Probabilistic Under Frequency Load Shedding Considering RoCoF Relays of Distributed Generators

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***Abstract*—The activation of Under Frequency Load Shedding (UFLS) is the last automated action against the severe frequency drops in order to re-balance the system. In this paper, the setting parameters of a multistage load shedding plan are obtained and optimized using a discretized model of dynamic system frequency response. The uncertainties of system parameters including inertia time constant, load damping and generation deficiency are taken into account. The proposed UFLS model is formulated as a mixed integer linear programming optimization problem to minimize the expected amount of load shedding. The activation of Rate-of-Change-of-Frequency (RoCoF) relays as the anti-islanding protection of Distributed Generators (DGs) are considered. The MCS method is utilized for modeling the uncertainties of system parameters. The results of probabilistic UFLS are then utilized to design four different UFLS strategies. The proposed dynamic UFLS plans are simulated over the IEEE 39-bus and the large scale practical Iranian national grid.**

***Index Terms*—Under frequency load shedding, inertia time constant, load damping, RoCoF, uncertainty.**

NOMENCLATURE

ΔP_s^{sh}	Amount of load shedding at stage s.
$V_{s,n}$	Binary variable for frequency set-point at stage s at time step n.
$TS_{s,n}$	Binary variable for timer at stage s at time step n.
ΔP^{gov}	Change of generation by governor action.
d	Deference operator.
n	Discrete time index.
R	Equivalent governor droop of entire system.
f_s^{sh}	Frequency set-point at stage s.
f_n	Frequency at center of inertia reference at time step n.
Δf_n	Frequency deviation at n^{th} time sample.
R_i	Governor droop of i^{th} machine.
ΔP_ρ^c	Generation deficiency at ρ^{th} scenario.
ΔP^c	Generation deficiency.
s	Index for load shedding stage.
H_i	Inertia time constant of i^{th} machine.
H	Inertia time constant of entire system.
D	Load damping.
Δf_{max}^{ss}	Maximum allowable steady state deviation of frequency.
ΔP_μ^c	Mean value of generation deficiency.
H_μ	Mean value of H.
f_{min}	Minimum allowable frequency(Nadir frequency).
N_g	Number of generators.
N_l	Number of load points.
N_r	Number of cycles in RoCoF window.
N_ρ	Number of input samples or scenarios.
f_0	Nominal frequency.
π_i	Probability of scenario i.
M	Parameter referring to the total generation at base scenario.
Δf^{ss}	Steady state deviation of frequency.
t	Time.
ΔP^{sh}	Total amount of load shedding.
Δt	Time step of discretization.
Δt_r	Time step for RoCoF calculation($20ms$ at $50Hz$).
T	Time constant of governor.
Δt_s^{sh}	Time delay before load shedding.
OF	Variable for representing the objective function.
H_ρ	Value of H at ρ^{th} scenario.

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I. INTRODUCTION

A. Aims and backgrounds

Frequency stability is the ability of a power system to maintain steady frequency following a severe contingency in generation and load balance. Without any automatic load shedding plan, the frequency instability may cause a partial or complete blackout of an interconnected power system [1], [2]. To stop the propagation of a cascading outage and to minimize the risk of damage to main equipment(turbines and generators), it is required to design and implement automatic UFLS plans. The activation of UFLS relays is the last automated action against severe frequency declines. Each UFLS plan consists of many UFLS relays installed at specific load points. The aim of under frequency load shedding study is to tune the UFLS relays, which are set conventionally, through dynamic off-line simulations.

The UFLS plans fall into one of three categories including a) multistage [3] b) adaptive [4], [5], and c) semi-adaptive schemes [6]. Multistage and semi-adaptive UFLS plans are implemented in transmission grid while the adaptive plans are widely used with small scale generators installed at distribution systems. The parameters of the adaptive UFLS plan are set only based on the rate-of-change-of-frequency. The RoCoF relays are widely used to detect the loss of main supply in distribution systems and to trip the small scale DGs. In multistage UFLS, a pre-determined amount of the load is curtailed when the system frequency falls below a threshold during a time delay. Therefore, for each stage of UFLS plan, three setting parameters including frequency threshold, amount of load to be shed, and time delay before load shedding are defined [3]. The required load shedding happens in a few subsequent stages until the normal frequency is restored. Several national or regional power systems around the world have implemented multistage UFLS plans [7]–[9].

To set the parameters of multistage UFLS plans it is required to carry out a large number of dynamic simulations under credible operational conditions [3]. As an alternative procedure, the system frequency response including the dynamics of governors, rotor swing, and load damping could be discretized in time and is then formulated as an optimization problem to achieve the minimum load shedding [3]. In multistage UFLS design instead of full-scale power system model the simplified system frequency response models are used [10], [11]. Center of inertia frequency is a useful definition of frequency under transient conditions. The center of inertia frequency approximately represents the system frequency under transient conditions [10]–[12].

However, new challenges are faced by multistage UFLS plans. Appearing new DGs and load types have brought about uncertainties in system parameters such as inertia time constant and load damping. To this end new computational tools are required to design UFLS plans considering such uncertainties. System parameters such as inertia time constant and load damping could be estimated using phasor measurement data under recorded specific events. The authors in [13] have utilized Kalman filter to estimate inertia time constant in real time using PMU data. In [14], authors have presented an identification method for power system load modeling. A probabilistic power flow is utilized in [15] for considering the uncertainty of active power imbalance under different configurations. The variation of load shedding at each stage (i.e. step size) is an important issue in UFLS design. As discussed in [16], the step size of load shedding is subject to uncertainty due to the variation of feeder loading, feeder outage and etc.

The main task of UFLS plan as a system wide protection scheme is to shed a pre-determined amount of the load when the system frequency crosses a threshold during a time delay. In addition of such uncertainties, the integration of small scale generating units or DGs causes new problems in protection and control schemes. The impacts of DG connection on distribution networks are discussed in [17]. The RoCoF relays of DG units are tuned to detect islanding conditions by measuring the rate-of-change-of-frequency. Therefore, the thresholds of these relays are set to detect islanding under small power exchange with upstream main network. However, the abnormal RoCoF values (caused by non-islanding conditions in upstream network) may cause the incorrect tripping of DG units and further deterioration of the frequency decline. Without considering such incorrect tripping the UFLS plan may lead to underestimated load shedding. In this paper, the setting parameters of a multistage UFLS plan are optimized considering all possible sources of load and generation changes(i.e. generation outage, governor action, load damping, and load shedding) including DG tripping due to abnormal and non-island conditions.

B. Contributions

The gap that this paper intends to fill is to consider the uncertainties of system parameters including the uncertainties of inertia time constant, load damping, and generation deficiency. Monte Carlo Simulation(MCS) method is utilized to handle the system uncertainties. The most commonly used anti-islanding protective devices for small scale synchronous generators are RoCoF relays. Under a sever generation deficiency in upstream transmission grid, the resulted frequency decline may cause the mal-operations of grid connected DGs. To this end, the multistage UFLS plan is modified to consider the anti-islanding protection of DGs. All the proposed UFLS models are solved using Genetic algorithm.

C. Paper organization

The rest of this paper is organized as follows. In section II, the RoCoF model and the discretized system frequency response are presented. The formulation of the proposed UFLS plans is described in Section III. The details of the utilized MCS method for modeling the uncertainties of system parameters are described in section IV. Section V, contains the results of the proposed probabilistic UFLS plan. Finally, the conclusions are provided in section VI.

II. System Frequency Response

To discretize the system frequency response, the set of differential equations of related dynamics are converted to a set of algebraic equations. As illustrated in Fig. 1, the system frequency response is developed with considering the dynamics of rotor swing, governor action, load damping and RoCoF relays. These algebraic equations are then formulated as the equality constraints of UFLS plan to minimize the total amount of load to be shed. The system frequency response is stabilized in three primary, secondary, and tertiary layers with different time responses. The primary response is provided by inertial, governor and load responses. The governor response is provided automatically by synchronous units without operator action. The secondary response is provided by synchronous units under Automatic Generation Control (AGC). The secondary response is slower than primary response ranging from tens of seconds (20 to 30 sec) to minutes. The tertiary response is activated within minutes after the event based on operator dispatch control. The system operator performs the tertiary response by deploying the spinning and non-spinning reserves to restore the steady state frequency to nominal value.

