Cascading Outage Simulation Based on Dynamic Fast Decoupled Load Flow Model

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Abstract—Frequency is an important indicator of balance between active power generation and load. Active power-frequency dynamics analysis is an important task of power system operation. This paper proposes a novel cascading outage simulation model based on dynamic Fast Decoupled Load Flow (FDLF) considering frequency deviation. A distributed slack bus model is considered in such a way that all of the dispatched generating units share the power imbalance according to their power frequency characteristics. It can reflect the frequency dynamics based on steady-state load flow calculation in the simulation of cascading outage. Also the frequency characteristics of the loads in response to the power imbalance are considered. A novel AC-OPF model introducing the system frequency deviation as a new state variable is proposed to search for a new operating condition when dynamic FDLF is not convergent. The case studies on a two-area, 4-machine power system and a Northeastern Power Coordinating Council (NPCC) 48-machine, 140-bus power system validate the proposed model. Frequency deviation obtained from dynamic FDLF model matches very well with that at the steady-state of time-domain simulation. The statistics of cascading outage samples indicates the frequency insecurity has great impacts on the severity of the cascading outage.

Index Terms—Cascading outage, dynamic FDLF model, frequency dynamic, novel AC-OPF, NPCC

I. INTRODUCTION

Cascading outages propagating in power grids may lead to catastrophic blackouts, such as that happened in North America on August 14th, 2003 [2], in Brazil on November 10th, 2009 [3], and in India on July 30th and 31st, 2012 [4]. The simulation, analysis, and mitigation of cascading outages pose a great challenge [5]–[9]. To simulate cascading outages, several models have been proposed, such as the CASCADE model [10]–[13], branching process model [14]–[18], OPA model [19]–[21], improved OPA model [22], AC OPA model [23], OPA model with slow process [24], Manchester model [25], [26], and hidden failure model [27], [28].

However, for the above models for simulation of cascading outage, their main focus is system collapse caused by voltage without considering the frequency insecurity. Frequency plays important role to indicate the balance between active power generation and load. Active power-frequency dynamics analysis is an important task of power system operators. For small-scale power systems, major disturbances such as large unit tripping will cause enormous active power imbalance, and lead to large frequency deviation, even system collapse. Frequency stability is a key concern of these power systems. For interconnected power systems, frequency is supposed to be stable with reciprocal reserve of each subsystem. However, greater inter-area power transfer and higher requirement for efficiency make power system operated under higher stress and strain. The risk of breaching frequency security or stability is increasing. Some large frequency incidents from the 1970s to the 1990s are reported in [29]. Some reports show that unit tripping due to turbine under frequency protection and improper setting of Under Frequency Load Shedding (UFLS) schemes play important roles in system collapse [30–32]. Therefore it is valuable to consider frequency security in the simulation of cascading outage.

Load flow calculation is the foundation of steady-state cascading outage analysis. In the conventional load flow model, the static power-frequency characteristic of generators and load is neglected. All generators output except the swing generator is set to be fixed value, and the unbalancing power is all allocated to the swing generator. The conventional load flow model utilizes this fictitious concept of slack bus. The concept of slack bus is somewhat mathematical and has reduced relation to the physical system. The real situation is, after a power disturbance happens, generators that have reserve capacity are all able to adjust the active and reactive power they input to system according to their own modulation characteristics [33]. Likewise, the load of system will also change the power they consume accordingly. Since the dynamic power flow calculation method [33–34] considers the frequency modulation effects of all generators and loads after power disturbance, it is more reasonable and therefore should be given attention. Reference [33–34] proposed dynamic load flow model and add system frequency as a new state variable for steady-state load flow model. It provides new viewpoint to consider frequency security in the simulation of cascading outages.

This paper proposes a novel model to simulate cascading outage based on dynamic FDLF model. It introduces frequency, an important indicator of system state into the simulation of cascading outage to consider frequency security in the propagation of cascading outage. The frequency deviation calculated through dynamic FDLF model has a high accuracy when compared to the time-domain simulation. The
novel simulation model based on dynamic FDLF is more practical comparing to other models. It indicates the frequency dynamics and power flow transfer are closely coupled with each other to affect the propagation of cascading process. Also, a novel AC-OPF model considering frequency deviation is proposed to search for a new operating condition when dynamic FDLF model is not convergent. When the frequency deviation is larger than the pre-determined threshold or system splitting occurs, under frequency load shedding (UFLS) schemes will apply load shedding to the load nodes. Frequency insecurity plays important role on the severity of cascading outage.

