An Improved UFLS Scheme based on Estimated Minimum Frequency and Power Deficit

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***Abstract*—In the event of a power system disturbance, it is important that the decision to implement under frequency load shedding is based on both the minimum frequency and the magnitude of the disturbance. In this paper, we propose the use of higher order polynomial curve fitting to estimate the minimum frequency. If the prediction shows that the minimum frequency threshold will be violated, the magnitude of the total disturbance is estimated using the swing equation. In addition, the minimum amount of load that must be shed to restore the frequency just above the minimum value can also be directly calculated. Simulations are carried out for the considered Taiwan power system and the results prove the efficiency of the proposed technique.**

***Index Terms*—Disturbance estimation, frequency prediction, polynomial curve fitting, under frequency load shedding**

I. Introduction

Modern power systems are usually loaded close to the steady state stability limit and this threatens their secure operation. Among the most common stability issues that arise in power systems, frequency stability is becoming very popular [1]. This is because when an online generator trips, or a heavily loaded transmission line is interrupted, the demand-generation balance is affected. In such cases the power systems frequency begins to decline also below the minimum thresholds if not quickly restored [2]. Under frequency load shedding (UFLS) technique comes as a tool to quickly curtail connected loads in order to restore the frequency. Through relaying action, trip signals are sent to load buses that participate in the load shedding. Traditional UFLS is a widely used technique to curtail load in emergency scenarios. However, this technique has proven to have challenges including not-optimum load shedding [3]. In this regard, researchers have come up with different techniques to address such problems. These techniques are generally classified as semi adaptive techniques, adaptive techniques and computational intelligent techniques [4]. Even if these techniques have shown great improvement from the old traditional technique, new research is still required to accurately define the indicators to trigger UFLS relays.

The initial issue to consider is the rate of decline of the frequency and from the value based on the swing equation, we can determine the magnitude of the disturbance. The use of the swing equation is the most popular technique used in disturbance estimation [5-8]. Recently, a new technique to estimate the loss of generation was proposed in [9]. The authors propose the use of the post-event system inertia in addition to the already known pre-event inertia. When the disturbance magnitude is known, optimization algorithms can then be used to minimize the amount of load to be shed. The major drawback with only relying on the magnitude of the estimated active power mismatch is that at times UFLS is triggered when it is simply wise enough to wait for slow spinning reserves to cover the deficit. It was also shown that it is not easy to come up with a best-fit relationship between the rate of change of frequency and the active power mismatch [10].

Therefore, in addition to the estimated disturbance the minimum frequency was also predicted. However, in [11] frequency prediction was coupled together with the time left before a threshold is violated to implement UFLS. Furthermore, the frequency prediction was done a few seconds before a threshold is violated. Another technique on frequency prediction is presented in [12], and makes use of the Newton technique, where it is assumed that the frequency behavior following a disturbance can be viewed as a second derivative function.

The last issue to consider is the availability of system information in real time. It is a known fact that real power systems cover vast geographical areas. In the past, monitoring systems only focused on a specific area within their coverage. With wide area measurement systems (WAMS), centralized monitoring of a power system of any size and geographical coverage can be easily done [13]. With the use of phasor measurement units (PMUs), the real time status of the power systems is easily available [14-15].

In this paper, we propose the use of PMU to provide the required system information, which is further used to set up a system frequency response model to be used in frequency analysis. When the model is set up, disturbance estimation using the swing equation is carried out to estimate the disturbance magnitude. In contrast to the previously indicated references, several higher order polynomial are also shown to be applicable in predicting the minimum frequency. In addition, we propose using the first few data samples to estimate the disturbance as compared to waiting and implementing frequency prediction a few seconds before a threshold is violated. Simulations are done for a reduced model of the Taiwan power system using Matlab/Simulink. Results shown the excellent performance of the proposed scheme. Generally, the main contributions in this paper are:

- the use of higher order polynomial to predict minimum frequency,
- the use of the first few data samples soon after the disturbance to carry out curve fitting,
- the estimation of the minimum load to be shed to restore frequency just above the minimum threshold,
- The use of the WAMS-based swing equation to estimate the disturbance just after the disturbance.