The primary response by governors is not activated for the frequency deviations within $\pm 0.5Hz$ from nominal value. It is the task of AGC and other types of generation reserve

to compensate the steady state errors. As a general rule it is advisable to rely on generator governor response (i.e. fast spinning reserve of the primary response) to restore the frequency under generation deficiencies [18], [19].
Technically, both load shedding with UFLS relaying and generator governor response act similarly and are automatic and can both be considered as dynamic reserve [19]. Regarding these issues, in this paper, the primary frequency response of governor is considered.

The complete system frequency response including the model of RoCoF relays of DGs is presented in next section.

A. Model of RoCoF relay

The principals of RoCoF relays for islanding detection is described in [20]. According to IEEE Std. 1547-2003 [21], the RoCoF relay must immediately disconnect the DG unit, in less than 2 seconds of the establishment of an island condition. In case of large penetration of synchronous DGs at distribution level, the incorrect tripping of these relays may deteriorate the frequency decline. The abnormal frequency declines under non-island conditions (i.e. caused by a sudden generation loss in upstream network) may cause the mal-operations of RoCoF relays. Therefore, it is required to design the UFLS plan of upstream network considering the settings of these relays. The average RoCoF over a measuring window is obtained as follows:

$$RoCoF \triangleq \frac{df}{dt} \approx \frac{1}{N_r}\sum_{i=1}^{N_r}(\frac{\Delta f_i}{\Delta t_r}) \tag{1}$$

where Δf_i denotes the frequency changes between two subsequent cycles.

The RoCoF relays of DGs detect the loss-of-main conditions based on the average rate-of-change-of-frequency. Due to the nonlinear dynamics of practical power systems, variations in frequency during active power imbalance do not follow any regular patterns.Therefore, the RoCoF relay is not permitted to make a decision about DG tripping based on instantaneous value of rate-of-change-of-frequency. By monitoring the average frequency change, a more secure decision can be made during contingencies. Indeed (1) is a low pass filter which approximate the RoCoF value by an average value. Practically the time interval or measuring window for calculating RoCoF value, may range from 5 cycles (i.e. 100^{ms} at 50 Hz) to 10 cycles (i.e. 200^{ms} at 50 Hz). In this paper, according to (1), the average frequency change over 5 subsequent cycles (i.e. $N_r = 5$) is defined as the RoCoF values. Therefore, the measuring window for RoCoF calculation is assumed to be equal to $N * \Delta t_r = 5 * 20^{ms}$ or 100^{ms}.

When there is a major generation deficiency in upstream network (i.e. due to generator outage) the system frequency response may cause abnormal RoCoF values. During these conditions the multistage UFLS relays are activated based on the predefined settings to restore the system frequency. However, under such conditions the RoCoF relays of DGs will incorrectly trip their related DGs due to detected abnormal RoCoF values without any loss of main in their protection zones. This unwanted tripping may deteriorate the frequency decline.

The focus of the proposed UFLS scheme is not to avoid the unwanted tripping of DG units by RoCoF relays. Also the aim of the proposed scheme is not to utilize the UFLS relays as backup protections of RoCoF relays. In this paper, the unwanted tripping of DGs is considered in UFLS design to reach the proper load shedding strategy. The authors in [22] have assessed different methodologies for DG protection related issues.

The aim of the proposed UFLS method in the present paper is to consider the effect of RoCoF relays of synchronous DG units during frequency decline caused by large generation outage in upstream network. In this study, it is assumed that the locations and sizes of DGs are known in priory.

B. System frequency response

The system frequency response is discretized considering the sources of load and generation changes. The swing equation of a synchronous generation unit is given as follows:

$$\frac{2H_i}{f_0}\frac{df_i\,(t)}{dt} = (P_{mi} - P_{ei}) \qquad i = 1, ..., N_g \tag{2}$$

UFLS design is highly challenging as, ideally, the system (rotor angle, frequency, and voltage) stability has to be preserved, while minimizing the load shed. Furthermore, other operational constraints have to be met in UFLS design (e.g. voltages, currents, and etc.). Regarding UFLS design, it is not practical to include all the dynamics of a power system into an optimization problem. Therefore in optimization based UFLS design the approximated system frequency response is used [10], [11]. According to [9], to compensate this approximation the obtained settings are then verified based on the full scale model of power system using a transient stability simulator.

For a multi-machine system the swing equation is represented on the Center of Inertia(COI) reference using the new base MVA, $S = \sum_{i=1}^{N_g} S_i$ as follows:

$$\frac{2H}{f_0}\frac{df\,(t)}{dt} = \sum_{i=1}^{N_g} P_{mi}\frac{S_i}{S} - \sum_{i=1}^{N_g} P_{ei}\frac{S_i}{S} \tag{3}$$

where

$$f \triangleq f_{COI} = \sum_{i=1}^{N_g}\frac{f_i H_i}{H} \tag{4}$$

$$H \triangleq H_{COI} = \sum_{i=1}^{N_g}\frac{H_i S_i}{S} \tag{5}$$

The frequency is the same throughout a synchronous grid in steady state condition. The center of inertia frequency depends only on the load-generation balance and is a useful definition of frequency under transient conditions. It approximately represents the system frequency under transient conditions [9]–[11]. As recommended in [9], to compensate this approximation the obtained settings using the UFLS plan are then finalized based on the full scale model of power system using a transient stability simulator. This will check the possible errors caused by the utilized approximations. The continuous form of swing

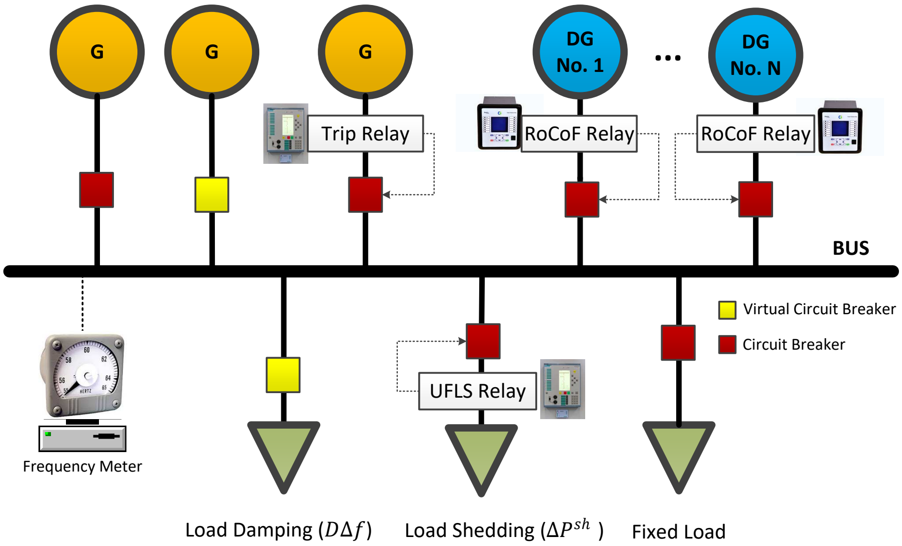

Figure 1. Sources of load and generation changes in system frequency response

equation given in (3) is linearized as follows:

$$\frac{d\Delta f\,(t)}{dt} = \frac{f_0}{2H}\Delta P^{im}(t) \tag{6}$$

where the power imbalance is determined as follows:

$$\begin{aligned}\Delta P^{im}(t) =& [\Delta P^{gov}\,(t) - \Delta P^{c} + \Delta P^{sh}\,(t) \\ & - D\Delta f\,(t) - \Delta P^{DG}\,(t)]\end{aligned} \tag{7}$$

