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A NEW ADAPTIVE UNDER-FREQUENCY LOAD SHEDDING SCHEME FOR MULTI-AREA POWER SYSTEM

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Abstract

Under-frequency load shedding (UFLS) is a critical function of frequency control in a power system. This paper presents a new adaptive UFLS scheme in multi-area power systems, where the frequency thresholds and load to be shed are adapted to the severity of the disturbance in each control area. In this approach, the frequency thresholds are adapted by a fuzzy logic controller using the rate of change of frequency (RoCoF), the tie-line transit, the amount of load to be shed is estimated according to the available tie-line capacity and spinning reserve. The objective is to avoid the collapse of the power system following a major disturbance, by shedding a sufficient amount of load while avoiding the tripping of the tie-lines. Numerical simulations are performed on the multi-area Algerian transmission power system and used to demonstrate the effectiveness of the proposed approach compared to the conventional and adaptive approaches. The results show the effectiveness of the proposed approach, with a better quality of frequency control by adapting the amount of load shedding to the severity of the disturbance, and ensuring a better stability of the system by avoiding tripping of the tie-lines.

Key Words

Under frequency load shedding, fuzzy logic, adaptive UFLS scheme, multi-agent approach

1. Introduction

Frequency emergency control is a critical function of the power system defence plan. As a result, load shedding represents a very important technical challenge, which has been the subject of several researches. For this purpose, various load-shedding strategies (schemes) have been developed to restore the balance between generation and consumption [1], [2].

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Conventional UFLS is the most used scheme, designed to disconnect a fixed amount of load in a predetermined frequency threshold. The main disadvantage of conventional UFLS is that the load shedding does not take the disturbance severity into consideration, which causes over- or under-shedding in the system. Shedding loads in non-perturbed areas and may cause Tie-line overload tripping which can lead to the islanding of some areas.

In order to overcome the drawbacks of the conventional UFLS, researchers have developed several methods including other control parameters such as the rate of change of frequency (RoCoF) [3], giving rise to the semi-adaptive UFLS schemes, where the thresholds are calculated according to the severity of the event [5], [4]. The authors in [6] and [7], according to the comparison between conventional and adaptive UFLS schemes, demonstrated the need for modern load shedding and introduced the new technology of the adaptive load-shedding scheme [8]. The authors in [9] and [10] have developed a new approach applied to an adaptive load-shedding scheme using PMUs. All generator frequencies measured by the PMUs are sent to the CPU where a disturbance magnitude will be calculated. These measured frequencies will also be used to determine the amount of load to be shed as well as the number of shedding steps.

However, several computational intelligent methods have been used to solve the load-shedding problem. These techniques can easily solve non-linear and multi-objective power system problems that cannot be solved by conventional methods with the desired speed and accuracy [11]. New adaptive load shedding based on ANN was proposed by [12], taking into account the total active power imbalance. The authors in [13] used the GA scheme as an offline method to obtain the appropriate amount of load shedding, on the other hand, the ANN-based scheme is presented as an online method. The authors in [14] used the genetic algorithm to support the training of backpropagation neural networks (BPNNs) to lead the minimum load shedding. A review of recent adaptive load-shedding schemes focusing on distribution system application based on the intelligent method is summarized in [15]. Several researchers have applied fuzzy logic for load-shedding problem because it

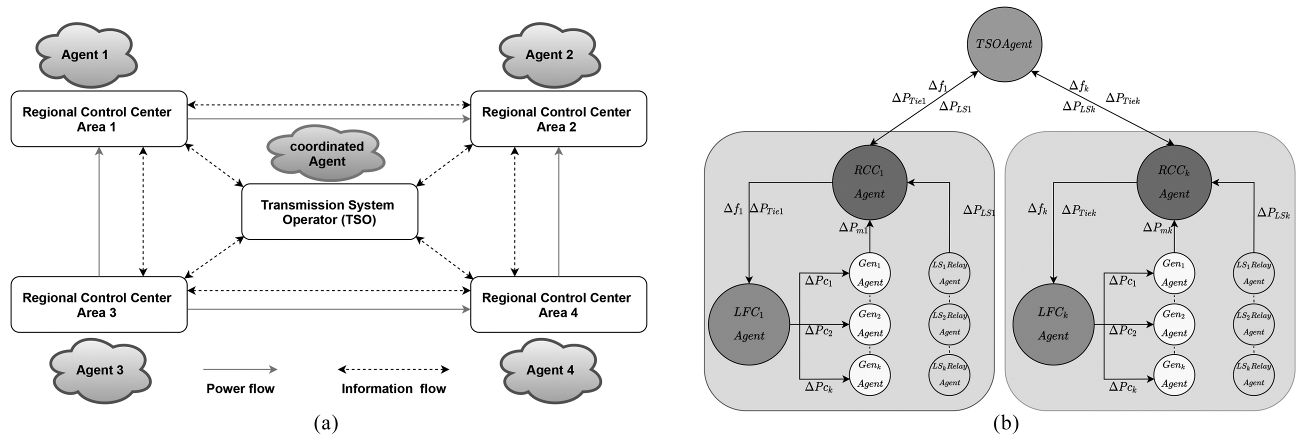


Figure 1. MAS representation of frequency control in multi-area power system: (a) frequency coordinated control; (b) frequency control in multi-area power system.

is very effective in solving control and decision-making problems [16].