The rest of this paper is organized as follows. Section II gives a specific introduction of the procedure for simulation of cascading outage based on dynamic FDLF model. Section III introduces dynamic FDLF model considering frequency deviation. Section IV gives the introduction of a novel AC-OPF model. Section V introduces Under Frequency Load Shedding (UFLS) scheme. Section VI gives the dynamic models of time-domain simulation as the benchmark. Section VII demonstrates the proposed cascading outage simulation model on a two-area, 4-machine power system and an NPCC 48-machine, 140-bus power system. Section VIII draws conclusions.

II. SIMULATION PROCEDURE OF CASCADING OUTAGE BASED ON DYNAMIC FDLF MODEL

The whole procedure for simulation of cascading outage with dynamic FDLF model is as follow:

1. **Start**
2. Parameters and network initialization
3. Initial outages
4. Dynamic FDLF calculation considering frequency deviation
5. Overloaded lines?
   - Yes: Open them, go to step 4
   - No: Go to step 6
6. Frequency deviation > threshold?
   - Yes: Apply UFLS scheme to the load nodes, then go to step 3
   - No: Go to step 7
7. Convergent?
   - Yes: Go to step 4
   - No: Go to step 8
8. End

Fig. 3. Simulation procedure of cascading outage based on dynamic FDLF model and novel AC-OPF model

- **Step 1:** Parameters and power network initialization.
- **Step 2:** Set up initial line outages.
- **Step 3:** Dynamic FDLF calculation, if the calculation is convergent, go to step 4, otherwise go to step 7.
- **Step 4:** If frequency deviation is larger than the pre-determined threshold, go to step 5, otherwise go to step 6.
- **Step 5:** Apply UFLS scheme to the load nodes, then go to step 3.
- **Step 6:** If there are overloaded lines, open them, go to step 3, otherwise go to step 8.
- **Step 7:** Apply the novel AC-OPF model considering frequency deviation to search for a new operating point and calculate the frequency deviation. If the result is convergent, go to step 4, otherwise go to step 8.
- **Step 8:** The end, record the path of cascading outage, frequency deviation and amount of load shedding, respectively.

From the above description, the core parts remarked by the red boxes are the dynamic FDLF model, the novel AC-OPF model considering frequency deviation and UFLS scheme. They will be introduced in Section III, Section IV, and Section V, respectively.

III. DYNAMIC FDLF MODEL CONSIDERING FREQUENCY DEVIATION

A. Power-Frequency Characteristics of Generator and Load

When the power system is operating at steady state, the active load will vary according to system frequency. Given that the ratio of load which is proportional to frequency’s high order power is very low, power frequency characteristic of load at steady state can be described by Fig. 1.

\[ P_D = P_{D0} + K_D \Delta f \]  
\[ \Delta f = f - f_n \]  

where \( P_{D0} \) is the active load at the nominal frequency value. \( K_D \) is the static power-frequency characteristic coefficient (pu) of load. \( \Delta f \) is the frequency deviation when compared to nominal value (pu). \( f_n \) is the nominal frequency value.

Frequency, the added unknown variable, is primarily impacted by P but rarely by Q, for the reason that frequency is determined by generator speed that affected by P mostly. In consideration of these physical properties, in this paper, only active load is considered affected by the frequency deviation which is described by Fig. 2.

\[ P_G = P_{G0} - K_G \Delta f \]

where \( P_{G0} \) is the active generator output at the nominal frequency value. \( K_G \) is the static power-frequency characteristic coefficient (pu) of generator.

![Fig. 1. Static power-frequency characteristic of load](image-url)
Fig. 2. Static power-frequency characteristic of generator

B. Dynamic FDLF Model Considering Frequency Deviation

By considering the frequency deviation of system, bus injection functions can be modified as [33-34]:

\[
\Delta P = P_{G0} - P_{D0} - (K_G + K_D)\Delta f
\]

\[
\Delta Q = Q_{G0} - Q_{D0}
\]

Assuming the \( n \)-th bus to be the reference bus, the bus injection functions can be written as:

\[
\begin{bmatrix}
\Delta P \\
\Delta P_n \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
H & F & \Delta \theta \\
L & & \Delta (\Delta f)
\end{bmatrix}
\begin{bmatrix}
\Delta \theta \\
\Delta (\Delta f)
\end{bmatrix}
\]

where \( H \) and \( L \) are the sub-matrices of Jacobi matrix in conventional FDLF model.

\[
\begin{bmatrix}
H \\
H_n
\end{bmatrix} =
\begin{bmatrix}
V_1^2B_1 & \cdots & V_1B_{i(n-1)}V_{n-1} \\
\vdots & \ddots & \vdots \\
V_{n-1}B_{i(n-1)} & \cdots & V_{n-1}B_{i(n-1)}V_{n-1}
\end{bmatrix}
\]

Then (6) can be decoupled into two iterations, one iteration of \( P - \theta - f \) followed by one iteration of \( Q - V \).