The input power imbalance may be caused by generation and load changes. The generation change is caused by generation outage(ΔP^c), governor action(ΔP^{gov}), and DG tripping by RoCoF relays(ΔP^{DG}). The load changes is incurred by load shedding(ΔP^{sh}), and load damping($D\Delta f$). By assuming $X \triangleq [\Delta f, \Delta P^{sh}, \Delta P^{c}, \Delta P^{gov}, \Delta P^{DG}]$,the system frequency response is discretized over time with time step Δt as follows:

$$\Delta X(n\Delta t) = \Delta X_n \tag{8}$$

The discretized dynamics of governor action and RoCoF relay are described as follows: Governor action will increase the unit input power during the emergency conditions. The dynamic response of governor is described as follows:

$$\frac{d\Delta P^{gov}\,(t)}{dt} = \frac{1}{T}\left(-\Delta P^{gov}\,(t) - \frac{\Delta f\,(t)}{R}\right) \tag{9}$$

$$\frac{1}{R} = \sum_{i=1}^{N_g}\frac{S_i}{R_i S} \tag{10}$$

The discretized governor dynamic is given as follows:

$$\Delta P^{gov}_{n+1} = \Delta P^{gov}_{n} + \frac{\Delta t}{T}\left(-\frac{\Delta f_n}{R} - \Delta P^{gov}_{n}\right) \tag{11}$$

The activation of RoCoF relay will cause the outage of the related DG. To model the activation of RoCoF relay under abnormal RoCoF values a binary Switch, US, is defined as follows:

$$\frac{RoCoF_n - RoCoF^{set}}{f_0} \leq US_n \tag{12}$$

$$1 + \frac{RoCoF_n - RoCoF^{set}}{f_0} \geq US_n \tag{13}$$

Based on (12) and (13) two conditions are possible. If $RoCoF_n$ is lower than $RoCoF^{set}$ then the value of binary switch is $US_n = 0$ and the related DG remain connected. However, if $RoCoF_n$ is greater than $RoCoF^{set}$ then the value of binary switch is $US_n = 1$ and the related DG will be disconnected. The undesired activation of RoCoF relays is implemented in swing equation using this binary switch.

The modified Euler approach is utilized to solve the discretized system frequency response. In modified Euler method, the arithmetic average of the slopes at t_n and t_{n+1} time steps are considered as follows:

$$RHS(t) \triangleq \frac{f_0}{2H}\Delta P^{im}(t) \tag{14}$$

$$\Delta f_{n+1} = \Delta f_n + \int_{t_n}^{t_{n+1}} RHS(t_n, \Delta f_n) \tag{15}$$

where (14) and (15) are the Right Hand Side (RHS) and left hand side of the swing equation as given in (6). The integral is approximated by trapezoidal rule:

$$\begin{aligned}\Delta f_{n+1} \approx \Delta f_n + \frac{\Delta_t}{2}[& RHS(t_n, \Delta f_n) \\ & + RHS(t_{n+1}, \Delta f_{n+1})]\end{aligned} \tag{16}$$

where:

$$RHS(t_n, \Delta f_n) = \frac{1}{2H}(A - B) \tag{17}$$

$$A = (\Delta P^{gov}_n + TS_{s,n}\Delta P^{sh}_s - D\Delta f_n) \tag{18}$$

$$B = (\Delta P^c + US_n \Delta P^{DG}_n) \tag{19}$$

It should be noted that (16) is the discretized system frequency response based on the swing equation and (17) to (19) represent all sources of load and generation changes including input disturbance (i.e. generation outage), governor action, load damping, load shedding, and DG tripping. The discretized system frequency response given by (11) - (19) is considered as the constraint of proposed UFLS plan. The deterministic and probabilistic UFLS models are described in next sections.

III. Deterministic UFLS Scheme

In deterministic formulation of UFLS plan, it is assumed that the actual values of all parameters are known in priory. The setting parameters of UFLS plan are optimized for the maximum possible amount of generation deficiency. Each stage of UFLS plan has three setting parameters including the frequency set point (i.e. f_s^{sh}), the amount of load to be shed (i.e. ΔP_s^{sh}), and the minimum time delay before load shedding (i.e. Δt_s^{sh}). To consider the delays of circuit breakers and protective relays a minimum time delay before load shedding is required to be included. Also an intentional time delay is required to permit the system frequency recovery. Considering all these issues, the time delay before load shedding is assumed to be equal to $200ms$. Therefore, two setting parameters must be optimized for each UFLS strategy. The objective function of deterministic UFLS is expressed as follows:

$$\underset{\Delta P_s^{sh}, f_s^{sh}}{Min} \; C.F. = \sum_{s=1}^{ns} \Delta P_s^{sh} \tag{20}$$

The obtained percentages of load shedding are distributed among load points fairly or according to their importance. The load group with the highest priority are the last one to be disconnected. For example in Iran national grid there are 16 Regional Electric Companies(REC) and the obtained percentages of load shedding are distributed fairly among all RECs throughout the country. The critical loads inside the territory of each REC such as social emergency centers and hospitals should not be interrupted. Additionally, in Iran national grid, the utilized UFLS scheme is designed to arrest frequency decline up to 50% of generation deficiency (i.e. power imbalance or overload). The UFLS relays have been installed in specific load points not all of them.

As recommended in [9], in one hand, excessive load shedding in the initial stages results in over-frequency conditions, or unnecessary loss of service continuity and revenue. In the other hand, too little shedding in the initial stages results in severe frequency decline, which may in turn lead to further loss of generation on under-frequency or even system wide blackout. Therefore to avoid such undesired consequences, it is preferable to have more stages and less load shed per stage rather than fewer stages and more load shed per stage [9].

According to [9], several national or regional power systems around the world have implemented multistage load shedding schemes. In [9], the stages of load shed, pickup frequencies, time delays, and percent of load to be shed in each step are reported for NERC regional coordinating councils and several additional entities in the U.S., France, Ireland, and Nordel, which coordinates operations in Denmark, Finland, Iceland, Norway, and Sweden. According to [9], Western Electricity Coordinating Council (WECC), East Central Area Reliability coordination agreement (ECAR), Florida Reliability Coordinating Council (FRCC), Northwest Power Pool (NWPP), and Nordel have implemented 5-stages UFLS plans. National power systems in Ireland and France have implemented 4-stages UFLS plans. Iran national grid now utilizes a 5-step UFLS plan. In this work, it is assumed that the UFLS plans of IEEE 39-bus and Iran national test system have 4 and 5 stages, respectively.

By increasing the number of load shedding stages, the number of required frequency set-points should be increased (i.e. each stage needs a unique frequency set-point). Therefore to have more load shedding steps it is required to reduce the interval between two subsequent frequency set-points. By decreasing the interval between the subsequent frequency set-points, the risk of undesired activation of subsequent shedding stages is increased. Generally, the number of load shedding steps may be considered as an optimization variable. However the implemented UFLS schemes in many national power systems [9] have 5-stage or 4-stage plans. The number of load shedding stages is assumed as a constant input parameter of the model.