This paper is organized as follows: Section II outline the calculation of the minimum load to be shed and the estimation of the minimum frequency using the reduced frequency model. In section III the use of polynomial curve fitting technique in minimum frequency prediction is presented. The system under investigation is presented in section IV and the simulations and results are presented in section V. A summary of the work in this paper is presented in section VI.

II. PREDICTION BASED ON SFR MODEL

The intricacies involved in designing a robust and optimal UFLS scheme led to the need of deriving a system load-frequency model to facilitate an easier design process. Such a model has been proposed and known as a system frequency response (SFR) model. It was shown to essentially represent the average, collective and coherent response of all the generators in the system following a load-generation imbalance. A common example of the SFR model based on turbines with reheaters is given in Fig.1. Based on this model, frequency prediction and calculation of the minimum load to be shed can be easily done.

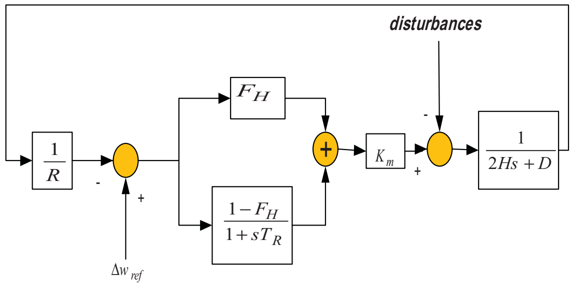

Fig1. System frequency response model

From Fig.1, T_R , F_H , R , D and K_m are the turbine's re-heater time constant, fraction of the total power generated by the high pressure turbine, generator's speed-droop response, system load damping and mechanical power gain factor, respectively.

Adaptive UFLS schemes depend on the estimated system disturbance to carry out protective actions. Since the generators in the system might have slight differences in frequencies, based on PMU measurements, the lumped frequency response is considered. By taking into account the theory of low-order frequency response model, the frequency response in p.u. for a system subject to a unit step disturbance is calculated as follows

$$\Delta w = \left(\frac{R\times\omega_n^2}{D\times R+K_m}\right)\left(\frac{1+T_R s}{s^2+2\zeta\omega_n s+\omega_n^2}\right)\left(\frac{P_{step}}{s}\right) \quad (1)$$

where the other introduced constants are defined as:

$$\omega_n^2 = \frac{D\times R+K_m}{2H\times R+K_m} \quad (2)$$

$$\zeta = \left(\frac{2H\times R+\left(D\times R+K_m\times F_H\right)\times T_R}{2\left(D\times R+K_m\right)}\right)\omega_n \quad (3)$$

By taking the Laplace inverse and expressing the frequency equation in time domain, we get

$$\frac{d\Delta\omega(t)}{dt} = \frac{a\omega_n\times R\times P_{step}}{D\times R+K_m}\left(e^{-\zeta\omega_n t}\sin\left(\omega_r t+\phi\right)\right) \quad (4)$$

where

$$\omega_r = \omega_n \sqrt{1-\zeta^2} \tag{5}$$

$$a = \sqrt{\frac{1-2T_R\zeta\omega_n + T_R^2\omega_n^2}{1-\zeta^2}} \tag{6}$$

$$\phi = \tan^{-1}\left(\frac{\omega_r T_R}{1-\zeta\omega_n T_R}\right) - \tan^{-1}\left(\frac{\sqrt{1-\zeta^2}}{-\zeta}\right) \tag{7}$$

The time domain equation is used to calculate the necessary system parameters. It is known that the maximum rate of change of frequency occurs at the beginning of the disturbance or at t=0. This relationship can be calculated as follows

$$\frac{d\Delta\omega(t)}{dt}\Big|_{t=0} = \frac{a\omega_n \times R \times P_{step}}{D\times R + K_m}\sin\phi = \frac{P_{step}}{2H} = m_0 \tag{8}$$

Based on the above relationship the disturbance is calculated as

$$P_{step} = 2H \times m_0 = \Delta P_{\max} \tag{9}$$

The above relationship is the well-known swing equation, which in most literature can be expressed as:

$$\frac{2Hdf}{f_{nom}dt} = P_m - P_e = \Delta P_{\max} \tag{10}$$

where f_{nom}, P_m, P_e and P_{step} are the nominal system frequency, mechanical power, and the electrical power and the system disturbance, respectively.

