A Multi-timescale Quasi-Dynamic Model for Simulation of Cascading Outages

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Abstract—**Many blackouts in electric power grids throughout the world are caused by cascading outages, which often involve complex processes in various timescales. The multi-timescale nature of cascading outages makes conventional quasi-static simulation methods inaccurate in characterizing actual evolution of outages. This paper proposes a multi-timescale cascading outage model using a quasi-dynamic simulation method. The model establishes a framework for simulating interactions among dynamics in quite different timescales. It realizes simulation of cascading outages with representation of time evolution, so it overcomes ambiguity of time in conventional cascading outage models and hence has better practicality. Moreover, the model considers dynamics, e.g. load variation and generator excitation protection which affect voltage and reactive power profiles. Also, an improved re-dispatch model based on sensitivity is proposed. These improvements facilitate better simulation for a realistic power system. Also, dynamic simulation can be flexibly incorporated into the simulation of short-term processes in this model as needed. Case studies with the proposed multi-timescale model on the IEEE 30-bus system discuss the role of generator protection in cascading outage evolution, and analyze stage characteristics in outages. The multi-timescale model is also demonstrated on a reduced 410-bus US-Canada northeast power grid. Moreover, impacts from dispatchers' involvements are analyzed.**

Index Terms— **cascading outage, time evolution, reactive power, multi-timescale, quasi-dynamic**

I. INTRODUCTION

CASCADING outages in electric power grids are dependent outage processes triggered by one or a set of initial faults.

Cascading outages gradually impact and deteriorate transmission systems and may cause large blackouts as well as massive losses [1]-[3]. Since in recent years power system operation is facing more uncertainty and stress, the simulation, analysis, prediction and mitigation of cascading outages have attracted more interests from both academia and industry [4].

Some models for simulation of cascading outages have been proposed [5] [6], such as CASCADE model [7], hi-level probabilistic models [8] [9], OPA model [10] and its extension [11] based on DC power flow. To further improve accuracy in the characterization of voltage and reactive power profiles, AC power flow based models such as Manchester model and AC-OPA model are proposed [12][13]. These models in essence use quasi-static simulation, which describe cascading outages as serial discrete transitions, neglecting distinct timescales of the dynamics.

Cascading outages are complex processes involving various dynamics in quite different timescales. The relay protection [14] and emergency control (e.g. load shedding [15]) usually take tens of milliseconds to seconds, while the load variation is much slower, in timescale of hours. Also, there are processes with timescales in between, such as overhead line outages caused by overheat and tree contact [16], and generator outages caused by over-excitation or under-excitation [2]. These slow outage processes are in the timescales of minute to hour depending on the extent of stress and many other random factors. Also, transmission loading relief (TLR) and re-dispatch [17] undertaken by operators against overloading generally last for 10-30 minutes or even longer. The conventional cascading outage simulation methods cannot reflect the multi-timescale characteristics of cascading outage process. Only with a proper methodology treating different timescales and representing time in cascading outage, can the model reasonably simulate interactions among related dynamics and obtain practical results with time information. Also, the representation of time facilitates practical application of cascading outage simulation, e.g. to assess and optimize the time performance with control actions. Therefore it is necessary to establish a new model to realize multi-timescale cascading outage simulation.

Papers [18] and [19] divide a cascading outage process sequentially into the slow cascade stage, fast cascade stage and restoration stage. Simulation of the slow cascade stage, including outages of lines and transformers are proposed, and fast cascades are simulated using dynamic simulation. The modeling of climate factors is also very useful aspect. However, from the perspective of timescales, the dynamics categorized into slow cascades such as load variation and tree-caused line outages still has very different timescales. Therefore a more generalized simulation methodology dealing with the nature of multi-timescales should be proposed. And simulation of processes related to reactive power can be improved. In the research field of earthquake studies, quasi-dynamic methods are proposed to overcome the drawbacks of quasi-static methods [20]. The basic idea of quasi-dynamic methods is to consider distinct timescales in nature throughout the whole process by simulating shorter timescale processes between neighboring longer timescale transitions. Such methods not

only improve the fidelity of simulation on the overall process compared with quasi-static methods but also avoid the time-consuming full-dynamic simulation in which differential equations need to be solved [21][22]. This paper aims to establish a multi-timescale cascading outage model using the quasi-dynamic methodology. The proposed model categorizes dynamics by timescales and explicitly represents time evolution in simulation. Thus, the model is expected to provide more reasonable and practical results on cascading outage simulation and risk assessment.

Moreover, the modeling of related dynamics in cascading outages can be improved. The system loading level is directly related to voltage stability. The early stage of a cascading process may last for hours and thus load variation has significant influence on outage development. Generators are vital sources of reactive power, and their reactive power outputs are limited by excitation system capabilities [23]. Over- or under-excitation may occur during cascading outages, causing overheating or loss of field [24] and leading to generator trips [2]. Generator outage is also a key factor contributing to cascading outages. These abovementioned dynamics have significant influence on voltage profile and cascading outages, so they should be considered in cascading outage simulation. Moreover, re-dispatch is commonly performed to relieve branch flow stress by adjusting generators or shedding loads, which is modeled as OPF formulation in existing cascading outage models[10][13]. However actual re-dispatch operations often use sensitivity-based approaches [25], so the modeling of re-dispatch also should be improved accordingly to match real system behavior. It should be noted that since all these dynamics are in quite different timescales, only with the multi-timescale simulation method can they be reasonably modeled and simulated.