In addition to discretized system frequency response given by (11) - (19), it is necessary to define a set of equality and inequality constraints for frequency set points and amount of load to be shed. According to (21) the automatic load shedding is not permitted for frequency decline above the f_{max}^{sh}. Generating units can operate continuously within $\pm 0.50 Hz$ of nominal value [9]. Therefore a UFLS plan is designed to settle the post disturbance frequency within this range. In other words, in $50Hz$ power systems the load shedding is not allowed for frequency deviations within $\pm 0.50Hz$ range. Therefore, the value of f_{max}^{sh} must be lower than $49.5Hz$. Based on (22), to permit the system frequency recovery and to avoid the overlaps of set-points a specific gap should be included between two subsequent stages(e.g. $0.2Hz$ or $0.3Hz$). According to (23) the system frequency is not allowed to fall below a minimum threshold in any circumstance.

$$f_{min}^{sh} \le f_s^{sh} \le f_{max}^{sh}, \quad s = 1, 2, \ldots, n_s \tag{21}$$

$$f_s^{sh} - f_{s+1}^{sh} \ge \Delta f_{min}, \quad s = 1, 2, \ldots, n_s - 1 \tag{22}$$

$$f_n = f_0(1 + \Delta f_n) \ge f_{min} \tag{23}$$

The steady state change of frequency must be remained in a safe range as expressed by (24) - (25).

$$-\Delta f_{max}^{ss} \le \Delta f^{ss} \le \Delta f_{max}^{ss} \tag{24}$$

$$\Delta f^{ss} = \frac{\left(-\Delta P^c - \Delta P^{DG} + \sum_{s=1}^{ns} \Delta P_s^{sh}\right)}{D + {}^1\!/_R} \tag{25}$$

A timer is needed to control the minimum time delay before load shedding. The model of timer is given in (26)-(29). In this paper, the time delay and the time step of discretization are assumed to be equal to $200ms$ and $50ms$, respectively. According to (28) to allow the load shedding at n^{th} time instant it is required to have $TS_{s,n} = 1$. In other words, to trigger load shedding, it is required to have $f_s^{sh} \le f_n$ during four subsequent time steps ($(\frac{200ms}{50ms}) = 4$). Based on (27) two conditions are possible. If f_n is greater than f_s^{sh} then the value of binary variable is $V_{s,n} = 0$ and vice versa. Indeed, this binary variable is activated when the frequency falls below the set-point. According to (28), the binary variable $V_{s,n}$ along with the binary variable $TS_{s,n}$ will count the time duration of condition where frequency (f) falls below the set-point (f_s^{sh}).

$$\Delta P_s^{sh} \leq \Delta P_s^{max} \tag{26}$$

$$\frac{f_s^{sh} - f_n}{f_0} \leq V_{s,n} \leq 1 + \frac{f_s^{sh} - f_n}{f_0} \tag{27}$$

$$\frac{\sum_{j=0}^{3} V_{s,n-j}}{3} - 1 \leq TS_{s,n} \leq V_{s,n-k}, k = 0, \ldots, 3 \tag{28}$$

$$TS_{s,n-1} \leq TS_{s,n} \tag{29}$$

IV. Probabilistic UFLS

Designing UFLS relays based on the maximum power deficiency may lead to excessive load shedding in most contingencies. Therefore, it is required to tune the UFLS scheme considering the uncertainty of generation deficiencies.The frequency decline is approximately initiated by generation deficiency or generation outage. Total amount of load assigned over all shedding stages is determined or optimized considering credible but worst-case scenario of maximum loss of generation. Indeed the amount of generation deficiency or power imbalance is the input of UFLS plan.

In this paper, it is assumed that the generation deficiency is a random normal variable with predefined mean and standard deviation. The mean value of this random variable is equal to the amount of input power imbalance or overload which the UFLS is designed for. MCS technique is utilized to generate credible scenarios of generation outage according to the assumed normal probability distribution function.

The reason behind the randomness of possible power deficiency is discussed in [23]. From the frequency stability's point of view, different contingencies with the same amount of generation deficiencies will cause the same system frequency response. Therefore optimizing the UFLS settings for generation deficiencies up to the maximum amount of input power imbalance(i.e. generation deficiency) which the UFLS is designed for, will stabilize the system frequency response under the related contingencies. In this paper, the efficacy of the proposed method is verified for different levels of generation deficiencies(e.g. in Iran test case, from 10% to 50% in steps of 5%).

Due to the advent of small scale generation technologies and new load types, the actual values of system inertia and load damping are unknown. Therefore, it is required to modify the setting of UFLS plans considering these uncertainties. The overall structure of the proposed probabilistic UFLS plan is illustrated in Fig. 2. According to Fig. 2, the proposed probabilistic UFLS model is implemented in two subsequent stages. The minimum possible load shedding is achieved in the first stage considering the uncertainties. In the second stage the mean value of the total load shedding obtained in the first stage is considered as the maximum amount of load allowed to be shed. Finally four different UFLS strategies are designed to reach the suitable system frequency response.

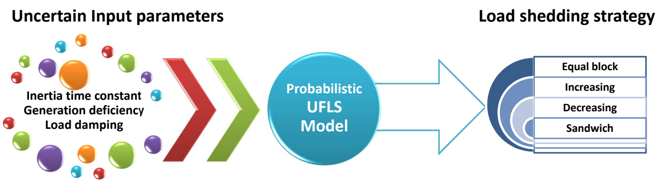

Figure 2. Inputs and outputs of the proposed probabilistic UFLS plan

The MCS method is used to model the uncertainties. According to the Probability Density Function(PDF) of a random variable, MCS method generates enough number of samples for the uncertain parameter. For each sample a deterministic problem is then solved. In MCS method, to solve a problem with p uncertain variables, N_ρ input samples (scenarios) are generated based on the PDF. The weight of each sample is $\frac{1}{N_\rho}$. Each output variable (Z) has N_ρ samples.

In MCS-based UFLS problem, the input random variables are inertia time constant, load damping and the generation deficiency ($X = (H, D, \Delta P^c)$), while the output random variable is the total amount of load to be shed ($Z = \Delta P^{sh}$). The mean value of load shedding is then utilized to optimize the parameters of UFLS plan. The value of inertia time constant depends on the available synchronous units. Therefore, the relation between the inertia time constant and generation deficiency at each scenario is defined as follows:

$$H_\rho = \frac{M + \Delta P_\mu^c}{M + \Delta P_\rho^c} H_\mu \tag{30}$$

According to (30), when the generation outage at scenario ρ is greater than generation outage at base scenario(i.e. $\Delta P_\mu^c \leq \Delta P_\rho^c$)), the equivalent inertia time constant of that scenario will be lower than the inertia time constant of the base scenario (i.e. $H_\rho^c \leq H_\mu^c$)). This assumption prevents the generation of unrealistic input probabilistic scenarios with high inertia time constant and high amount of generation outage or vice-versa. The objective function of MCS-based UFLS plan is formulated as follows:

$$\min_{\Delta P_{s,i}^{sh}, f_{s,i}^{sh}} OF = \sum_{i=1}^{N_\rho} \sum_{s=1}^{n_s} \pi_i \Delta P_{s,i}^{sh} \tag{31}$$

The constraints of probabilistic UFLS plan at each time step n, of each stage s, for each scenario i are expressed as follows.

$$\begin{aligned} \Delta f_{n+1,i} \approx & \Delta f_{n,i} + \frac{\Delta t}{2} [RHS_i\left(t_n, \Delta f_n\right) \\ & + RHS_i\left(t_{n+1}, \Delta f_{n+1}\right)] \end{aligned} \tag{32}$$

$$\begin{aligned} RHS_i\left(t_n, \Delta f_n\right) = & \frac{1}{2H_i} (\Delta P_{n,i}^{gov} - \Delta P_i^c + TS_{s,n,i} \Delta P_{s,i}^{sh} \\ & - D_i \Delta f_{n,i} - US_n \Delta P_n^{DG}) \end{aligned} \tag{33}$$

$$\Delta P_{n+1,i}^{gov} = \Delta P_{n,i}^{gov} + \frac{\Delta t}{T} \left(-\frac{\Delta f_{n,i}}{R} - \Delta P_{n,i}^{gov} \right) \tag{34}$$

The rest of constraints are expressed at time instant n of simulation and stage s of load shedding for scenario i. These constrains include activation of RoCoF relays ((35)- (36)), constraints of minimum and maximum set-point frequency((37)-(39)), steady state frequency ((40)-(41)), and constraints for time delay of load shedding ((42)-(45)) as given below, respectively.