The next step is to be able to predict the minimum frequency the system will reach before load-shedding decisions are taken. The frequency trajectory in the event of a disturbance follows a graph similar to a second order polynomial. Based on this fact the minimum system frequency occurs at:

$$\frac{d\Delta\omega(t)}{dt} = 0 \tag{11}$$

At this point the time of frequency decline (t_z) to reach the minimum frequency ($f_{\min}$) can be calculated as follows:

$$t_z = \frac{1}{\omega_r}\tan^{-1}\left(\frac{\omega_r T_R}{\zeta\omega_r T_R - 1}\right) \tag{12}$$

The minimum frequency in the event of a disturbance is then given as:

$$f_{\min} = f_0 - \frac{R\times\Delta P_{\max}}{D\times R + K_m}\left(1 + ae^{-\zeta\omega_n t_z}\sin\left(\omega_r t_z + \phi\right)\right) \tag{13}$$

If $P_{f_{\min}}$ is the minimum amount of load that must be shed to restore the frequency to just above the minimum threshold we can also calculate it as follows

$$P_{f_{\min}} = \frac{\frac{\left(f_{nom} - f_{\min}\right)}{60}\times\left(D\times R + K_m\right)}{R\times\left(1 + ae^{-\zeta\omega_n t_z}\sin\left(\omega_r t_z + \phi\right)\right)} \tag{14}$$

III. PROPOSED POLYNOMIAL CURVE FITTING

Polynomial curve fitting aims to construct a curve, or relationship that has the best fit to a series of a fewer data points. In general, the fitting techniques can involve either interpolation, where an exact fit to the data is required, or smoothing, in which a smooth function is constructed that approximately fits the data. The least squares method is the commonly technique used for curve fitting in reality. Generalizing from a straight line (i.e., first degree polynomial) to a k^{th} degree polynomial functions which have the following form

$$y = a_0 + a_1 x + \ldots + a_k x^k \tag{15}$$

The residual of the above function is given by

$$R^2 = \sum_{i=1}^{n}\left[y_i - \left(a_0 + a_1 x_i + \ldots + a_k x_i^k\right)\right]^2 \tag{16}$$

Partial derivatives of the residual are obtained and they lead to a series of equations. The Vandermonde matrix is then constructed and we can also obtain the matrix for a least squares fit. Finally, the coefficients of (15) can be obtained and are used to construct the desired fit. The polynomial curve fitting technique is used to come up with a curve of any order, which traces the frequency behavior to come up with a minimum value. The mathematical formulations are not expressed in detail due to space limitation but the equations are basic algebra.

By adding prediction to UFLS techniques, one does not necessarily have to know the reason behind the frequency decline in the system. The main aim is to predict the future behavior of the system frequency. If prediction indicates that the minimum system frequency to be reached will be less than the minimum system requirements restorative actions are to be implemented. Based on the predicted minimum frequency, load shedding will be carried out in real time to restore the frequency to acceptable values. Whenever a load shedding command is issued, the prediction algorithm will continue to check if the system minimum operating conditions are satisfied. Due to the inherent prediction uncertainties, before WAMS this method was even more complicated to implement. By using WAMS, the prediction error is significantly reduced to tolerable values. The main advantage with prediction schemes is that the problems which arise as a result of frequency oscillations are significantly reduced since the only input required is the frequency itself. Another advantage of adding frequency prediction to our scheme is that the minimum frequency to be reached is known beforehand and in some cases it will not be necessary to shed any load. Instead, with traditional UFLS once a threshold is violated a corresponding amount of load is shed regardless of the minimum frequency to be reached. To initiate the prediction process the previous system information is required. There should be a safe margin between the prediction and the actual frequency decline. The frequency prediction algorithm must be fast enough to determine the minimum frequency to be reached and implement load shedding before the operating conditions are violated. From the time when a disturbance is detected a period of about 2 seconds to complete the prediction is safe enough. Using PMU devices, local frequency measurements are obtained and the values sent to the control center via any global communication technique. At the control center, the center of inertia frequency for the system is obtained. Based on the center of inertia initial values of frequency prediction is done. In the proposed scheme, we are more interested in the minimum frequency the system will reach.

IV. TEST SYSTEM

In this section, the system under consideration is briefly presented. A reduced SFR model with re-heat turbines is considered in the simulations as earlier presented in Fig.1. The system is typical of the Taiwan power system under real time operating conditions. System parameters used for the frequency response model are given in table I [16]. The disturbance scenarios considered are as follows.