Simulation on transient dynamics with each failure or transition during a cascading process is valuable for uncovering how outages propagate. However, pure dynamic simulation for the entire cascading process lasting for tens of minutes is not practical for any utility-scale power system models because of the high computational burdens and the difficulties in dealing with uncertainties in system operations. The dynamic models currently used by electricity utilities are mainly developed for transient stability simulation for a short post-contingency period (typically 10-30s), and do not guarantee the accuracy for a mid-term or long-term simulation period of, e.g., tens of minutes, which is usually the minimum requirement for simulating cascading outages. While in risk assessment of cascading outages, since large numbers of cascading outages need to be sampled, applying dynamic simulation to every sample requires huge computational resources and is not practical, especially in situations requiring high efficiency. And techniques reducing dynamic simulation invocations still face many problems [19]. Moreover, some factors playing important roles in the propagation of cascading failures, e.g. human factors and failures in communication, are not modeled in dynamic simulation, but can be studied in a quasi-dynamic simulation environment. Thus, power-flow based steady-state or quasi-dynamic models still play important roles in the simulation and analysis of a cascading process. It is true that in the fast cascade stage, nonlinear transients are often prominent.

Yet in many cases the transients fade away and system reaches steady state again, so power flow is sufficient in representation of the cascading process at the high level. Also, literature [26] compares methods based on dynamic simulation and DC power flow, and the results show that for cascading outages triggered by branch outages, the DC power-flow based model remains effective for a long period in the whole process of cascades. Therefore power flow is a reasonable approximation in the simulation of fast cascades. While in applications requiring higher accuracy, the quasi-dynamic framework proposed in this paper is also compatible to dynamic simulations, bridging power flow to transients to enhance accuracy.

Besides the above focuses addressed in this paper, there are still many problems in the scope of cascading outage study that are definitely related to this paper and are of great significance. For example, the selection of initial outage combinations or sequences is a critical problem closely related to the simulation and risk assessment of cascading outages. Since the set of combinations or permutations of multiple initial outages is extremely large, an efficient selection of probable contingencies as the input of cascading outage simulation should be addressed for the practicality in application. Various methods are proposed to enhance the efficiency in contingency screening, including index-based contingency screening methods [27], selection of high-risk N-k contingency events caused by protection failures [28], efficient selection of N-k contingency combinations that leads to system malignancy [29], contingency probability sorting methods [30], etc. Moreover, communication and control play significant roles in power system operations. Failures or ineffective configurations of control and communication as well as human errors have been confirmed as major causes or contributing factors in historical blackouts. Modeling human behaviors, controllers, communication networks and their reliabilities is essential and is also difficult due to their highly discrete, fuzzy and uncertain characteristics. Some works have addressed these factors in security analysis and vulnerability assessment. Paper [31] uses Petri-Net to identify the vulnerable portion in communication network. The performance and dependability of dispatchers as human in a general system is modeled in [32]. Paper [33] discusses the impacts from dispatchers' risk preferences. In a word, besides the main focus of this paper, much work is still needed in the overall cascading outage study, including the abovementioned contingency screening and modeling of human, control and communication system, which also constitute our future work.

As an outline, comparing with existing cascading outage models, the proposed model has these advantages:

- *Multi-timescale quasi-dynamic simulation is realized*. The quasi-dynamic approach enables approximate simulation of various dynamics in accordance with their actual timescales, thus accuracy and practicality is improved.
- *Representation of time is added*. Quasi-dynamic method provides approximate time evolution in cascading outage process. With the representation of time, the model potentially can be used in risk assessment and evaluation of mitigations against cascading outages in real systems.
- *More accurate modeling on dynamics related to voltage and reactive power*. Processes such as load variations, generator

outages have significant impacts on the voltage profile and hence on cascading outages as well.

- *Improved re-dispatch simulation.* The re-dispatch operation is modeled as a series of sensitivity-based operations instead of conventional OPF models. The former is closer to actual dispatcher behaviors.
- *Compatible to dynamic simulation in short timescale processes.* On the basis of multi-timescale quasi-dynamic approach for cascading outage simulation that enhances accuracy and practicality, this model supports simulation of short-term processes with dynamic simulation to further enhance accuracy.

The proposed model can be utilized in offline risk assessment, evaluation and optimization of planning, system backup and dispatch actions, etc. [34]. This model also has potential in online monitoring and assessment, since the model is generally based on power flow and is able to achieve satisfactory efficiency. In different application situations, the details such as initial outage time sampling, the simulation method in short-term processes, etc. may vary.

The rest of the paper is organized as follows: Section II presents the quasi-dynamic modeling of cascading outages, including categorization of dynamics by timescales and modeling of interactions between those dynamics, which is the methodological basis for the complete model. In Section III, the complete multi-timescale cascading outage model is established and its features are elucidated. Section IV is a case study of the IEEE 30-bus system with detailed demonstration and discussion of multi-timescale cascading outage processes and stage analysis of outage evolution. Section V demonstrates the proposed model on a reduced US-Canada northeast power system model. Section VI draws conclusions.

II. QUASI-DYNAMIC MODELING OF CASCADING OUTAGES

A. Categorizing dynamics into timescales

As stated previously, power system cascading outages involve various dynamics with distinct timescales. Fig. 1 shows time scales of typical dynamics involved in cascading outages [2], [35], [36]. To utilize quasi-dynamic concept in simulation, the dynamics should be categorized by timescales so that in cascading outage simulation, faster processes can be simulated between neighboring slower process transitions. To establish multi-timescale cascading outage simulation, the related dynamics are grouped into 3 categories:
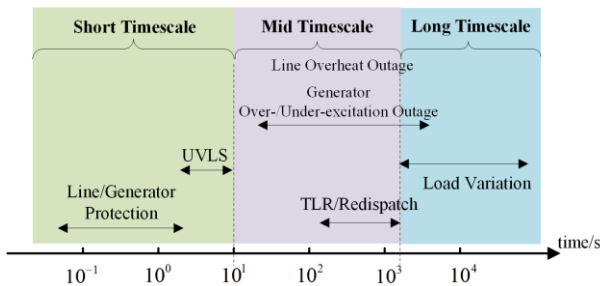

Fig.1. Time scales of dynamics in cascading outages

1) Short-term process. This include overloading or faults directly causing branch and generator protections, as well as emergency load shedding, which usually last a few seconds.