$$\frac{RoCoF_{n,i} - RoCoF^{set}}{f_0} \leq US_{n,i} \tag{35}$$

$$1 + \frac{RoCoF_{n,i} - RoCoF^{set}}{f_0} \geq US_{n,i} \tag{36}$$

$$f^{sh}_{min} \leq f^{sh}_{s,i} \leq f^{sh}_{max} \tag{37}$$

$$f^{sh}_{s,i} - f^{sh}_{s+1,i} \geq \Delta f_{min} \tag{38}$$

$$f_{n,i} = f_0(1 + \Delta f_{n,i}) \geq f_{min} \tag{39}$$

$$-\Delta f^{ss}_{max} \leq \Delta f^{ss}_i \leq \Delta f^{ss}_{max} \tag{40}$$

$$\Delta f^{ss}_i = \frac{\left(-\Delta P^c_i - \Delta P^{DG} + \sum_{s=1}^{ns} \Delta P^{sh}_{s,i}\right)}{D_i + {}^1/_R} \tag{41}$$

$$\Delta P^{sh}_{s,i} \leq \Delta P^{max}_{s,i} \tag{42}$$

$$\frac{f^{sh}_{s,i} - f_{n,i}}{f_0} \leq V_{s,n,i} \leq 1 + \frac{f^{sh}_{s,i} - f_{n,i}}{f_0} \tag{43}$$

$$\frac{\sum_{j=0}^{3} V_{s,n-j,i}}{3} - 1 \leq TS_{s,n,i} \leq V_{s,n-k,i} \tag{44}$$

$$k = 0, \ldots, 3$$

$$TS_{s,n-1,i} \leq TS_{s,n,i} \tag{45}$$

Power systems have many fast and slow dynamics. Fast dynamics(e.g dynamics of AVRs, excitation winding, and damper wingdings) die out rapidly. The dynamics of system frequency response are not fast enough to be affected by rapid dynamics of generators and AVRs. In other words, the time constants of dynamics involved in system frequency response vary from few seconds to few minutes. At this time scale, it is theoretically and practically reasonable to assume that the fast dynamics of generators and AVRs die out rapidly. This is a common acceptable assumption in power system analysis. Without such time decomposition, the computational burden of even small power systems will be increased significantly. This fundamental decomposition is discussed in [12].

V. Simulation Results

The standard IEEE 39-bus system and Iran national grid are used to simulate the proposed UFLS plans. The static and dynamic data of IEEE 39-bus test system could be found in [24]. The input parameters for both grids are given in Table I. The per-unit data for IEEE 39-bus system and Iran national grid are expressed on a base of 6500 MVA and 50000 MVA, respectively.

The load damping constant is expressed as a percent change in load for one percent change in frequency. Typical values of load damping constant are 1 to 3 [12]. A value of $D = 2$ means that a 1% change in frequency would cause a 2% change in load [12]. Regarding this fact, we have selected the load damping as $D = 2$ for IEEE-39 bus test system and $D = 3$ for Iran national grid. The peak load in Iran national grid occurs at summer. During the summer and due to the high temperatures (e.g. more than 40^0C in central and south regions) a big portion of domestic and commercial loads (in addition to industrial loads), utilize the induction-motor based cooling system. Therefore, the load damping constant in Iran national grid is approximately assumed to be as as $D = 3$.

The simulation results are presented for both deterministic and probabilistic UFLS plans with and without considering the unwanted activation of RoCoF relays. The UFLS models are optimized using Genetic Algorithm. Parameters of utilized genetic algorithm are assumed to be as: Population Size = 100, Maximum Number of Iteration= 500, Crossover= 0.80, and Mutation rate = 0.05. The proposed formulations for UFLS plans are coded in MATLAB. The proposed UFLS schemes will determine the frequency set-points (f^{sh}_s) and load shedding (ΔP^{sh}_s) of each stage s. For both deterministic and probabilistic schemes four different strategies including Increasing, Decreasing, Equal Block, and Sandwich plans are designed. The performances of these load shedding strategies are investigated under different conditions.

Table I
Input Parameters for both test grids

Parameter	Description	Value(39 bus)	Value(Iran)
D	Load damping	2	3
R	Equivalent droop of governors	0.22^{pu}	0.1^{pu}
T	Time constant of governor	$5\ sec$	$5\ sec$
f_0	Nominal system frequency	$50\ Hz$	$50\ Hz$
H	Equivalent inertia time constant	$4.3\ sec$	$4\ sec$
Δf_{min}	Minimum difference between subsequent stages	$0.1\ Hz$	$0.1\ Hz$
f^{shed}_{min}	Minimum value of frequency set-points	$47.7\ Hz$	$47.7\ Hz$
f^{shed}_{max}	Maximum value of frequency set-points	$49\ Hz$	$49.5\ Hz$
f_{min}	Minimum allowable frequency	$47.5\ Hz$	$47.5\ Hz$
Δf^{ss}_{max}	Maximum deviation of steady state frequency	$1\ Hz$	$0.5\ Hz$

European Network of Transmission System Operators (ENTSO), has proposed three different types of UFLS plans including Late UFLS, Linear UFLS and Early UFLS schemes [7]. In Late UFLS plan (i.e. Increasing UFLS), the amount of load shedding is gradually increased based on the frequency decline. It obviously leads to more load shedding at the last moment. This scheme is favorable for light frequency decline. However, in case of severe frequency decline, it might fail to stop the frequency instability. The Early UFLS plan (i.e. Decreasing UFLS), a larger amount of the load is shed at the first stage of UFLS plan [25]. This scheme is favorable for large frequency decline caused by large generation outages. Unlike the Late UFLS plan, this scheme may shed large amount of load under moderate frequency declines. This scheme may arrest the large RoCoF values and avoid the unwanted tripping of DGs. In Linear UFLS(i.e. Equal Block UFLS), the same amount of load is shed at each stage. It may provide acceptable but non-optimal performance under both large and light frequency declines. Another plan is the Sandwich plan in which more load is shed at the first and last stages of scheme [26]. Lower amount of load is shed at the middle stages of this scheme.

In this paper, these four schemes are optimized in the presence of uncertainties and RoCoF mal-operations.In this work, the type of UFLS strategy has not been considered as an optimization variable. Indeed based on the optimized load shedding in the first stage of the proposed probabilistic UFLS, in second stage, the settings of a given UFLS strategy are optimized. The characteristics of these strategies are as recommended by [8]. The design of Equal Block load shedding strategy is straightforward. In Increasing scheme, the load shed values of late stages must be greater than the early stages, while in Decreasing scheme the situation is vice versa. As recommended in [8], the first and last stages of Sandwich plans must be equal and greater than the middle stages. The middle stages of Sandwich plan has equal percentages. The proposed UFLS optimization model determines the load shedding patterns considering the formulated system frequency response.

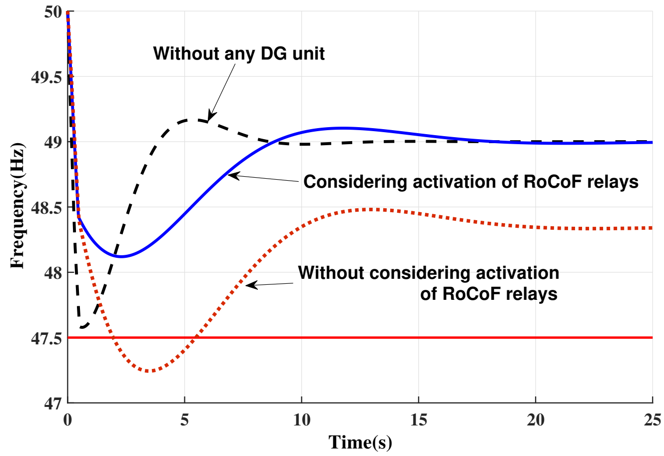

Figure 3. System frequency response using deterministic UFLS

A. UFLS Model for IEEE 39-Bus

1) Deterministic UFLS Model: It is assumed that, there are 10 DGs in different buses of IEEE 39-bus system. Power generation of these DGs are equal to 1000 MW and all of them are equipped with RoCoF relay. Ten pick-up values are assumed for RoCoF relays from 0.4 Hz/s to 1.3 Hz/s in steps of 0.10 Hz/s. In other words, to consider the diversity of RoCoF settings throughout the network, it is assumed that each DG has a different RoCoF setting (i.e. $RoCoF_{DG1}^{set} = 0.4\ Hz/s$, $RoCoF_{DG2}^{set} = 0.5\ Hz/s$, ..., $RoCoF_{DG10}^{set} = 1.3\ Hz/s$).