Scenario 1: Most critical disturbance system was operating at 25000 MW load and single contingency in the system was the trip of a major transmission line when it was delivering 1900 MW generation from a nuclear power plant.

Scenario 2: A medium disturbance when the power system was operating at 20200 MW demand, a single contingency 1100 MW occurred.

Scenario 3: A small disturbance when the power system was operating at 21500 MW demand, a single contingency (650 MW unit trip) occurred.

TABLE I
SYSTEM PARAMETERS FOR THE FREQUENCY RESPONSE MODEL

Parameter	R	H	Km	FH	TR	D
value	0.15	7	0.951	0.28	8	0.5

V. SIMULATION AND RESULTS

In this section, the simulations and results are presented in three parts. The first part shows the efficiency of using different higher order polynomials in frequency prediction. The second part deals with the use of the swing equation in disturbance estimation. Finally, the under frequency load shedding results are implemented.

A. Frequency prediction

Fig. (2-4) show the frequency prediction for scenario 1 when considering Taiwan Power System. Due to space limitations scenarios 2 and 3 are not included in the prediction results however, the technique is the same only the disturbance magnitude is different. It is important to take note of the frequency decline when doing frequency prediction as it determines how soon a threshold will be violated. In real systems whenever three data points are available frequency prediction is started. The prediction process is continued online as more samples are gathered. The higher the number of used samples the better the prediction.

Fig.2 shows the curves used to estimate the minimum frequency when a 0.076 p.u. (1900/25000MW) disturbance occurs. A data window of 0.5 sec is considered in Fig.2 and Table II. Table II further shows the data analysis of different polynomials used. In table II, the 7th order polynomial had a zero estimation error. In other words, it accurately estimated the power system minimum frequency. Third order polynomial gave the greatest error of 0.24%.

Fig.3 shows the curves used to estimate the minimum frequency for the same 0.076p.u. disturbance but with a data window of 1 sec.. Table III then shows the data analysis of different polynomials used in Fig. 3. In table III, the 7th and the 8th order polynomials had a zero estimation error. Third order polynomial again gave the greatest estimation error of 0.20%.

Fig.4 shows the curves used to estimate the minimum frequency for the same 0.076 p.u. disturbance but with a data window of 2 sec. Table IV then shows the data analysis of different polynomials used in Fig.4. In table IV, the 7th, 8th and 10th order polynomials had a zero estimation error. Third order polynomial again gave the greatest estimation error of 0.15% but this time much lower than the two previous scenarios.

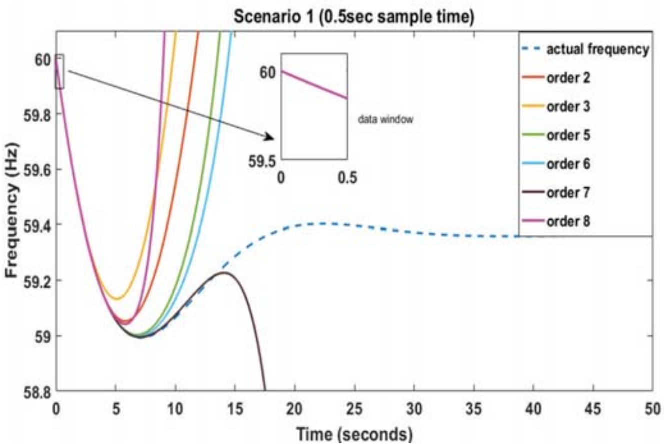

Fig.2 curve fitting for scenario 1 with data window of 0.5sec

TABLE II
COMPARISON BETWEEN THE ACTUAL MINIMUM AND THE PREDICTED MINIMUM FREQUENCY FOR SCENARIO 1 WITH DATA WINDOW OF 0.5SEC

Order	ΔP (p.u.)	Actual f_{min} (Hz)	Estimated f_{min} (Hz)	Error (%)
2	0.076	58.99	59.05	0.10
3	0.076	58.99	59.13	0.24
5	0.076	58.99	59.00	0.02
6	0.076	58.99	59.00	0.02
7	0.076	58.99	58.99	0.00
8	0.076	58.99	59.04	0.08
10	0.076	58.99	-	-