2) Mid-term process. This category includes overhead line outages caused by overheat and tree contact, generator outages by over-excitation or under-excitation, named as "Mid-term Random Outage" (MTRO). This timescale also includes re-dispatch operation taken by operators. The mid-term process usually lasts for minutes, and often with notable uncertainty.

3) Long-term process. This process refers to variation of load, which is slow and continuous throughout the entire process of cascading outages.

The categorization of timescales is expected to facilitate cascading outage simulation in that when simulating processes of shorter timescales, the states and parameters of longer timescale processes can be regarded as constant. Thus the decomposition of simulation according to timescales can be realized, which will be elucidated in the following sections.

B. Modeling and Simulation of the Short Timescale Process

The short timescale processes e.g. relay protection and emergency load shedding are much faster than the processes of other timescales, so they are hardly intervened by other dynamics in cascading outages. Therefore, in the proposed cascading outage model, the simulation of short timescale process can be wrapped as an individual submodule. The modeling of short timescale process is stated as follows.

1) Simulation of cascading protection actions

If severe overloading is detected on any line, protection is triggered and the line is tripped. In this cascading outage model, a loading rate threshold β_{Li} is set (practically 1.8-2.4) for each line [14]. If loading rate of line i exceeds β_{Li}, then cut the line quickly. Similarly, generators are equipped with voltage protection with over-voltage threshold v_G^{max} and under-voltage threshold v_G^{min}. If voltage of a generator bus goes beyond the limits, then the generator is cut off by protection.

2) Simulation of Load Shedding

Load shedding is a commonly-used emergency control scheme in order to relieve system from collapse. In cascading outage simulation based on power flow, the divergence of power flow often corresponds to instability or severe stress. Therefore, in cascading outage simulation, once power flow fails to converge, load shedding is performed for up to a preset number of rounds N_U until power flow converges [12].

The emergency load shedding, e.g. under-voltage load shedding (UVLS) is utilized to relieve the already stressed system and prevent a system collapse. Since the load shedding is usually triggered based on the steady-state condition, e.g. the voltage level, and a time delay is often set before load shedding to avoid the influence from transient dynamics, it is reasonable to simulate load shedding in a power flow based model. If power flow still cannot converge after certain rounds of load shedding, this probably means that the system is experiencing a severe problem. In the simulation procedure, it may not be appropriate to consider the system as completely collapsed since probably only a partial system is experiencing the problem. As a rough but intuitive method, diverged power flow calculation results (with Newton-Raphson method) may give

clues about ongoing outages. For example, if a two-area system with weak connection is unstable, the weak connection will often be tripped due to severe overload or oscillation, while correspondingly as we observed in test cases, the diverged power flow results usually show large difference in voltage or angle on the two ends of the weak connection. So in this model, with diverged power flow results, the branches with voltage or angle difference larger than certain thresholds will be tripped in simulation. However, this is only an intuitive method which works in simple systems but still needs further verification.

In real system analysis, the proposed model supports more accurate simulation of emergency control schemes such as UVLS and system splitting measures [37] given the logics and configurations of control schemes, and dynamic simulation could be incorporated into the short-term processes.

The emergency control measures such as UVLS and line disconnection in current systems are passive actions. Their strategies are usually generated offline and their objectives are restricted to local benefits. In contrast, it is more desirable to realize globally coordinated strategic control. Literature [38] presents a research of active line tripping strategy for mitigating cascading outages. To deal with the computational difficulty for global optimality, a heuristic line tripping method was proposed, which requires moderate computation power and thus has potentials for a practical use. Yet as pointed out by the authors, tests on other grids and further improvements are needed, and it is important to obtain strategies with time information. To effectively mitigate cascading outages, system-wide risk assessment is required, and the time horizon of cascading outages development is necessary information for making decisions on feasible control strategies. Our proposed model can provide the required time information and an efficient platform for studying globally coordinated control thanks to its power-flow based quasi-dynamic simulation.
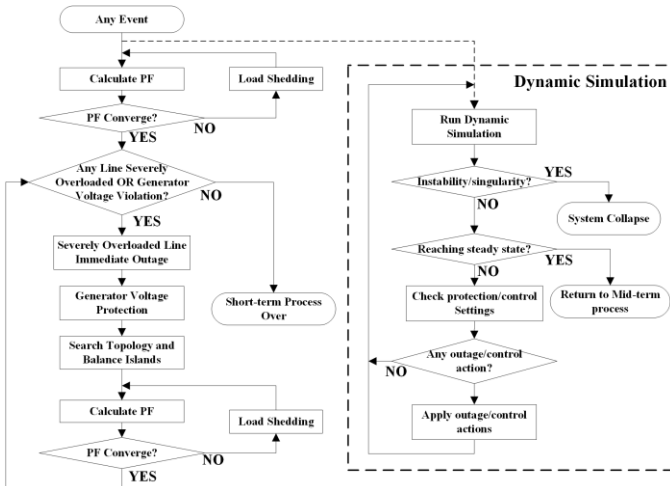
3) Simulation of the short-term process

Fig.2. Short-term Process Simulation Procedure

Fig. 2 demonstrates the flowchart of short timescale process simulation. The simulation can be performed in two ways: with power flow or dynamic simulation. The power flow based approach includes simulation of line/generator protection and load shedding, while the dynamic simulation rigorously traces

the whole process until system collapse or reaching steady state. In cascading outage model, short-term processes should be always checked and simulated once system state changes. The simulation procedure is repeated until there are no further short-term events.
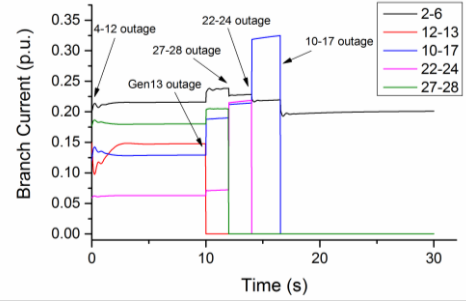