IV. A Novel AC-OPF Model Considering Frequency Deviation

With the propagation of line outages, dynamic FDLF model may not be convergent due to severe outages or system separation. Then AC-OPF will be triggered to search for a feasible operating point. Different from the conventional AC-OPF model, the frequency deviation needs to be considered in this AC-OPF model. Therefore a novel AC-OPF model considering frequency deviation is formulated to search for a new operating condition. The objective is to minimize the total amount of load shedding.

\[
\min \sum P_D
\]

subject to:

\[
\Delta P_i = P_{G_i} - P_{D_i} - (K_{G_i} + K_{D_i})\Delta f
\]

\[
\Delta Q_i = Q_{G_i} - Q_{D_i}
\]

\[
\begin{bmatrix}
\Delta P_i \\
\Delta P_n \\
\Delta Q_i
\end{bmatrix} =
\begin{bmatrix}
B_1 & \cdots & B_{i(n-1)} & F_1 \\
\vdots & \ddots & \vdots & \vdots \\
B_{i(n-1)} & \cdots & B_{i(n-1)} & F_{n-1}
\end{bmatrix}
\begin{bmatrix}
\Delta \theta \\
\Delta (\Delta f)
\end{bmatrix}
\]

\[
\begin{bmatrix}
\Delta \theta \\
\Delta (\Delta f)
\end{bmatrix} \times
\begin{bmatrix}
\Delta \theta V_1 \\
\Delta \theta V_{n-1}
\end{bmatrix} =
\begin{bmatrix}
\Delta \theta V_1 \\
\Delta \theta V_{n-1}
\end{bmatrix}
\]

\[
\Delta Q_i = B_{i(n)} \Delta V_i
\]

where \( n \) is the number of nodes in the system and \( m \) is the number of PQ nodes.
where $P_{Gi}$ and $Q_{Gi}$ are the active and reactive power generation of $i$-th node. $P_{Di}$ and $Q_{Di}$ denote the active and reactive load of $i$-th node. $\Delta P_i$ and $\Delta Q_i$ are the active and reactive power injection. $V_i$ and $\theta_i$ are the voltage magnitude and phase angle of $i$-th bus. $\theta_{ref}$ are the phase angle of the reference bus. $P_g$ and $Q_g$ indicate the active and reactive power flow on line $i-j$. $K_{Gi}$ and $K_{Di}$ are the static power-frequency characteristics of generator and load of $i$-th node. $\Delta f$ is the frequency deviation of the system.

The objective function (11) can vary depends on different optimization goals. In this paper, the objective function is chosen as to minimize the amount of load shedding.

Constraint (12) and (13) enforce the AC power flow constraints. Constraint (14)-(21) restrict real power generation, reactive power generation, voltage magnitude, phase angle, active load, reactive load, frequency deviation and line flow to be between upper and lower bounds.

In some cases, the feasible point cannot be obtained and AC-OPF is not convergent. Then constraint (21) will be released in order to search for a feasible point by violating the constraint of line flow limit. A new kind of variables is introduced into the model. Constraint (21) will be modified to (23)-(24), AC-OPF model will be updated as:

$$\min -\sum P_D + \sum w_j a_j$$

s.t.

$$12) - 20)$$

$$P_j^2 + Q_j^2 + a_j \leq S_{j, max}^2$$

$$a_j \geq 0$$

Where $a_j$ is the compensate factor for the line flow of $i-j$, $w_j$ is the punishment factor of line $i-j$. The above model will be applied if the novel AC-OPF model (11)-(21) is not convergent.

V. UNDER FREQUENCY LOAD SHEDDING

Under Frequency Load shedding (UFLS) is one of the last automatic defenses to prevent system collapse. The purpose of UFLS is to rebalance generation and load when a significant drop of system frequency occurs. Obviously, operations of UFLS will cause load loss directly. Thus, its great impacts on the severity of cascading failure show the necessity to consider UFLS in this paper. The amount of load shedding can be estimated after dynamic FDLF or novel AC-OPF model calculation

$$\Delta P_{UFLS, cal} = (\sum K_G + \sum K_D) \Delta f$$

where $\Delta P_{UFLS, cal}$ is the calculated amount of load shedding (active power imbalance) in order to recover the system frequency to the nominal value.