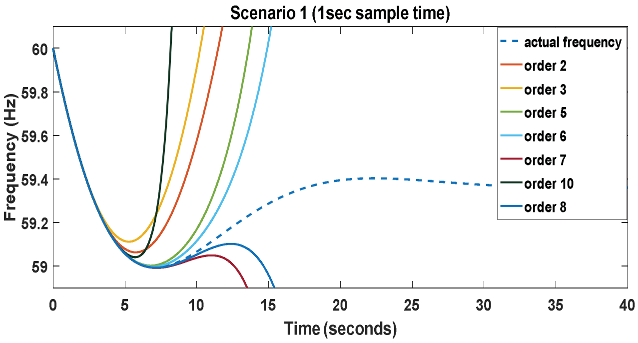

Fig.3 curve fitting for scenario 1 with data window of 1sec

TABLE III
COMPARISON BETWEEN THE ACTUAL MINIMUM AND THE PREDICTED MINIMUM FREQUENCY FOR SCENARIO 1 WITH DATA WINDOW OF 1SEC

Order	ΔP (p.u.)	Actual f_{min} (Hz)	Estimated f_{min} (Hz)	Error (%)
2	0.076	58.99	59.06	0.12
3	0.076	58.99	59.11	0.20
5	0.076	58.99	59.00	0.02
6	0.076	58.99	59.00	0.02
7	0.076	58.99	58.99	0.00
8	0.076	58.99	58.99	0.00
10	0.076	58.99	59.04	0.08

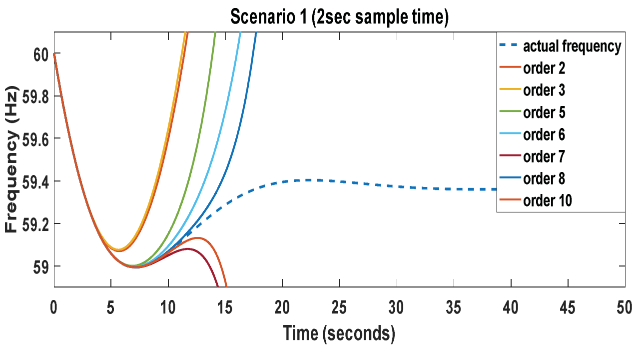

Fig.4 curve fitting for scenario 1 with data window of 2sec

TABLE IV
COMPARISON BETWEEN THE ACTUAL MINIMUM AND THE PREDICTED MINIMUM FREQUENCY FOR SCENARIO 1 WITH DATA WINDOW OF 2SEC

Order	ΔP (p.u)	Actual f_{min} (Hz)	Estimated f_{min} (Hz)	Error (%)
2	0.076	58.99	59.07	0.14
3	0.076	58.99	59.08	0.15
5	0.076	58.99	59.00	0.02
6	0.076	58.99	59.00	0.02
7	0.076	58.99	58.99	0.00
8	0.076	58.99	58.99	0.00
10	0.076	58.99	58.99	0.00

The simulated scenarios show that the lower order polynomials from the 2nd order to the 10th order except for the 4th and 9th order polynomials can be used to estimate the minimum frequency the power system will reach in the event of a disturbance. The 7th order polynomial gave the best results in all disturbance scenarios. 5th, 6th and 8th order polynomials also had very negligible errors.

The minimum frequency can also be calculate using equation (13) but the curve fitting technique gives a better estimation especially when using the 5^{th}, 6^{th}, and 7^{th} order polynomial. Table V shows the estimation results for the three scenarios.

TABLE V
ESTIMATED MINIMUM FREQUENCY USING EQUATION (13)

Scenario	ΔP (p.u)	Actual f_{min} (Hz)	Estimated f_{min} (Hz)	% error
1	0.076	58.99	58.9599	0.05
2	0.054	59.28	59.2547	0.04
3	0.030	59.60	59.5862	0.02

B. Disturbance estimation

Taiwan Power system is also considered, as it is more close to the real power system. Three disturbances, which were earlier presented are used here. Equation (10) is used to estimate the magnitude of the disturbances. Fig. 5 shows the results of the simulated disturbances. The bigger the disturbance the less accurate the estimation. In table VI, scenario 3 had zero estimation error since the disturbance was also very small. Scenarios 1 and 2 had estimation errors of 2.63% and 1.85% respectively, depending on the magnitude of the disturbance.