According to the authors in [17], besides the frequency variation, the frequency derivative is also used to perform the load-shedding operation and to ensure that the tie-line does not disconnect in order to avoid cascading events, however, according to scenario 2, the loss of the two generators, respectively, at 1.3 and 1.5 s caused the trip of the second tie line, resulting in a higher load-shedding quantity. According to the authors in [18], the gaps of the literature in implementing the load-shedding schemes are that most researchers focused, either in the quantity, see [19] to be shed and the economic benefits gained [20], or in the frequency thresholds, see [21]. The transit in the tie lines is an important information to identify the location and severity of the event in the schemes proposed in the literature, this information has not been used to adapt the load shedding in the fault areas.

1.1 Contributions of the Paper

The aim of the paper is to enhance the UFLS in a multi-area power system by solving the over and the under-shedding problems associated with conventional UFLS schemes, based on a better estimation of the load to be shed based on the estimation of power deficit, tie-line transit and spinning reserve. While preventing the tripping of the tie-lines by managing the transit and managing the spinning reserve.

The main contribution of this paper is to propose an adaptive UFLS scheme that overcomes some of the drawbacks of the conventional schemes used in a multi-area power system. In this approach, each control area is equipped with a UFLS scheme adapting its frequency thresholds and load to be shed to the severity of the disturbance using two main steps. Firstly, the UFLS frequency thresholds are adapted through a fuzzy logic controller (FLC) using the RoCoF and tie-lines transit as indications of the severity of the disturbance. Secondly, the amount of load to be shed is estimated based on the power deficit, tie-lines transit, and spinning reserve in order to ensure that enough power is shed to avoid the disconnection of the tie-lines, and sufficient reserve is available to allow the LFC control to restore the frequency to its nominal value.

2. Under-frequency Load Shedding

2.1 Frequency Control in a Multi-area Power System

In order to improve the performance of frequency control in a multi-area power system, a multi-agent system is proposed and shown in Fig. 1. In this frequency control framework, each regional control centre (RCC) is represented by an agent, and the transmission system operator (TSO) represents a coordinating agent between the various RCCs.

Figure 1(b) shows the information exchanged between the different agents responsible for the frequency control and regulation in a multi-area power system. The TSO is a coordination agent and communicates with all RCC agents in the system. While the RCC agents are responsible for the frequency control in their areas controlling:

1. Gen agent: Generator's agent executes the primary control,
2. Load frequency control (LFC) agent: The LFC agent as the secondary control,
3. RCC agent can request a Tertiary control by a re-dispatching to restore power reserve.
4. Under-frequency load shedding (ULFS) agent: ULFS agent executes the emergency control, is activated in case of major disturbance, $0.2 - 0.3(s)$ from the event, to avoid a frequency collapse of the system.

2.2 Proposed Under Frequency Load Shedding

In the proposed approach, each control area is equipped with its own centralised ULFS system. The system monitors the frequency of the zone, its RoCoF, the power flow in the tie-lines and the available spinning reserve. Following the detection of a disturbance, measured in terms of frequency deviation and magnitude and direction of power transit in the tie-lines, the adaptive ULFS estimates

	Ptie						
	Exports				Imports		
ROCOF	HE	ME	LE	N	LI	MI	HI
LL	0	0	0	0	1	1	2
L	0	0	0	1	1	2	3
M	0	0	1	1	2	3	4
H	0	1	1	2	3	4	5
HH	1	1	2	3	4	5	5

Figure 2. FLC Rule base table.

the frequency threshold and the amount of load to be shed so as to ensure the stability of the system, while limiting the transit in the tie-lines to avoid their tripping.

2.2.1 Frequency Threshold Adaptation

The basic idea behind this fuzzy controller is to adapt the frequency threshold to the severity of the disturbance: Disturbances with high power import and high RoCoF values are the most severe. Disturbances with less power imports and low RoCoF value are less severe and do not require a load shedding if the area is exporting power instead of importing it. If the controlled area exports power meaning that the disturbance is not in the area. So, the contribution of this area to the load-shedding will depend essentially on the value of the RoCoF: A low RoCoF value does not require shedding. On the other hand, if the area imports power, meaning that the disturbance is in the area, combined with high RoCoF value, a high shedding is required at a higher frequency threshold, to prevent system collapse.

The RoCoF at area i is calculated by [21]:

$$\mathrm{ROCO}F_i \triangleq \frac{\Delta f_i}{\Delta t} \approx \frac{f_i(t) - f_i(t - N * \Delta t)}{N * \Delta t} \tag{1}$$

With f_i is the bus frequency at i, Δt is the calculation step.