Fig. 3. Transient process in IEEE-30 bus system (stable case)

Fig.'s 3-4 demonstrate the short-term processes after triggering outages simulated with dynamic simulation. As Fig 3 shows, the system finally reaches a steady state and the short-term process ends. It can be seen that before each outage, the transients caused by the previous outage have basically faded away, so the simulation of such a short-term process based on power flow is reasonable. Fig. 4 demonstrates a process of fast cascades that leads to system collapse (instability). In other cases, the system may also undergo oscillations, frequency or transient instabilities, etc. Under these circumstances the process has high nonlinearity and the analysis only using power flow may be inadequate.
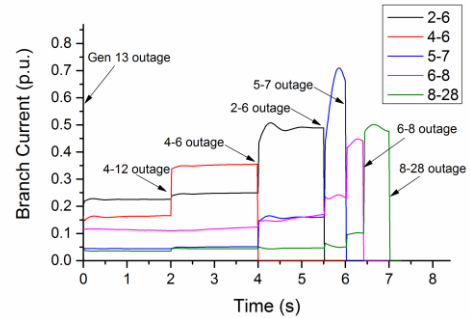

Fig. 4. Transient process in IEEE-30 bus system (instable case)

Choosing power flow or dynamic simulation is a tradeoff between efficiency and accuracy, depending on the application requirements. Dynamic simulation is able to more accurately reflect the interactions among system states, protection actions and emergency controls. But its high requirement of computational resources and difficulty in dealing with uncertainty is a major issue in practice. As the commonly adopted method in cascading outage simulation [10]-[13], power flow can achieve a satisfactory accuracy in tracing potential risks and in analysis of the mechanism of cascades propagation, and it has the advantage of efficiency. As discussed in introduction, power flow is also a practical approximation method in simulation of short-term processes. And the proposed multi-timescale quasi-dynamic model allows dynamic simulation to be easily embedded into the short-term process as demonstrated in Fig. 3 and Fig. 4 to further improve the accuracy on judging the stability of the system at the end of each outage. This paper will focus on the quasi-dynamic

mechanism of the proposed model, and power flow is utilized to simulate short-term processes in the test cases demonstrated in the following sections.

C. Quasi-Dynamic Framework: Simulate Interactions among All Timescales

As stated above, the dynamics and processes involved in cascading outages can be categorized as three types according to their timescales. To realize the multi-timescale simulation of cascading outages, it is necessary to figure out the dominant physical characteristics in each timescale and analyze their interactions. Fig 5 illustrates the interactions among timescales. In cascading outages, load variation is the slow driving force changing system states. The variations of system states directly influence the loading of elements and the heat accumulation, thus directly or slowly causing elements outages. The outages in turn render transients and redistribution of power flow pattern. The risky system states or transients may trigger re-dispatch operation or emergency control. As analyzed in Figs 1 and 5, the simulation procedures can be designed using the decomposition of timescales, and interactions among all the related processes should be realized.
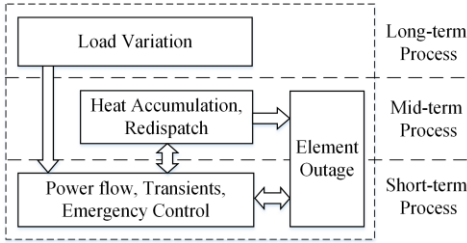

Fig. 5. Interactions among timescales

The interactions between mid-term and long-term dynamics account for most of the time in the cascading outage process. Considering the related dynamics as shown in Fig. 1, the quasi-dynamic simulation procedure can be regarded as a loop of MTROs and re-dispatch operations accompanied with long-term system state changes (e.g. load variations). Here select a reasonable time interval Δt_{Mid} of the mid-term process and discretize the long-term process with Δt_{Mid}, then the simulation is performed as a loop including simulation of the mid-term process during interval Δt_{Mid} and updating long-term states to the next interval, as shown in Fig. 6. Besides, the interactions between the mid-term and short-term processes can be described using the quasi-dynamics method. Short-term processes are checked and simulated once they are triggered.
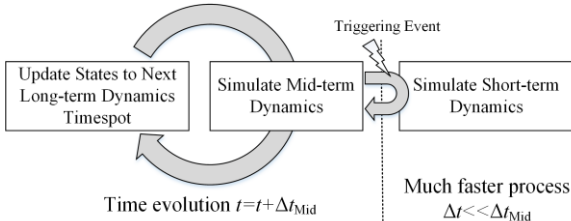

Fig. 6. Quasi-dynamic structure of Multi-timescale simulation framework

Basically, Δt_{Mid} should not be shorter than the timeframe of re-dispatch operation, which is generally longer than 10 minutes [17]. And Δt_{Mid} should not be too long, in order to

avoid large load variation during each interval. We suggest that for cascading outage simulation involving human dispatchers, Δt_{Mid} should be between 15 minutes and 1 hour. Although this equal-interval discretization and simulation differs from the fact that actual random outage events may occur at any time, in the perspective of risk assessment, such an equal-interval discretization of time reflects the average effect of all possible cascades occurring at arbitrary time during the interval. Thus the statistical validity of this approach is kept thanks to random outage sampling on time interval Δt_{Mid}, which also adds flexibility to the selection of Δt_{Mid}. This will be stated afterwards and verified by case studies (Section IV.D).