According to NERC requirement [2], UFLS installation is designed to shed at least 25-30% of the load in steps within each reliability coordinator region if frequency reaches a low frequency. UFLS triggers vary by regional reliability council—New York and all of the Northeast Power Coordinating Council, plus the Mid-Atlantic Area Council use 59.3 Hz as the first step for UFLS. In this paper, the amount of load shedding to be shed is calculated by (26)

$$\Delta P_{UFLS, final} = \min\{\Delta P_{UFLS, cal}, \Delta P_{UFLS, NERC}\}$$

(26)

$$\Delta P_{UFLS, NERC} = 0.25\sum_{i=1}^{m} P_{Di}$$

(27)

$$\Delta P_{Di, UFLS} = \sum_{i=1}^{m} P_{Di} \Delta P_{UFLS, final}$$

(28)

where $\Delta P_{UFLS, final}$ is the amount of load to be shed. $\Delta P_{Di, UFLS}$ is the amount of load shedding for node $i$. $P_{Di}$ is the amount of load of node $i$ before applying UFLS. $\Delta P_{UFLS, NERC}$ is the amount of load shedding based on NERC requirement.

VI. DYNAMIC MODELS WITH TIME-DOMAIN SIMULATION

In order to verify the calculation of frequency deviation, time-domain simulation is used as the benchmark for the calculation of frequency deviation.

Round rotor generator with quadratic saturation which is donated as "GENROU" in PSS/E format is a standard generator model, widely used in practical dynamic analysis of power systems. It is used in this paper for time-domain simulation.

For turbin-governor model, lumped generator turbine governor is a simple model representing governor action and the reheater time constant effect for a steam turbine. The typical parameters of the turbine governor are shown in Table I.

| Parameter | Typical value |
|-----------|---------------|
| Governor time constant $T_g$ | 0.2s |
| Steam chest time constant $T_c$ | 0.3s |
| Reheat time constant $T_r$ | 10s |
| High-pressure turbine fraction $F_p$ | 0.3 |
| Mechanical power gain factor $K_m$ | 0.95--1 |
| Inertia constant $H$ | 3--6s |
| Governor speed regulation $R$ | 0.05 p.u. |
| Load damping coefficient $D$ | 1 p.u. |

IEEE load model which is donated as “IEEELBL” in PSS/E format is used in this paper, the constant MVA load is replaced by a new load component defined by:

$$P_D = P_D (a_1 V'_{n1} + a_2 V'_{n2} + a_3 V'_{n3})(1 + a_4 \Delta f)$$

(29)

$$Q_D = Q_D (a_1 V'_{n4} + a_2 V'_{n5} + a_3 V'_{n6})(1 + a_4 \Delta f)$$

(30)

where $P_D$ and $Q_D$ are active and reactive components of load when bus voltage is $V$. $P_D$ and $Q_D$ are the values of respective variables at rated operating condition. $n_1$ to $n_6$ are exponents of each load component. $a_1$ to $a_4$ are proportion coefficients of each component satisfying
\[ a_1 + a_2 + a_3 = 1 \text{ and } a_4 + a_5 + a_6 = 1 \]. \( a_7 \) and \( a_8 \) are coefficients of frequency dependency. In this paper, \( a_1, a_4, \) and \( a_7 \) are all set up to be 1, and the rest of coefficients are set up as 0.

VII. CASE STUDIES

A. Parameter Preparation

A two-area, 4-machine power system [36] and an NPCC 140-bus power system [37] are used for the case studies.

Line flow limits are critical parameters in the simulation of cascading outage. Here N-1 criterion is applied to the system and there is no overloaded line after N-1 contingency. Therefore the initial outage for the simulation will select from at least N-2 contingencies.

For the power-frequency characteristics of generator and load, \( K_G \) and \( K_D \) are set up as 0.05 p.u and 1 p.u. The threshold to apply UFLS is 59.3 Hz. UFLS will be applied to recover the frequency of system if the frequency deviation is larger than 0.7 Hz after dynamic FDLF calculation.