The total power transited to the area i thought its tie-lines can be calculated using [22] :

$$P_{\mathrm{Ti}} = \sum_{j=1}^{N} K_{\mathrm{ij}} \Delta f_i = \sum_{j=1}^{N} P_{\mathrm{Tij}} \tag{2}$$

The linguistic variables for the inputs and output are given as follows:

1. **ROCOF ($\mathbf{[-1.5, 0]}$):** Very low (LL), low (L), medium (M), high (H), very high (HH);
2. $\mathbf{\Delta} P_{Ti}$**:** Export: High export HE, Medium Export ME, Low Export LE; No exports and no imports N; Import: High import HI, Medium Import MI, Low Import LI;
3. **UFLS frequency threshold**: No load shedding F_{th0}, $F_{\mathrm{th1}} = 0.3(\mathrm{Hz})$, $F_{\mathrm{th2}} = 0.25(\mathrm{Hz})$, $F_{\mathrm{th3}} = 0.20(\mathrm{Hz})$, $F_{\mathrm{th4}} = 0.15(\mathrm{Hz})$, $F_{\mathrm{th5}} = 0.1(\mathrm{Hz})$.

The rule base table is presented in Fig. 2.

It should be noted that the higher the frequency threshold, the faster the load shedding had to take place. The amount of load to be shed is estimated at this threshold using the methodology developed in the next section.

2.2.2 Load Shedding Quantity Estimation

The power deficit in an area of the power system can be estimated using the swing [22]

$$\frac{2H_i}{f_n}\frac{df_i}{dt} = P_{mi} - P_{ei} = \Delta P_i \tag{3}$$

Using (3), at each area i, the power deficit ΔP_i at the frequency threshold f_{th} can be estimated using the measured RoCoF at t_{sh} the time when the shedding action is initiated, as follows:

$$\Delta P_i = \frac{2H_i}{f_n}\frac{\Delta f}{\Delta t}|_{t=t_{sh}} = \frac{2H_i}{f_n} ROCOF_i \tag{4}$$

The quantity of load to be shed at area i can be estimated using the power deficit ΔP_i (4), tie-lines transit ΔP_{Ti} (2), and the available spinning reserve:

$$P_{\mathrm{shed}} = \begin{cases} \Delta P - \frac{2}{3}P_{\mathrm{spin}}, & \frac{2}{3}P_{\mathrm{spin}} < P_{\mathrm{Tie}} \\ \Delta P - P_{\mathrm{Tie}}, & \text{otherwise} \end{cases} \tag{5}$$

The flowchart of the proposed UFLS scheme is presented in Fig. 3.

3. Simulation and Results

To test the effectiveness of the proposed approach, the proposed adaptive UTLS scheme is tested on the Algerian power system RIN (Northern Interconnected Grid) [23]. In this study, the Algerian power system is divided into four frequency control areas, with interconnection to the neighbouring networks Morocco (M) and Tunisia (T) (See Fig. 4).

The simulations are performed in GNU-Octave. The Algerian defence plan and the conventional load shedding scheme used in the simulations and the areas data are presented in Tables 1 and 2.

3.1 Case Study

In order to test the efficiency of the proposed method, a comparative study with the conventional schemes and the adaptive UFLS proposed in [21] is performed considering three scenarios which are the worst-case scenarios leading to the activation of the load-shedding protection. In all the scenarios, the system is initially at equilibrium and the transit in the tie lines is zero, primary frequency regulation, LFC (secondary regulation), along with generators and tie-lines power limits are considered.