III. PROPOSED CASCADING OUTAGE MODEL

A. Procedure of Cascading Outage Simulation

Fig. 7 shows the overall procedure of proposed cascading outage model. The model consists of several loops representing the evolution of cascading outages in different time scales. Also, related dynamics are modeled in the cascading outage simulation procedure. The detailed procedure and related dynamic modeling methods are described as follows.
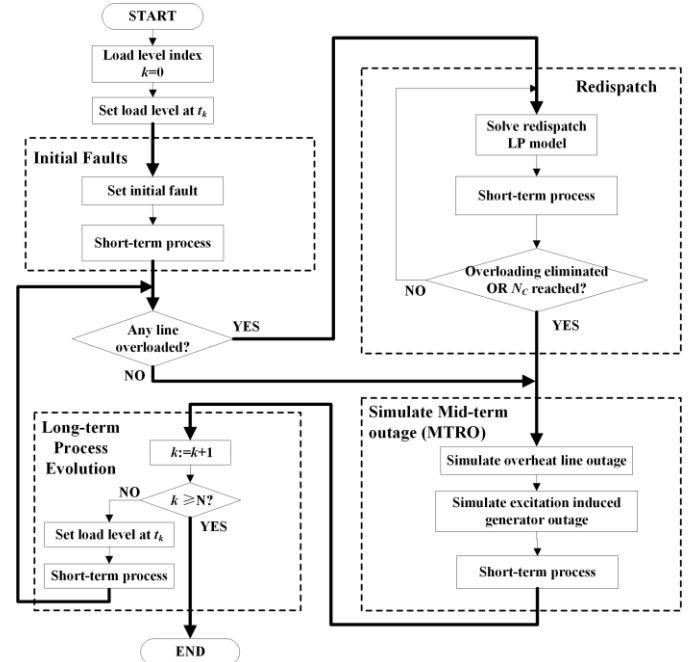

Fig.7. Quasi-dynamic Multi-timescale Cascading Outage Model

1) **Step 1.** *Set the system initial loading level.*
   1a. Assign load level index $k=0$.
   1b. Set load level at randomly selected time T_0.

The determination of initial outages greatly depends on the application situations. In offline assessment, since the time and elements of initial outages are highly uncertain, the initial outages are usually sampled to reflect the overall risk character. While in online operation, the uncertainties of initial outages are rather limited so that the initial outages are sampled in smaller sets or are even designated deterministically.

Here take the offline risk assessment as an example. Since cascading outages may start at any time in a day, the initial outages are sampled according to a given distribution. Fig. 8

illustrates a real power system load curve, suggesting significant load variation during a day. In the proposed model, randomly choose a starting time T_0, set the load level at T_0 as the system condition before the initial outage.
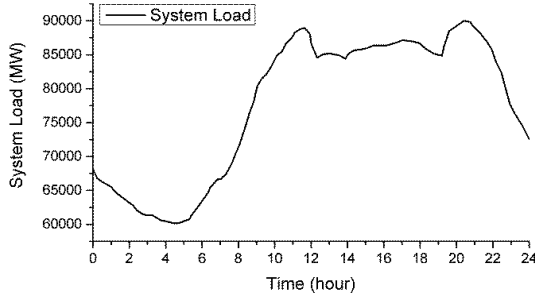

Fig.8. Daily load curve of a real power system

In the following procedures, this model simulates evolution of outages with load variations. Assume cascading outages is expected to end before time T_{N_d}, equally divide time interval $[T_0, T_{N_d}]$ into N time slots bounded by instants t_k

$$t_k = T_0 + k(T_{N_d} - T_0)/N_d, k = 0, 1, \ldots N_d \quad (1)$$

The length of each time slot is

$$\tau_D = (T_{N_d} - T_0)/N_d \quad (2)$$

According to the load curve, the system base condition at each moment t_k can be determined. The complete cascading outage process can be represented approximately by simulating mid-term and short-term processes at discrete moments t_k, and τ_D is the mid-term interval Δt_{Mid} introduced in Section II.

2) Step 2. Simulate the initial failure

2a. Randomly or deterministically select one or several elements to outage, as the initial failure.

2b. Run short-term process simulation.

3) Step 3. Simulate re-dispatch operations

3a. If there are overloaded lines, continue to *Step 3b*, otherwise go to *Step 4*.

3b. Solve re-dispatch model, apply solved generation and load adjustment to system.

3c. Run short-term process simulation.

3d. Check if overloading is completely eliminated or re-dispatch execution round has reached limit N_C, if true then go to *Step 4*, otherwise go to *Step 3b*.

In this paper, the adjustment of power flow on an overloaded branch i is performed using sensitivity, which better reflects the actual operation behavior. As (3) shows

$$\Delta S_{li}(\Delta P_G, \Delta P_D, \Delta Q_D) \le \lambda_{li} S_{li}^{max} - S_{li} \quad (3)$$

where S_{li}^{max} is the flow limit of branch i, S_{li} is the power flow before re-dispatch. Re-dispatch performs generation adjustment ΔP_G and load shedding ΔP_D, ΔQ_D to adjust ΔS_{li}, thus lowers branch loading. Using branch flow-bus injection sensitivity, ΔS_{li} can be expressed as linear functions of ΔP_G, ΔP_D and ΔQ_D. The coefficient $\lambda_{li} \le 1$ is to compensate flow adjust error brought by linearization and it also reflects risk preference of re-dispatch. Using sensitivity, the re-dispatch model is established as a linear programming problem, significantly enhancing solvability comparing with AC-OPF.

Due to the nonlinear nature of power flow, dispatchers cannot guarantee completely eliminating overload by one round of operation. In this paper, multiple rounds of re-dispatch are executed until overloading is eliminated, or the number of rounds reaches limit N_C which defines dispatcher operation speed and will be analyzed in case studies.

4) Step 4. Simulate MTROs

4a. Sample overheating-caused line outages.

4b. Sample excitation-induced generator outages.