The proposed deterministic UFLS plan is optimized for the 0.5^{pu} of generation deficiency. The obtained settings for deterministic UFLS plan without considering the unwanted activation of RoCoF relays in system frequency response are given in Table II. It can be observed that a total load of 0.375^{pu} (37.5%) must be curtailed in four subsequent stages.

Table II
SETTINGS FOR IEEE 39-BUS USING DETERMINISTIC UFLS

Frequency Set Points (Hz)	Load Shedding Blocks (%)	Time delay (sec)
Without consideration RoCoF relays		
48.95	Block1= 10 %	0.2
48.75	Block2=8.0 %	0.2
48.45	Block3=15 %	0.2
47.90	Block4=4.5 %	0.2
With consideration RoCoF relays		
48.95	Block1=6.0 %	0.2
48.65	Block2=13.5 %	0.2
48.40	Block3=8.5 %	0.2
48.15	Block4=17.5 %	0.2

Now, the activation of RoCoF relays is considered in UFLS plan. The new optimized settings are obtained as given in Table II. It can be observed that, due to activation of RoCoF relays some DGs are tripped and the required load shedding is increased to 0.455^{pu}. The system frequency responses for three scenarios are shown in Fig. 3. In first scenario, it is assumed that there is no DG unit in the network. According to Fig. 3, in this condition the obtained UFLS plan presents a safe frequency response. In second scenario, the settings of UFLS plan are obtained in the presence of DG units. However, in this scenario the UFLS settings are determined without considering the undesired activation of RoCoF relays.

According to Fig. 3, it can be observed that without considering the activation of RoCoF relays, the obtained UFLS plan fails to provide an acceptable system frequency response. In this condition, the RoCoF relays will trip the grid-connected DGs. If this issue is ignored in UFLS model then the obtained load shedding is not enough for stabilizing the system frequency response(i.e. the amount of load shed is underestimated).

The third scenario implies that with considering the activation of RoCoF relays in UFLS design, the obtained settings make the system frequency response stable. The RoCoF variations are depicted in Fig. 4. The system frequency response including frequency nadir(i.e. the lowest or deepest point of the system frequency response) must be greater than the minimum allowable system frequency at all circumstances. According to [8], the minimum allowable frequency is assumed to be equal to $47.5Hz$ at $50Hz$ power systems. Therefore the frequency nadir must be greater than $47.5Hz$ in all circumstances. Based on Fig. 4, it can be observed that without considering the undesired activation of RoCoF relays the system frequency response falls below the minimum allowed frequency nadir.

2) Probabilistic UFLS model: In this paper, the MCS method [27] is used to model the uncertainty of generation deficiency, load damping and inertia time constant. A normal PDF is assumed for uncertain parameters. The PDF of system inertia time constant is determined as a function of generation deficiency as given by (30). The mean values of generation deficiency and load damping are assumed to be equal to 0.5^{pu} and 2^{pu}, respectively. The mean value of system inertia time constant is 3.7 sec. According to Table II, it is assumed that the mean values of uncertain parameters are known in prior and the proposed probabilistic UFLS plan handles the uncertainties of these parameters. For practical large scale power systems,

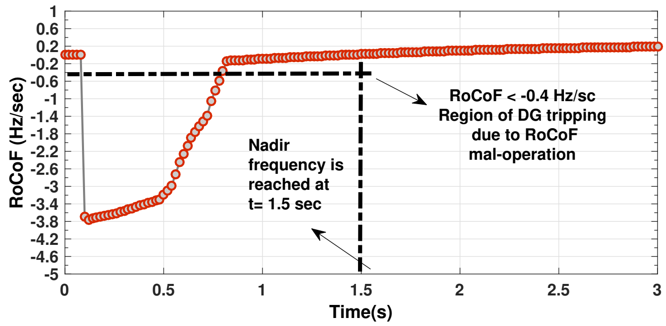

Figure 4. RoCoF variations using deterministic UFLS strategy

it is possible to estimate the system parameters such as inertia time constant and load damping using phasor measurement data under recorded specific events [13], [14].

The standard deviations of generation deficiency and load damping are chosen as 0.1^{pu} and 0.2^{pu}, respectively. A total number of 1000 samples are generated as the input of MCS method. The PDFs of input and output variables are illustrated in Fig. 5.

The settings of probabilistic UFLS plan are now determined in two subsequent stages. In first stage the probabilistic UFLS is optimized. The PDF of load shedding is then obtained. In second stage, according to the mean value of load shedding (i.e. 0.479^{pu}) four deterministic UFLS strategies including Sandwich, Equal Block, Increasing and Decreasing UFLS are designed as given in Table III. The objective function of UFLS is to reach the minimum amount of load shedding subject to normalization of the system frequency response. Therefore, the mean value of the probabilistic load shedding (i.e. value of load shedding determined via the probabilistic UFLS plan) is assumed as the maximum allowable amount of load shedding. However in the second stage of the procedure the new frequency set-points are determined to normalize the system frequency response without exceeding the maximum value of load shedding obtained in the first stage.

As the aim of UFLS is to reach the minimum amount of load shedding, considering the requirements discussed in Section III, frequency set-points must be greater than frequency nadir (i.e. 47.5 at $50Hz$ system) and lower than the threshold of the secondary frequency control by AGC (i.e. 49.5 at $50Hz$ system) with a pre-determined interval between two subsequent set-points. In this regard for normalization of different UFLS schemes and to have a fair comparison the frequency set-points are chosen the same as reported in Table III.

In an optimization problem, the solution space is reduced by adding more constraints. In other words, by considering constraints of the second stage (i.e. constraints related to the load shedding strategy) to the first stage, a single stochastic optimization problem is created. In such situation, it is possible to lose the global minimum amount of load shedding. Since the main goal of each UFLS scheme is to reach the minimum amount of load shedding, the first stage will determine the minimum possible load shedding for restoring system frequency, and the second stage will optimize the load shedding strategy. All load shedding strategies are optimized considering all sources of load and generation changes including DG outages due to activation of RoCoF relays.

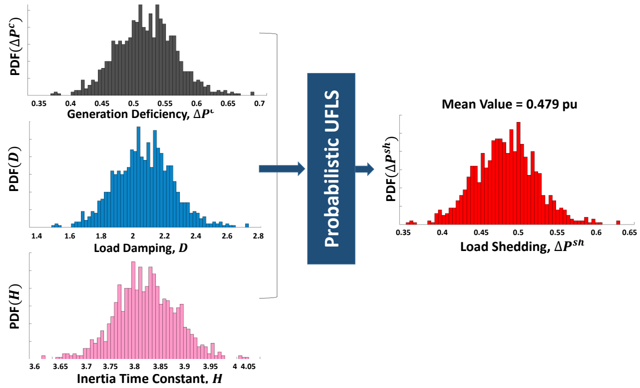

Figure 5. PDFs of inputs and output variables for IEEE-39 bus grid

Table III
UFLS SETTINGS FOR IEEE 39-BUS SYSTEM USING PROBABILISTIC MODEL

Frequency Set Points (Hz)	Load Shedding (%) Inc.	Dec.	San.	Eq.	Time delay (sec)
49.0	2.0 %	25%	15.0%	12%	0.2
48.8	7.0 %	13%	9.0%	12%	0.2
48.5	15 %	8.0%	9.0%	12%	0.2
48.2	24 %	2.0%	15%	12%	0.2

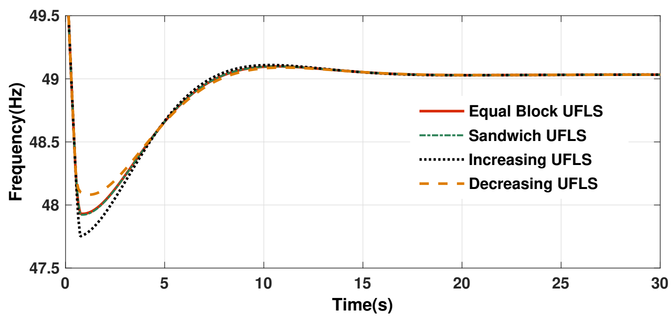

Figure 6. System frequency response using four UFLS strategies

The system frequency responses for these schemes (i.e. schemes with settings given in Table III) are depicted in Fig. 6. According to Fig. 6, due to severity of initial frequency decline, the Decreasing UFLS plan provides a better frequency response.