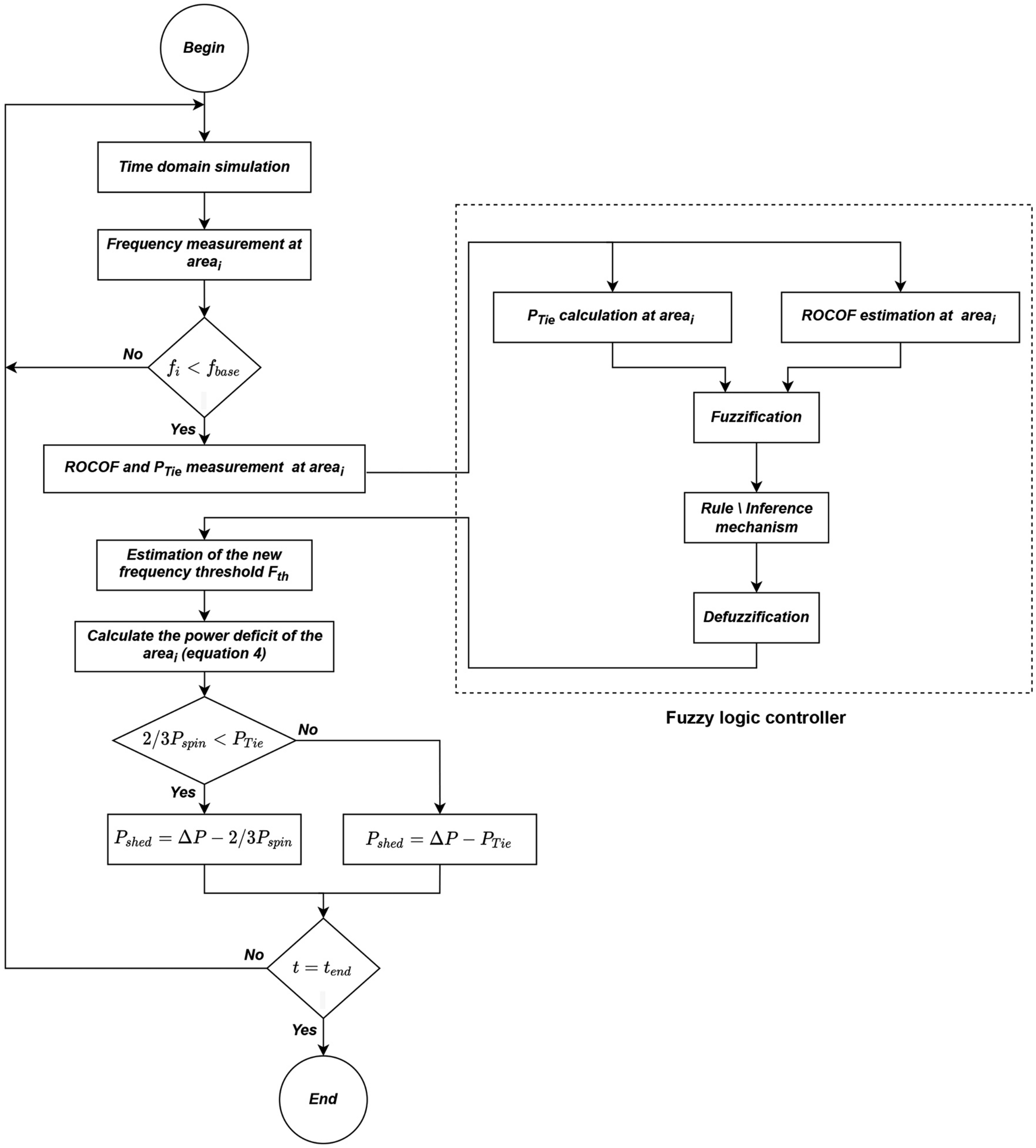


Figure 3. Fuzzy adaptive UFLS flowchart.

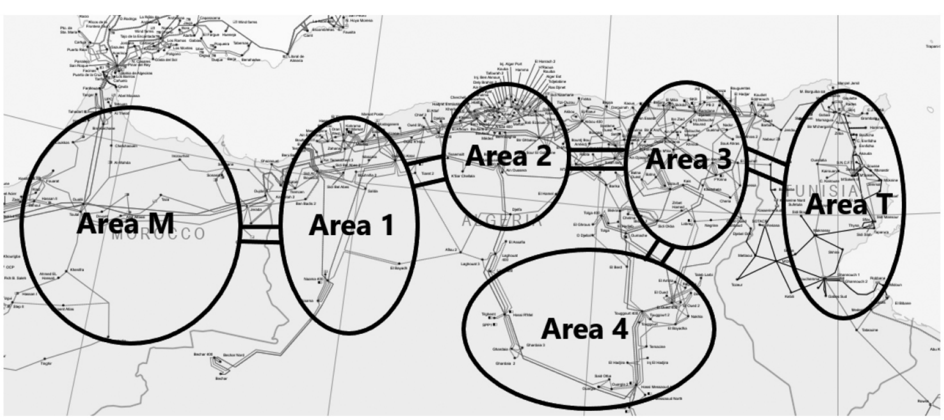


Figure 4. Algerian power system areas representation.

Table 1
System Data

Area	Generation [pu]	Rate [pu]	Spinning Reserve [pu]	Inertia H[s]	R[Hz/pu]	D[pu/Hz]	Tie-lines
Z1	15.48	17.55	2.07	4.875	0.67	1.0	$P_{12}^{\max} = 12$ pu, $T_{12} = 1.0$ [pu/Hz]
Z2	18.30	24.60	6.30	9.750	0.67	1.0	–
Z3	18.70	22.31	3.61	3.250	0.67	1.0	$P_{23}^{\max} = 12$ pu, $T_{23} = 1.0$ [pu/Hz]
Z4	5.76	7.86	2.10	4.875	0.80	1.0	$P_{34}^{\max} = 12$ pu, $T_{34} = 1.0$ [pu/Hz]
ZM	–	3.00	3.00	1.625	2.00	1.0	$P_{1M}^{\max} = 3.00$ pu, $T_{1M} = 0.5$ [pu/Hz]
ZT	–	2.75	2.75	1.625	2.00	1.0	$P_{3T}^{\max} = 2.75$ pu, $T_{3T} = 0.5$ [pu/Hz]

Table 2
Existing Conventional UFLS Scheme

Stages	Threshold (Hz)	Temporisation (s)	Amount of load to be shed (%)
Threshold 1	49.3	0.2	10
Threshold 2	49	0.2	10
Threshold 3	49	10	10
Threshold 4	48.5	0.2	10

1. **Scenario 1:** Loss of the largest power plant of two 400 MW generators in area 2 at $t = 2$ s.
2. **Scenario 2:** Loss of the largest power plant of two 400 MW generators in area 1 at $t = 2$ s.
3. **Scenario 3:** Loss of two power plants: A two-generator power plant 2×400 MW in area 1 at $t = 2$ s, and a two-generator power plant 2×400 MW in area 3 at $t = 4$ s.

