should be taken up within the design of adaptive RAS for modern electrical networks.

VII. CONCLUSION

Remedial Action Schemes are of great importance during the correct operation of an electrical network, as they are the last line of defense during unacceptable operating conditions caused by critical contingencies. Therefore, the design of these protection schemes has become a topic of great interest for power system operators thanks to the great potential they have shown to maintain the stability of the power grid in recent years. Moreover, the operation and control of the power grid has become more complex due to the large dimensions and integrating variable renewable generation in the modern electricity networks, causing that the conventional design philosophies of the typical RAS become unreliable. This review has focused solely on the design of UVLS and UFLS, showing what has been achieved in these protection schemes from their inception to the present. Originally the first schemes collected in this review used conventional techniques and were very deterministic, as the protections were designed on a case study in specific (the most overloaded), from this, the operating parameters for the load shedding were obtained (amount, location, thresholds) being static parameters that were not modified during the operation of the system, they were kept constant until the RAS was updated. This type of design philosophy was very strong for systems dominated by synchronous machines, as the time constant of the power grid was greater, in addition to the inertia of the system being large enough to withstand large-scale transients. Furthermore, the trend of modern electrical networks is the incorporation of large-scale renewable energy sources based in power electronics devices, where their impact is directly reflected in the inertia of the system. As shown throughout the article, the tendency is to give flexibility to the operating parameters of the UVLS and the UFLS, allowing them to consider the magnitude of the event and perform optimal load shedding. That is, shed adequate amounts of power, in the best locations and only when necessary through various modeling approaches and various optimization techniques. In this work, it was shown that the tendency to adaptive schemes is very marked, and it is clear to note that the amount of power to shed is the parameter that is widely studied, for the UVLS and UFLS schemes. Similarly, the location of the load shedding has also been studied from various approaches. It was also possible to observe that thresholds are a parameter that has not been given the necessary follow-up and, therefore, it would be important to consider it as an important research gap, because they can be used as a smooth and reliable transition to adaptive RAS schemes. Similarly, time delay for the load shedding is also an area of opportunity. Although load shedding is intended to be made as fast as possible, there is always a time delay caused by delays in communications, and in the execution times of protection algorithms, which are factors that directly impact the performance of these schemes. There are scenarios where the system and its continuous controls can overcome the problems that contingencies lead and, therefore, it is important to give a time delay to wait for this type of system response and avoid severe control actions such as a load shedding. On the other hand, from this revision, it was possible to classify the adaptable load shedding schemes according to the operating parameters that are being given flexibility in the scheme. It also clearly indicates the methods that have been used to make each operating parameter more flexible, so that common methods can be identified, for example, UFLS that adapt the amount of load shedding have in common that are based on the swing equation. Finally, this review shows an overview of the evolution of the design and operation of the adaptive load shedding schemes, obtaining an overview of the areas that have been addressed, methods used and areas that could still be explored further.

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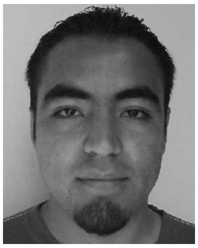

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