3) DG penetration sensitivity analysis: In this part, the performance of the UFLS strategy is investigated under different DG penetration levels. The system frequency responses are depicted in Fig. 7 assuming $\Delta P_c = 50$ %, with and without considering the activation of RoCoF relays.

The system frequency response with considering the activation of RoCoF relays is depicted in dashed line. This frequency response is the average of four different schemes as illustrated in Fig. 6. The system frequency responses without considering the activation of RoCoF relays is shown in Fig. 7 in solid blue curves. The notation LSH in Fig. 7 stands for load shedding value.

It can be observed that for DG penetrations greater than 10

% the system frequency responses fall below the minimum allowed frequency (i.e. 47.5 Hz). In this condition, the large scale synchronous generators will trip due to under frequency relays and the entire grid will goes toward a catastrophic cascading failure. However, it can be seen that using the modified UFLS plan(i.e. UFLS plan with considering the activation of RoCoF relays of DGs), the system frequency is restored to the safe range. The system frequency responses illustrated in Fig. 6

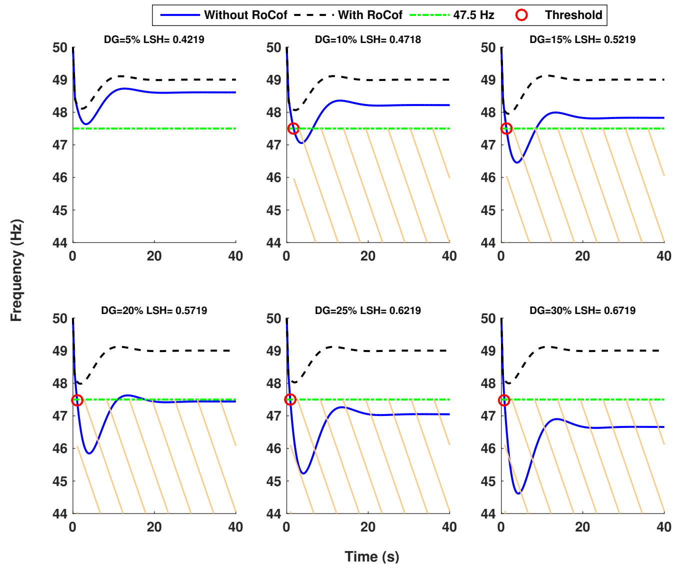

Figure 7. System frequency response under different values of DG penetration, With/without malfunction of RoCof Relays for 50 % contingency

and Fig. 7 are obtained for a maximum generation deficiency of $\Delta P_c = 50$ %. (i.e. the mean value of generation deficiency was assumed to be as 0.50 pu with standard deviation of 0.10 pu). The system frequency responses in Fig. 6 and Fig. 7 are depicted using probabilistic UFLS settings.

The performance of the obtained settings are now investigated under the input contingency of $\Delta P_c = 30$ %. The system frequency responses using four UFLS plans including Increasing, Decreasing, Equal Block, and Sandwich schemes are depicted in Fig. 8 under different levels of DG penetrations. According to Fig. 8, the system frequency responses using Increasing, Decreasing cause frequency overshoots especially under high levels of DG penetration. However the Equal Block and Sandwich schemes have provided a smooth frequency response under different levels of DG penetration.

B. UFLS Model for Iran National Grid

Iran national grid is the owner of 51757 km-circuit 230kV and 400kV transmission lines. The total installed generation capacity of Iran grid is 75,000 MW and the peak demand during summer 2015 was about 50,000 MW. The proposed probabilistic UFLS plan is optimized for 50% generation deficiency. A total number of 1000 samples are generated as the input of MCS method. Without loss of generality, the level of DG penetration in Iran national grid is assumed to be 10% and the settings of RoCoF relays for these DGs units are assumed to be the same as IEEE 39-bus test system.

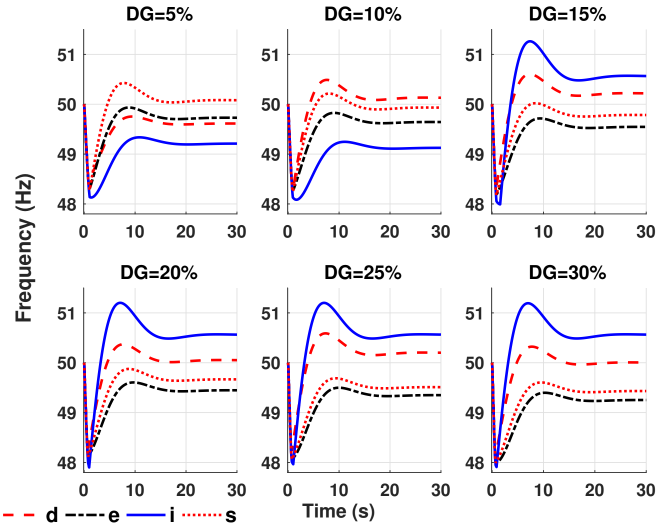

Figure 8. Comparison between Decrease (d), Increase (i), Sandwich (s) and equal (e) load shedding plans for 30% contingency

Table IV
UFLS SETTINGS FOR IRAN'S NATIONAL GRID

Frequency Set Points (Hz)	Load Shedding (%) San.	Eq.	Dec.	Inc.	Time delay (sec)
49.4	8.9 %	7.4%	15.4%	1.6%	0.2
49.2	6.4 %	7.4%	9.4%	3.9%	0.2
49.0	6.4 %	7.4%	6.9%	6.9%	0.2
48.7	6.4 %	7.4%	3.2%	11.3%	0.2
48.4	8.9 %	7.4%	2.1%	13.3%	0.2

The mean value of load shedding obtained by probabilistic UFLS plan is 37%. As given in [9], the total amount of load shedding for different power systems are as follows: Western Electricity Coordinating Council (WECC): 31.1%, East Central Area Reliability coordination agreement (ECAR): 25%, Florida Reliability Coordinating Council (FRCC): 34%, Northwest Power Pool(NWPP): 28%, and Nordel(Denmark, Finland, Iceland, Norway, and Sweden): 50%, Ireland: 65%. These values refer to just the amount of total load to be shed. To estimate the maximum overload or generation deficiency that the UFLS plans are designed for, it is required to add the primary response by governors and load damping to these values.

As an example according to [9], Western Electricity Coordinating Council (WECC) shed 31.1% of its system load during five subsequent stages if all those stages be activated. It doesn't mean that for any contingency, 31.1% of its system load is curtailed. Iran national grid now utilizes a 5-step UFLS plan. The maximum generation deficiency or overload is assumed to be equal to 50%. According to the obtained results, for a maximum overload of 50%, the designed UFLS shed 37% of the load during five subsequent stages, if all those stages are activated. It doesn't mean that for any contingency 37% of the system load is curtailed. The rest of power deficiency is compensated by governors and load damping.