3.1.1 Scenario 1

The first scenario consists of the loss of a total generation power of 800 MW in area 2, at $t = 2$ s. Fig. 5(a)–(c) depicts the evolution of frequency, tie-lines power transit, and spinning reserve after the event, obtained with the three schemes. Table 3 gives the amount of the shed load and frequency 60 s after the event. With the conventional load shedding scheme, two load-shedding thresholds are activated: 182 MW for the first threshold at 49.3 Hz and 164 MW for the second threshold at 49 Hz, for a total load shed quantity of 346 MW. The steady-state frequency is 49.99 Hz.

The load-shedding scheme proposed in [12] adapts the amount of load to be shed according to the RoCoF and sheds a load of 282 MW with a single shedding threshold at 49.3 Hz, the frequency is restored to 49.98 Hz. The scheme proposed in this paper sheds 175 MW at a single load shedding threshold (49.45 Hz), less load than the conventional and [21] schemes. This difference is due to the fact that the proposed scheme estimates the power deficit better, by taking into consideration the spinning reserve, using (5).

3.1.2 Scenario 2

The second scenario consists of the loss of the largest power plant in area 1 with a total generation power of 800 MW, Fig. 6(a)–(c) depicts the evolution of frequency, tie-lines power transit, and spinning reserve after the event with the three schemes. According to the obtained results, the conventional scheme, after shedding a total quantity of 418 MW, does not succeed in rectifying the frequency to an acceptable value 49.74 Hz, see Fig. 11, because in order to compensate the power deficit, area 1 has imported more than 300 MW from area M, which has excited the watt-metric protection, thus causing the tie-line tripping. On the other hand, both the UFLS scheme proposed in [23] and the proposed scheme succeed stabilising the frequency, respectively, at 49.98 Hz and 49.93 Hz, see Table 3. The proposed UFLS scheme with 614 MW in a single load shedding threshold shed a lower quantity of load than the one proposed in [23], with a load of 723 MW, in two thresholds, at 49.3 Hz (365 MW) and at 49 Hz (357 MW). This amount of load shed allows the system to remain connected with area M, by reducing the power transit in its tie lines, see Fig. 6(b).

3.1.3 Scenario 3

The third scenario consists of a cascade of two successive events, the largest power plant in area 1 2×400 MW at $t = 2$ s, and the largest power plant in area 3 2×400 MW at $t = 4$ s. Figure 7(a)–(c) depicts the evolution of frequency, tie-lines power transit, and spinning reserve after the event with the three schemes. Table 3 gives the amount of the shed load and frequency 60 s after the event.