TABLE VI
COMPARISONS BETWEEN ACTUAL AND ESTIMATED DISTURBANCE USING SWING EQUATION (TAIWAN POWER SYSTEM)

Scenario	Actual Disturbance (p.u)	Estimated Disturbance (pu)	% error
1	0.076	0.074	2.63
2	0.054	0.053	1.85
3	0.030	0.030	0

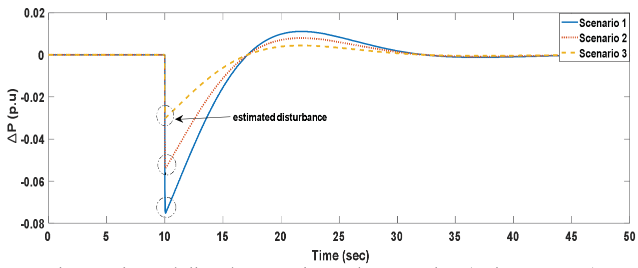

Fig.5 Estimated disturbance using swing equation (Taiwan Power)

C. UFLS implementation

In these simulations, only two disturbance scenarios (scenario 1 and 2) are considered. Scenario 3 is not included in the shedding process because the frequency fell to a minimum of 59.60Hz and it returned a settled at a steady state of 59.74Hz both values above the limits. The prediction using the 7^{th} order polynomial accurately predicted the minimum frequency.

In scenario 1 a (1900/25000) p.u. disturbance occurred. Without UFLS the frequency fell to a minimum of 58.99Hz and then returned and settled at a steady state of 59.36Hz. Both the minimum and the steady state frequency were below the stipulated thresholds. To restore the frequency to above 59.2Hz, using equation (14) 439MW of load was shed as shown in Fig. 6 by UFLS1. In addition to the 439 MW, additional 566 MW of the load were shed to restore the steady state frequency to 59.7 Hz as shown in Fig.6 by UFLS2. Load shedding in both cases is carried out at 59.7Hz.

In scenario 2 a (1100/20200) p.u, disturbance occurred. Without UFLS, the frequency reached a minimum of 59.28 Hz and then returned and settled at a steady state of 59.54 Hz. The minimum frequency was above the set threshold of 59.2 Hz and the frequency prediction also confirmed this value. However, the steady state frequency was below the stipulated threshold of 59.7 Hz. To restore the frequency to above 59.7 Hz, 400 MW of load was shed. Fig.7 shows the frequency before and after restoration.

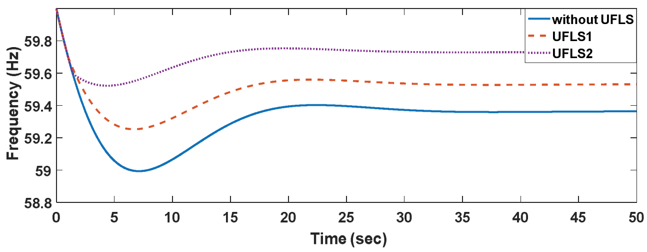

Fig.6 Scenario 1 before and after load shedding

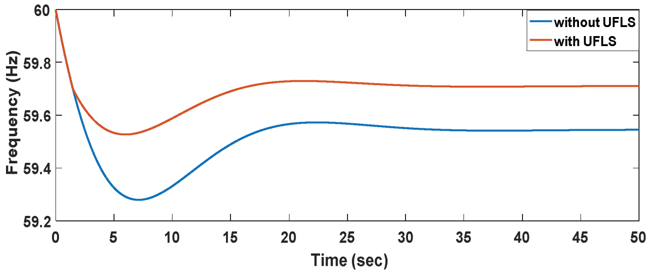

Fig.7 Scenario 1 before and after load shedding

VI. Conclusions

More intelligent techniques are required to implement under frequency load shedding. In order to achieve this, decision parameters must be clearly defined. In this paper, we showed that including the predicted minimum frequency in the load shedding decision is an important step. With the minimum frequency known sometimes, load shedding can be delayed without effect on the system. The swing equation was also shown to be an important tool in disturbance estimation, though errors are present. In future, algorithms can be developed based on the predicted minimum frequency only, which accurately determine the load to be shed. Since modern systems consist of renewables based generators with very low inertia, that is also varying, using the frequency only in considering the lost generation can significantly improve under frequency load shedding techniques.

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