4c. Apply outages obtained in *Steps 4a* and *4b*;

4d. Run short term process simulation.

a) Generator outages due to over- or under-excitation

Both over-excitation and under-excitation may lead to generator outage after a period of time. A probabilistic generator outage simulation method is proposed as below. For operating conditions of a generator near its reactive power limits, assume generator outage probability as piecewise linear function of its reactive power output, as illustrated in Fig. 9.
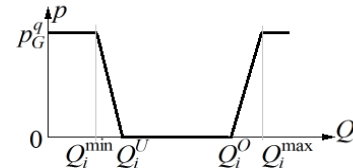

Fig.9. Probability of generator outage as function of reactive power

Moreover, deep over-excitation or under-excitation causes generator voltage deviation, and possibly trigger generator voltage protection. Similar to [39], we assume the function as shown in Fig. 10 to represent the relationship between the generator outage probability and terminal voltage.
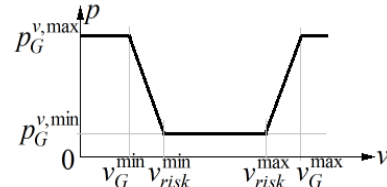

Fig.10. Probability of generation outage as function of terminal voltage

Since the whole generator outage process may last for minutes [2], and the process of heat accumulation or voltage deviation depend on various external factors with significant uncertainty, the outages are modeled as stochastic processes.

The probability of an outage event largely depends on the time window of observation. Assume the time to failure (TTF) of generator reactive power outputs corresponding to probabilities p_G^q, $p_G^{v,min}$ and $p_G^{v,max}$ are τ_G^q, $\tau_G^{v,min}$ and $\tau_G^{v,max}$ respectively. And assume the occurrence of MTROs satisfies Poisson process [40], then the probability parameters p_G^q, $p_G^{v,min}$ and $p_G^{v,max}$ are set as

$$p_G^q = 1 - e^{-\tau_D/\tau_G^q} \quad (4)$$

$$p_G^{v,min} = 1 - e^{-\tau_D/\tau_G^{v,min}} \quad (5)$$

$$p_G^{v,max} = 1 - e^{-\tau_D/\tau_G^{v,max}} \quad (6)$$

Since the parameters p_G^q, $p_G^{v,min}$ and $p_G^{v,max}$ in (4)-(6) consider the length of observation interval τ_D and are derived from Poisson process, they are more reasonable than the

conventional models and are more practical for application use. The TTF is a real-time reliability concept [41]-[43], which is determined by the real-time states in operation. The parameters τ_G^q, $\tau_G^{v,min}$ and $\tau_G^{v,max}$ can be obtained through reliability tests [42] or using historical events. For example, according to the record of East Lake 5 unit in Aug. 2003 blackout[2], the TTF τ_G^q of similar generators can be approximately set as 45min. Q^O can be set as 300 Mvar, which is above the East Lake 5 Mvar output before undergoing stress.

b) Line outages due to overheat

Overloaded lines may keep sagging slowly due to overheating and eventually be tripped when contacting objects. The expected time from overloading to tripping τ_{Li} can be determined by the line loading rate and multiple external factors, e.g. the environmental temperature, wind speed, heights of objects on ground [16][44]. However, the actual time to tripping has strong uncertainty. Therefore in this paper, τ_{Li} is regarded as expected time to failure and line outage events are sampled using the probability p_{Li} determined by τ_{Li}.

$$p_{Li} = 1 - e^{-\tau_D/\tau_{Li}} \tag{7}$$

5) **Step 5. Load variation.**
   5a. Assign $k=k+1$.
   5b. If $k \geq N_d$ then exit, otherwise go to *Step 5c*.
   5c. Set the load level at time t_k.
   5d. Run short term process simulation. Go to *Step 2*.

During cascading outage simulation, the load and generation may change due to re-dispatch or load shedding. From actual power at t_k as $P_j(t_k)$, $Q_j(t_k)$ and power levels from load curve $P_j^0(t_k)$, $Q_j^0(t_k)$, $P_j^0(t_{k+1})$, $Q_j^0(t_{k+1})$, the actual load and generation powers at t_{k+1} are

$$P_j(t_{k+1}) = P_j(t_k) \cdot P_j^0(t_{k+1}) / P_j^0(t_k) \tag{8}$$

$$Q_j(t_{k+1}) = Q_j(t_k) \cdot Q_j^0(t_{k+1}) / Q_j^0(t_k) \tag{9}$$

Besides the simulation of uniform load variation across the system, the proposed model can also accommodate the changes in distribution of load given the load curves on nodes or areas, which better matches actual load variation. In this case, the values of $P_j^0(t_k)$, $Q_j^0(t_k)$, $P_j^0(t_{k+1})$, $Q_j^0(t_{k+1})$ in (8)-(9) follow nodal/area load curves respectively. In the application of retrospective simulation, nodal/area load curve records are required for representing heterogeneous load variation across nodes and areas, while for rehearsal and predictive analysis, load forecasts on nodes or on areas are needed.

The proposed model divides the time horizon of cascading outages into intervals, and samples MTROs on the load levels at the beginning of each interval. So there exists some error from neglecting load variations in the interval. But the error is limited since proper division of intervals guarantees that the load variation inside each interval is not large. The accuracy can be further enhanced by calculating an average state in the interval, but this requires more power flow computation, so there is a tradeoff between accuracy and efficiency. Moreover, the sampled MTROs are exerted simultaneously on the system so that their dependencies are neglected. The way to account for

more dependencies is to simulate on larger N_d so that the MTROs are more likely divided into different intervals. Yet tests on different N_d's in Section IV.D show consistency in risk metrics, which verify that the dependencies of MTROs within intervals can be reasonably neglected.

IV. CASE STUDY ON IEEE 30-BUS TEST SYSTEM

The proposed model is illustrated in details on the IEEE 30-bus system with 6 generators and 41 branches. The system load is 137.8MW. Set $\beta_L = 2.0$, $N_d = 6$, $T_{N_d} - T_0 = 3$h, so that $\tau_D = 0.5$h. The load is assumed to increase by 12% per hour.

A. Impact of Generator Outages

To analyze the influence of generator outage on cascading outages, cascading outage processes with and without generator outage simulation are compared in Table I.