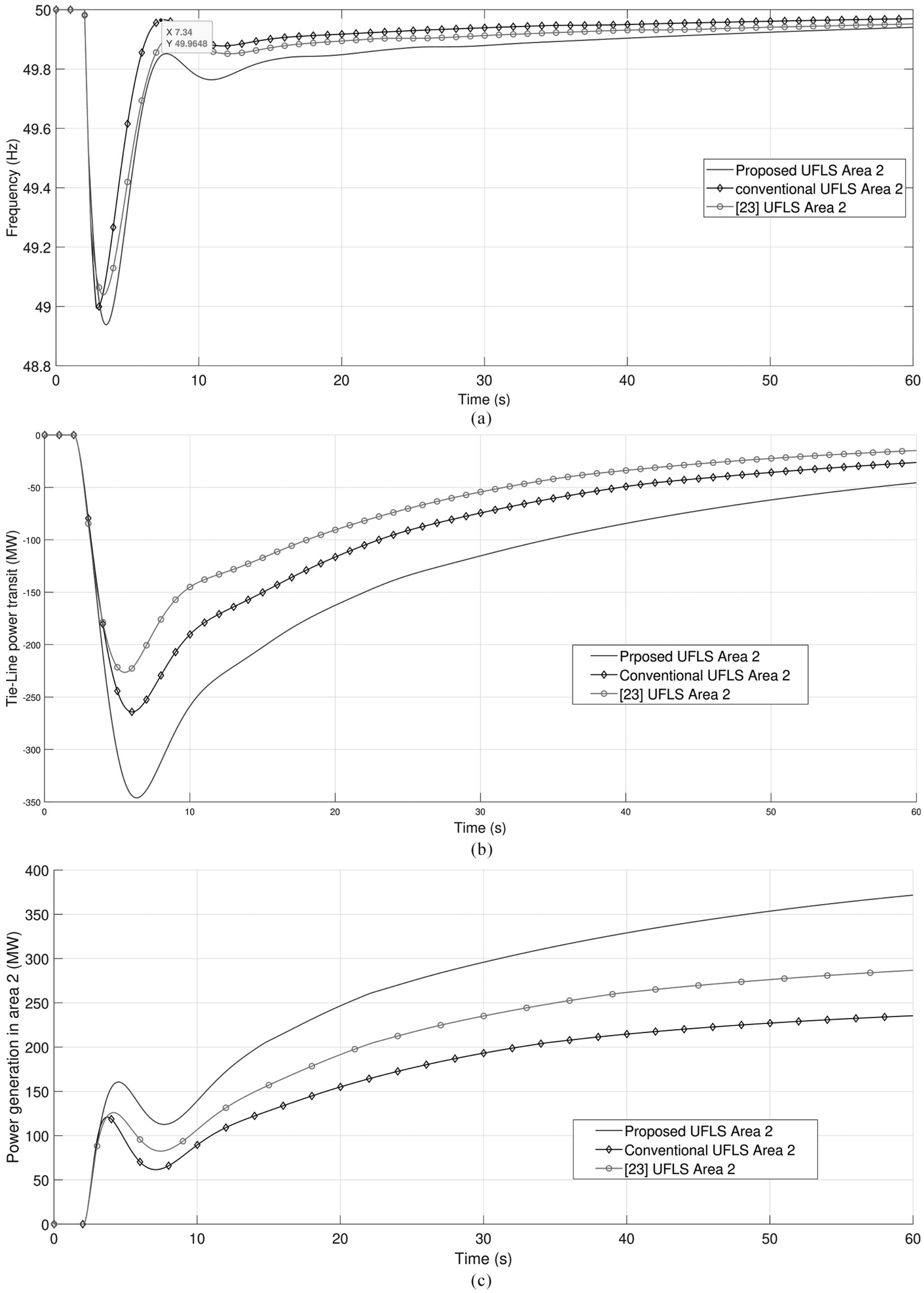


Figure 5. Frequency, tie-lines power transit, and spinning reserve in scenario 1: (a) frequency; (b) tie-lines power transit; (c) generated power in area 2.

According to the results obtained in Fig. 7(a) and Table 3, it is clear that in the case of the conventional scheme, the frequency (49.45) Hz does not return to the permissible limits value, despite the tripping of the three thresholds in area 1 and area 3, which caused the loss of the interconnection lines with areas T and M, leading to a drop in frequency in areas 2 and 4, with a total load shedding of 1015 MW. As for scenario 2 both the UFLS scheme proposed in [23] and the proposed scheme in this work succeed stabilising the frequency, respectively, at 49.96 Hz and 49.89 Hz, see Table 3. But, the proposed UFLS scheme with 1124 MW shed an amount less than 20% compared

Table 3
A Comparison between the Performance of the Proposed, Conventional, and the UFLS in [23] Schemes

		Load Shedding									
		Area 1		Area 2		Area 3		Area 4			
Scenario	Method	Fth (Hz)	PLS (Mw)	Fth (Hz)	PLS (Mw)	Fth (Hz)	PLS (Mw)	Fth (Hz)	PLS (Mw)	PLS Total (Mw)	Steady-state Frequency (Hz)
1	Proposed	–	–	49.45	175	–	–	–	–	175	49.98
	Conventional	–	–	49.3 49	182 164	–	–	–	–	346	49.99
	[23]	–	–	49.3	282	–	–	–	–	282	49.985
2	Proposed	49.57	614	–	–	–	–	–	–	614	49.93
	Conventional	49.3	154								
		49	139	–	–	–	–	–	–	418	49.74
		48.5	125								
	[23]	49.3 49	365 357	–	–	–	–	–	–	723	49.98
3	Proposed	49.57	614	–	–	49.55	510	–	–	1124	49.89
	Conventionnel	49.3 49 48.5	154 139 125	49.3	182 182	49.3 49	176 158 158	49.3	57	1015	49.46
	[23]	49.3 49	365 357	–	–	49.3 49	427 289	–	–	1441	49.96

to the proposed scheme in [23] 1441 MW. This amount of shedded load allows the system to remain connected with area M and T, by reducing the power transit in its tie lines, see Fig. 12.

3.1.4 Discussion

The results presented in Table 3 and the scenario figures illustrate the performance of the proposed UFLS scheme. The main advantages of the proposed methodology compared to the conventional scheme are:

1. The frequency threshold is adapted, using an FLC, at each area to the severity of the disturbance, measured in terms of RoCoF and active power transit in the tie-lines, meaning that the load-shedding process is initiated in the areas subject to the disturbance. This behaviour is illustrated by the results of scenarios 1, 2, and 3.
2. The amount of load to be shed is estimated based on the spinning reserve and tie-lines transit, which is more accurate than the fixed thresholds used in conventional UFLS. In scenario 3, the proposed UFLS shed enough load to avoid the disconnection of the tie-lines M and T by watt-metric protection, hence, ensuring a better security and frequency stability for the system.

Compared to the adaptive UFLS proposed in [21], the proposed methodology has a more accurate estimation of power deficit, by considering spinning and transit reserve. Scenarios 1, 2, and 3 show that the proposed approach has a similar performance to [21], with less power to be shed.

4. Conclusion

In this paper, a new approach to UFLS was proposed for multi-area transmission power system. In this approach, the frequency thresholds and amount of load to be shed are estimated based on the severity of the disturbance, measured in terms of RoCoF, tie-lines transit, and the available spinning reserve.

In the proposed approach, an FLC is developed in order to estimate the frequency threshold, this estimation is based on the RoCoF and tie-lines transit in the control area. Meaning that the area affected by the fault triggers the load-shedding procedure more rapidly, to avoid damage to non-affected areas. The amount of load to be shed, in each area, is calculated based on the frequency deviation, spinning reserve, and tie-lines available capacity and the transit at the time of the disturbance. This procedure allows a sufficient amount of load to be shed to avoid the degradation of the frequency, while preserving the tie lines to avoid the islanding of one or more areas, thus ensuring a better stability of the system.