Unlike the equivalent system inertia and load damping con-

Table V
PERFORMANCE OF THE OPTIMIZED UFLS PLANS IN FOUR STRATEGIES UNDER DIFFERENT POWER DEFICIENCIES

Load shed of activated stages using four different UFLS strategies(% of total load)																				
Generation Deficiency	Sandwich Plan					Equal Block Plan					Increasing Plan					Decreasing Plan				
	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}	1^{st}	2^{nd}	3^{rd}	4^{th}	5^{th}
10 %	8.9	-	-	-	-	7.4	-	-	-	-	1.61	-	-	-	-	15.39	-	-	-	-
15 %	8.9	-	-	-	-	7.4	-	-	-	-	1.61	3.94	-	-	-	15.39	-	-	-	-
20 %	8.9	6.4	-	-	-	7.4	7.4	-	-	-	1.61	3.94	6.91	-	-	15.39	-	-	-	-
25 %	8.9	6.4	-	-	-	7.4	7.4	7.4	-	-	1.61	3.94	6.91	-	-	15.39	9.4	-	-	-
30 %	8.9	6.4	6.4	-	-	7.4	7.4	7.4	-	-	1.61	3.94	6.91	11.93	-	15.39	9.4	-	-	-
35 %	8.9	6.4	6.4	-	-	7.4	7.4	7.4	-	-	1.61	3.94	6.91	11.93	-	15.39	9.4	6.89	-	-
40 %	8.9	6.4	6.4	6.4	-	7.4	7.4	7.4	7.4	-	1.61	3.94	6.91	11.93	13.27	15.39	9.4	6.89	-	-
45 %	8.9	6.4	6.4	6.4	8.9	7.4	7.4	7.4	7.4	-	1.61	3.94	6.91	11.93	13.27	15.39	9.4	6.89	3.87	-
50 %	8.9	6.4	6.4	6.4	8.9	7.4	7.4	7.4	7.4	7.4	1.61	3.94	6.91	11.93	13.27	15.39	9.4	6.89	3.87	2.11

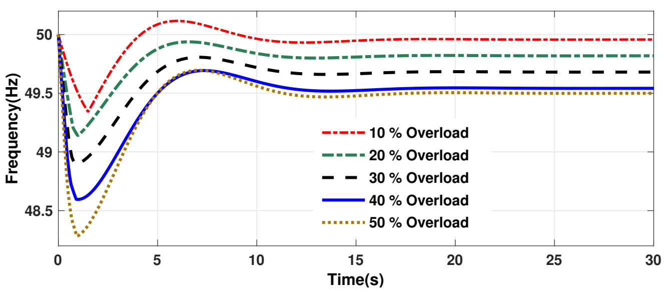

Figure 9. System frequency response using Sandwich UFLS plan

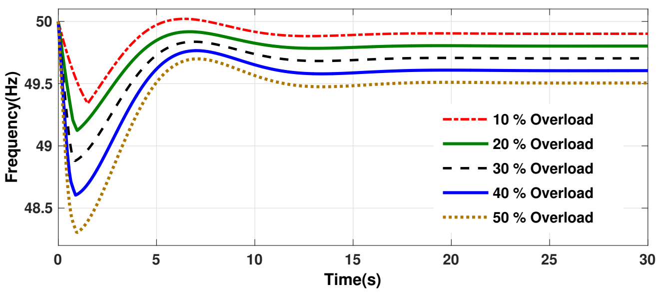

Figure 10. System frequency response using Equal Block UFLS plan

stant, the value of governor droop is a control and adjustable parameter. To harvest the maximum contributions of governors in generation compensation, the equivalent droop is set at a small value and vice versa. The Iran national grid can be simulated under a low value of governor droop (e.g. 5%) to have a significant participation of all governor-equipped generators or under a high value of governor droop (e.g. 15-20 % or more) to have a lower participation of governor-equipped generators. Technical comparison of primary frequency control parameters in various countries is available in [18].

In Iran national grid, the annual peak load occurs at the second or third month of summer. At summer, due to climate changes (i.e. dry seasons) many hydroelectric powerplants are energy limited. Therefore, the participation of some hydro powerplants in primary frequency control is reduced. Considering all these issues, the input parameters for Iran national grid are assumed to be as given in Table I (the equivalent governor droop is assumed to be equal to 10 %). Without loss of generality, any set of input parameters could be considered in the proposed UFLS scheme. According to the mean value of load shedding, four UFLS plans are introduced for Iran national grid including Sandwich UFLS, Equal Block UFLS, Decreasing UFLS and Increasing UFLS plans. The optimized settings for each plan are given in Table IV.

The frequency responses of Sandwich and Equal Block UFLS plans are plotted in Fig. 9 and Fig. 10, respectively. Both plans present acceptable frequency responses. The Sandwich plan has more frequency overshoot with respect to Equal Block plan specially under small overloads. The frequency nadir is approximately similar in both schemes. The frequency responses of Increasing and Decreasing UFLS plans have been depicted in Fig. 11 and Fig. 12, respectively.

The frequency overshoot in Decreasing UFLS is higher than other schemes. In other words, in case of large generation outages (i.e. high RoCoF values) the decreasing scheme is a good choice. In case of significant generation deficiency, the Decreasing UFLS presents a soft frequency response with respect to other UFLS plans.The activated stages of load shedding under different generation deficiencies are given in Table V.

It is noted that all stages of UFLS plans are activated only under a cascading failure or blackout. In other conditions, based on the amount of generation deficiency, the required stages of UFLS are activated to compensate the generation deficiency. For both simulated test cases (IEEE 39-bus and Iran national grid), it can be deduced that under sever contingencies (i.e. large generation deficiencies) the Decreasing plan present acceptable response. Under moderate generation deficiencies the Increasing scheme may present a soft system frequency response. However in both test cases the Equal Block and Sandwich plans have provided smooth frequency responses under different generation deficiencies(i.e. from low to large generation deficiencies).

VI. CONCLUSION

A probabilistic UFLS plan was proposed with incorporating the uncertainties of system parameters and generation deficiency into the traditional multistage UFLS design. It is shown

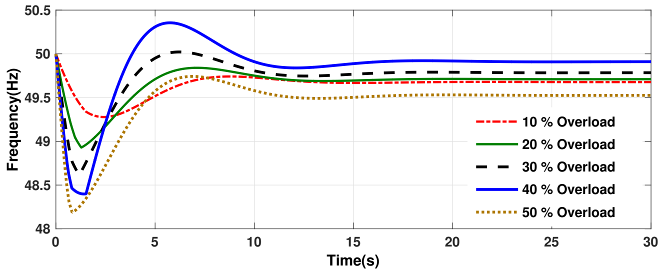

Figure 11. System frequency response using Increasing UFLS plan

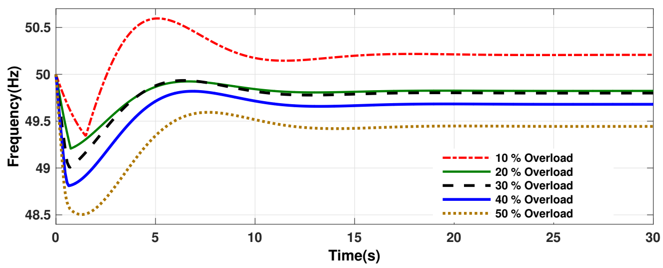

Figure 12. System frequency response using Decreasing UFLS

that without considering the mal-operations of RoCoF relays of DGs, the resulted setting parameters may result in inappropriate(i.e. underestimated) load shedding. The discretized system frequency response was modified to include uncertainties of system parameters and generation outage along with the undesired activation of RoCoF relays. Four different UFLS strategies including Increasing, Decreasing, Equal Block, and Sandwich plans were developed to design the proper UFLS plan under large and light frequency declines. It was shown that the proper UFLS scheme could be selected based on the maximum credible generation deficiency and the penetration level of DGs. The results of applying the proposed UFLS plan over the IEEE-39 bus and Iran national grid verified its capability in providing a stable system frequency response.

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