Results in Table I indicate that generator outages have significant influence on the voltage profile and further cascades, and eventually leading to system separation and blackout. From the perspective of overall cascading outage risk, Table II lists risk metrics of scenarios with different reactive power capacities. The insufficient reactive power case means that reactive power limits of generators are lower. Results in Table I & II show that generator outages contribute to more cascading outages, especially severe ones. The results verify that it's important to simulate generator outages in cascading outage simulation, or the risk will be underestimated.

TABLE I
IMPACT OF GENERATOR OUTAGE SIMULATION ON CASCADING OUTAGES

H:mm	No generator outage	With generator outage
0:00	Transformer 4-12 outage (initial failure)	Transformer 4-12 outage (initial failure)
0:00-0:30	Line 9-10 outage (overheat)	Line 9-10 outage (overheat)
		Generator 5 outage (over-excitation)
	Line 25-27 outage (protection)	Line 25-27 outage (protection)
0:30-1:00	Line 24-22 outage (overheat)	Line 24-22 outage (overheat)
		Generator 13 outage (over-excitation). Minimum voltage reaches 0.85 and then rises to 0.98 after re-dispatch.
1:00-1:30	--	--
1:30-2:00	Line 6-8 outage (overheat)	Line 6-8 outage (overheat)
		Line 8-28 outage (protection)
2:00-2:30		Generator 2 outage (over-excitation)
		Lines 18-19, 10-17 outage (protection); system split
	Total load loss 33.5MW	Total load loss 116MW

TABLE II
IMPACT OF GENERATOR OUTAGE SIMULATION ON RISK METRICS

	Generator Outage		No Generator Outage	
Reactive power	Sufficient	Insufficient	Sufficient	Insufficient
EDNS/MW	10.23	12.55	7.98	8.96
VaR(0.95)/MW	41.21	67.50	36.26	55.17
CVaR(0.95)/MW	46.00	72.00	40.00	64.00

B. Multi-timescale cascading outage process study

Table III demonstrates a typical cascading outage process, showing related dynamics in different time scales. The right

column of the table indicates the timescales of events, short-term as "S", mid-term as "M", long-term as "L".

TABLE III
CASCADING OUTAGE PROCESS IN IEEE-30 BUS SYSTEM

| Time		Type
1) Initial fault.		
0.0h	Transformer 4-12 (flow 25MW+15Mvar) outage	
	Flows on branches 1-2, 2-6, 6-10, 13-12 increase highly, but there is no overloading.	M
2)Mid-term outages develop		
0.5h	Load grows by 6%.	L
Generator area line outage, generator 1 lost		
1.0h	Load grows by 6%.	L
	Branch 1-2 faults due to overheat (loading 97%).	M
	The loading of branch 1-3 rise up to 220%; relay cuts off the branch; generator 1 is separate from the system.	S
	Generator 13 reaches its reactive power upper limit.	M
Generator 13 trip due to over-excitation		
1.5h	Load grows by 6%	L
	Generator 13 outage due to over excitation. The loss of reactive power source near load region causes voltage drop.	M
Overheat-caused outages continue		
	Branch 2-6 faults due to overheat. The transmission channel from generators to loads is further weakened. Yet generators 2, 5, 8 and 11 still have reactive power capacity. To this moment, power can only be transmitted through bus 10 and 28. Branches linked with these two nodes are overloaded.	M
2.0h	Load grows by 6%.	L
	Re-dispatch is executed to eliminate branch overloading, shed load 13.2MW. Some branches are still under stress.	M
3) Cascades accelerate		
2.5h	Load grows by 6%.	L
	Branches 9-10, 10-17 fault due to overheat. The electrical distance between generators and loads is much larger, and voltage stability issue begins to emerge. Voltage drops significantly and some lines are severely overloaded.	M
4)Fast cascades		
	Line 25-27 (loading 225%) outage by protection.	S
	Line 22-24 (loading 239%) outage by protection.	S
	Lines 10-20 (loading 299%), 18-19 (loading 261%) outage by protection.	S
5)System separation, blackout and stop of cascading outages		
	Load buses 12, 14-20, 23-26 are separate from other parts of the system, without generators to supply power, this area completely blackouts.	
	The rest of system has more generation than load. After balancing, there is no further stress in the system. Cascading outages stop. The system loses 10 branches and 97.5MW load in total.	
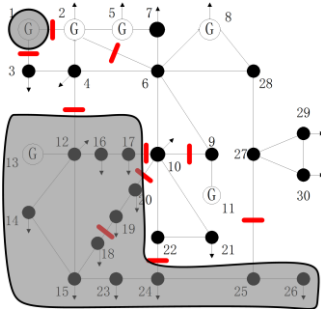
Fig.11. Tripped branches and affected areas in cascading outage

All the elements lost and the blackout areas are illustrated in Fig. 11. It should be noted that outages of several heavily loaded lines contribute to the final blackout, even though these lines never exceed flow limits. This situation may occur under hot weather with little wind. In fact, if re-dispatch is conducted more aggressively, the risk of cascading outages and blackouts

can be greatly reduced at much smaller cost of additional load shed. For example, if λ_{li} is reduced from 0.95 to 0.9, only 13.75MW load will be shed with no further events.

C. Analysis on stages of cascading outages

Since the proposed model can simulate cascading outages with representation of time, we can use the model to analyze the development speed and stage characteristics of cascading outages. Cascading outage simulations in IEEE 30-bus system are repeated 5000 times. Each simulated cascading outage process is split into 3 stages with equal time duration, for each stage, calculate the outage number and load loss per hour as indices reflecting the speed of cascading outages evolution.
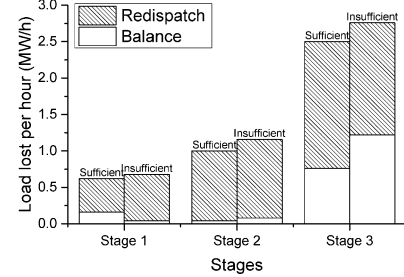

Fig. 12. Load losses per hour in IEEE-30 system by stage

In this case, two scenarios are considered: sufficient and insufficient reactive power. Fig. 12 demonstrates load lost with two scenarios in each stage. The load lost is categorized into 3 types, i.e. load shed by 1) re-dispatch, 2) balancing islands and 3) load shedding. Since the system is small and easier to control, in 5000 times of simulations, the load shedding was not triggered.