B. Comparison for the Frequency between Proposed Model and Time-domain Simulation on a Two-area Power System

![Fig. 5. Schematic diagram of Kundur's Two-Area System](image)

A two-area, 4-machine power system can be seen from Fig.5. They are only two load buses, i.e. bus 7 and bus 9. Different scenarios of load increment and load shed are tested on this two-area, 4-machine power system.

Scenario 1: Shed the load on bus 7 for different percentages.
Scenario 2: Shed the load on both bus 7 and bus 9 for different percentages.
Scenario 3: Increase the load on both bus 7 and bus 9 for different percentages.

![Fig. 6. Frequency variations for load shed on bus 7](image)

For scenario 1 and 2, the system frequency will increase since some amount of load is shed. We can see the two curves of frequency variation representing time-domain and dynamic FDLF model are almost overlapped.

For scenario 3, the system frequency will decrease since there is load increment. The two curves of frequency variation representing time-domain and dynamic FDLF model are almost overlapped.

The above scenarios can verify the correctness of dynamic FDLF model to reflect the steady-state frequency deviation accurately.

C. Comparison for the Frequency between Dynamic FDLF Model and Time-domain Simulation on an NPCC 140-bus Power System

![Fig. 9. Schematic diagram of NPCC power system](image)
The schematic diagram of NPCC power system is shown by Fig.9. In order to have a better comparison between proposed model and time-domain simulation, the set of open lines which will trigger large real power imbalance are set up. Two scenarios are selected to illustrate the validation of proposed model from the perspective of frequency. In time-domain simulation, line outages in each stage are set up to be the same with dynamic FDLF model artificially. The time interval between different stages is set up as 100s since it is enough for the system to reach a new steady-state.

Scenario 1: The path of cascading outage is stage 1 [130-131 131-133 131-135 131-139], stage 2 [124-128 125-128 126-128 127-128 128-130]. Stage 0 is the normal condition before contingency.

| Scenario 2: The path of cascade outage is stage 1[85-86], stage 2[78-79], stage 3[131-133 132-133 133-135]. |

| Model type | Stage 0 | Stage 1 | Stage 2 |
|------------|---------|---------|---------|
| Proposed model | 60 | [60.127 0] | [60.147 0] |
| TSAT | 60 | [60.147 0] | [60.268 0] |

Note: For stage 1 and stage 2, the system is splitting into two islands.

TABLE III. Frequency Comparison between Proposed Model and Time-Domain Simulation with the Propagation of Cascading Outage (Scenario 2)

| Model type | Frequency (Hz) |
|------------|----------------|
| Proposed model | 60 [59.779 60] [59.622 60] [59.498 60] |
| TSAT | 60 [59.802 60] [59.649 60] [59.532 60] |

Note: For stage 1, stage 2 and stage 3, the system is splitting into two islands, three islands and four islands.

From Tab. II and Tab. III, we can find that the system frequency between proposed model and time-domain simulation during the propagation of cascading outages are close enough, which validates the proposed cascading outage simulation model based on dynamic FDLF model. These two scenarios are corresponding to over frequency and under frequency situation, respectively.

**D. Comparison for the Distributions of load shedding between Proposed Cascading Outage Simulation Model and Conventional Model on an NPCC 140-bus Power System**

5000 samples of cascading outages are simulated with dynamic FDLF model to be compared with that from conventional FDLF model. The procedure for simulation of cascading outages with conventional FDLF model can be seen from Fig.10. The main difference with proposed model is that it uses the conventional FDLF model and AC-OPF as the core part and ignores UFLS scheme since it does not consider frequency deviation in the simulation.

**VIII. CONCLUSION**

Dynamic FDLF model is proposed to simulate cascading outage in power systems. It introduces new state variable to monitor the propagation of cascading outage, which suggests the frequency insecurity to the severity of cascading outage. Dynamic FDLF model is more practical for the operation of power systems since it introduces a concept of distributed slack bus that all of the dispatched generating units can compensate the power imbalance according to their power frequency characteristics. It can reflect the frequency dynamics based on steady-state load flow calculation in the simulation of cascading outage. Also the frequency characteristics of the loads in response to the power imbalance are considered. A novel AC-OPF model considering system frequency deviation is also proposed to search for a new
operating point when the dynamic FDLF is not convergent. The case studies on a two-area, 4-machine power system and an NPCC 140-bus power system validate the proposed model and frequency deviation at the steady-state is validated with the time-domain simulation. The statistics of the probability distribution of total amount of load shedding of cascading outage samples indicate that the frequency insecurity has great impacts on the severity of the cascading outage which cannot be ignored in the risk analysis of cascading outages.

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