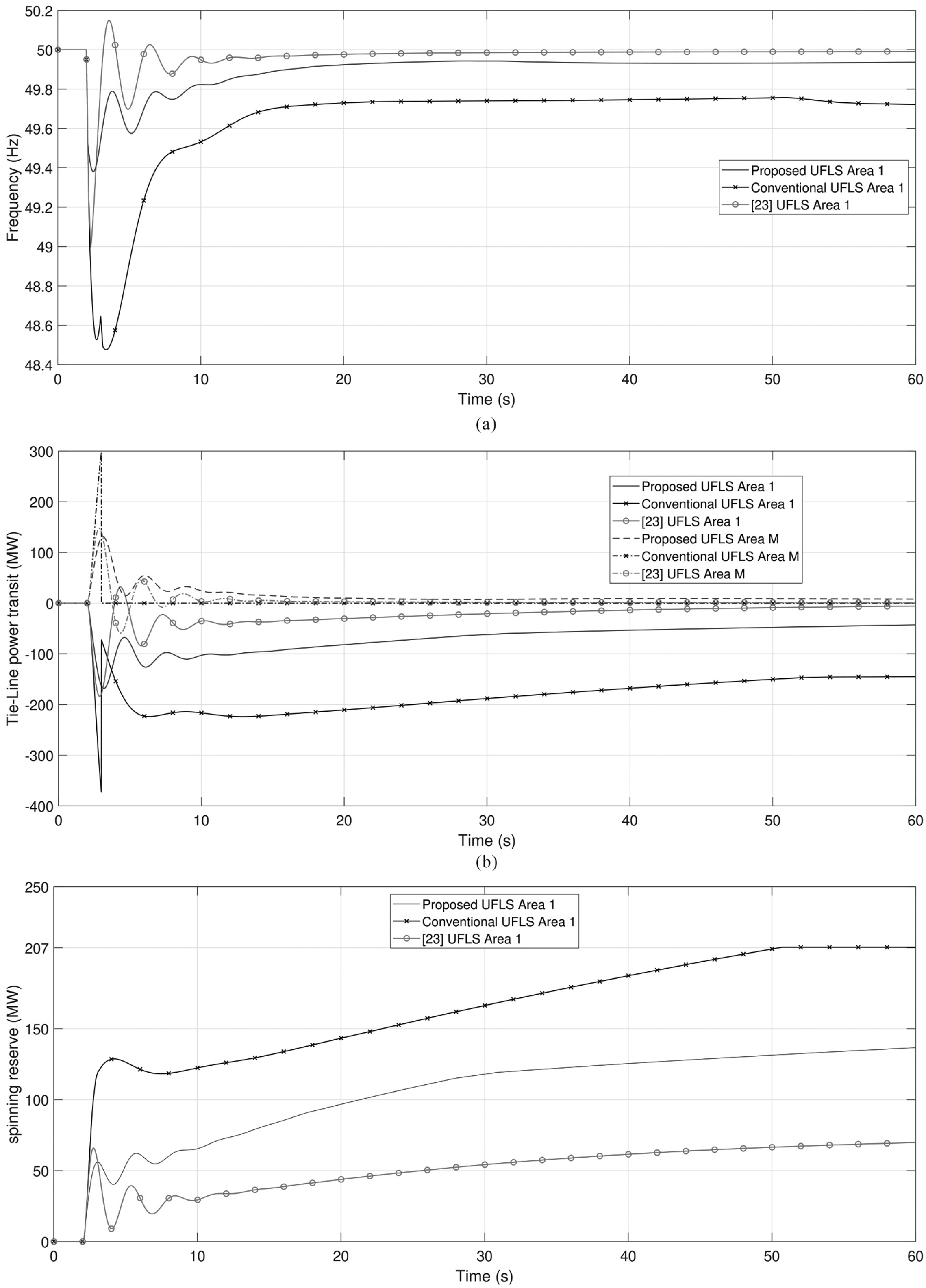
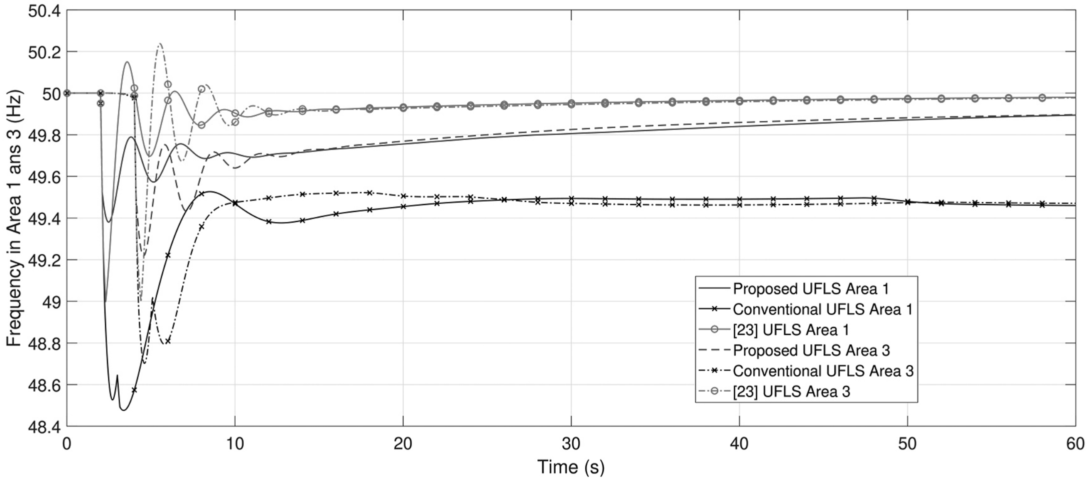
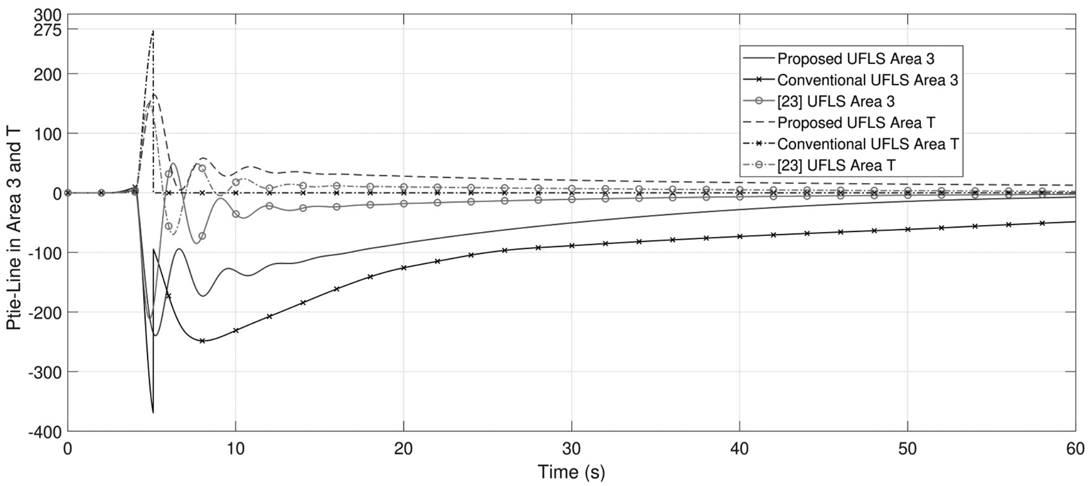


Figure 6. Frequency, tie-lines power transit, and spinning reserve in scenario 2: (a) frequency; (b) tie-lines power transit; (c) generated power in area 1.

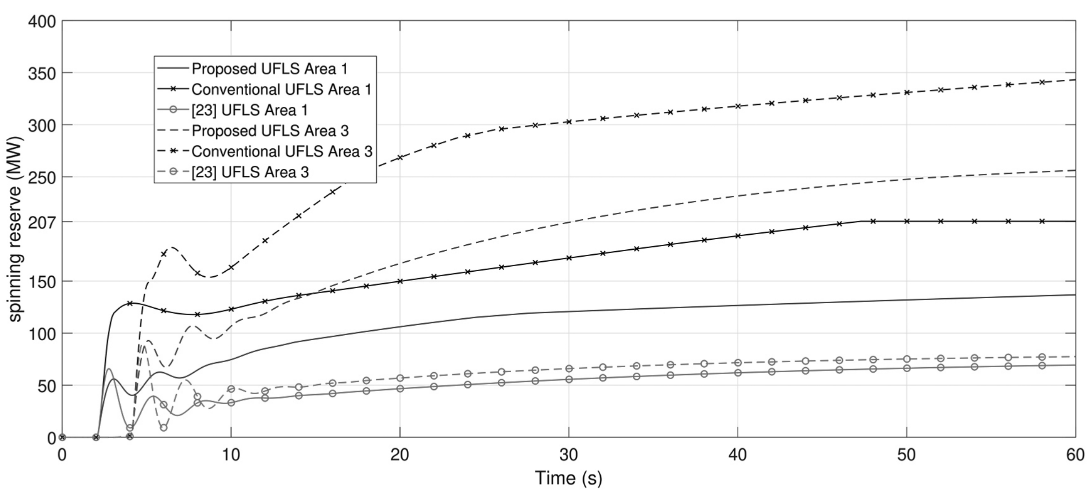
In order to assess the efficiency of the proposed approach, three scenarios were tested in the Algerian multi-area interconnected power system, the results were compared to other UFLS schemes. The results show that the proposed methodology gives better results in terms of the quantity of load to be shed, tie-line transit, and spinning reserve usage. By shedding sufficient quantities and preserving interconnection lines, the proposed approach maintains the system frequency within its operational limits, hence ensuring a better stability by frequency regulation.



(a)



(b)



(c)

Figure 7. Frequency, tie-lines power transit and spinning reserve in scenario 3: (a) frequency; (b) tie-lines power transit; (c) generated power at area 1 & 3.

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