Fig. 12 shows an increasing speed of load losses as cascading outages evolve. In the last stage, much more load is shed due to island balancing compared with the first two stages. These clues indicate outage development acceleration and severe load losses at the last stage with system separation. Moreover, it can be concluded that in this case, insufficient reactive power tends to cause more load losses.
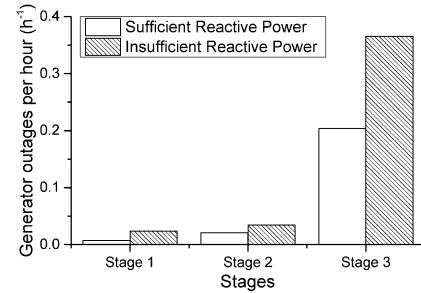

Fig. 13. Generator outages by stage

Fig. 13 and Fig. 14 show average number of generator and line outages per hour in each stage of cascading outages respectively. Both scenarios reveal the acceleration of outages. The last stage has an outage speed much faster than the first two stages. Results in Fig. 13 verify that insufficient reactive power directly causes heavier burden of generators, and causing more outages. Also, from the comparison in Fig. 14, it is obvious that insufficient reactive power relates to much higher line outages in the last stage while the outages in the first two stages are slightly fewer. The reason of differences in stages in Fig. 14 is attributed to multiple factors including re-dispatch, reactive

power margin and generator outages. In the early stages, the reactive power margins in either scenario are enough, also the voltage is maintained at the normal level and the total reactive power consumed on branches is trivial. Since there are more load shed by re-dispatch in the insufficient reactive power case (Fig. 12), the loadings on branches are lower and outages are less likely to occur. While in the last stage, as cascades develop and the system is weakened, the reactive power deficiency is more possible to occur due to tighter margin and more generator loss (Fig. 13), leading to prominent voltage drop in the system and even higher burden on branches (Fig. 15), and finally rendering higher risk of branch outages.
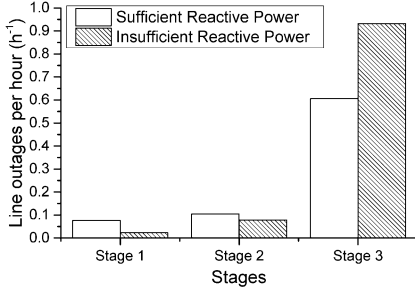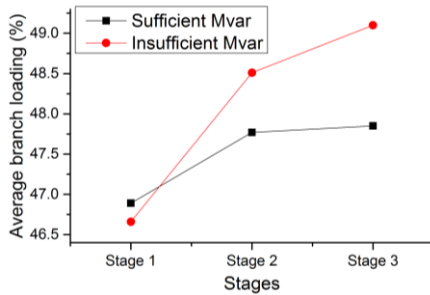

Fig. 14. Line outages by stage

Fig. 15. Average branch loading trends of IEEE-30 system by stage
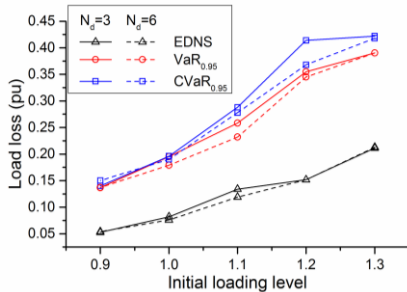
D. Selection of time interval parameters

Fig. 16. Risk metrics with different interval selections and initial loadings

In the proposed cascading outage model, N_d and N_C are important parameters representing the resolution of long-term process discretization and the speed of re-dispatch operation. As discussed above, since the probability of MTROs has taken τ_D into consideration, statistical characteristics of simulation results should be consistent under different τ_D. Assume the average speed of re-dispatch is given, the product of N_d and N_C should be constant. In the IEEE 30-bus system, we test two sets of parameters: 1) $N_d = 3, N_C = 10$ and 2) $N_d = 6, N_C = 5$. To compare more comprehensively, tests are conducted under different initial loading levels. Fig. 16 shows general consistency in risk metrics with the two sets of parameters. This

indicates that the selection of simulation intervals has some flexibility without affecting statistical results.

However, the selection of N_d and N_C still have limits. We choose the case of 0.9 times the initial loading level, changing N_d to a wider range (maintaining $N_d \cdot N_C$ constant) and run simulations. The risk metrics are demonstrated in Fig.17.

Results in Fig. 17 indicate that the results with N_d between 3 and 10 are more consistent while other results have more significant deviations. Thus it can be inferred that in this case, reasonable N_d should be 3~10, and correspondingly the suggested interval of τ_D is 18min~1hr.
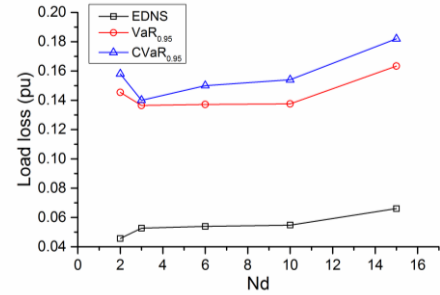
Fig. 17. Risk metrics with different N_d selections

V. CASE STUDY ON US-CANADA NORTHEAST POWER GRID

The proposed model is utilized to study the US-Canada Northeast power grid. This case study uses a reduced model of the system having all transmission lines of 230kV and above, and all generator buses. There are 410 buses, 882 branches and 200 generators in total. The system load is 162121.5 MW.

A. Studying patterns of cascading outage evolution

The proposed model is utilized to simulate possible patterns of outage evolutions. We simulate cascading outages of up to 2 hours with $T_{N_d} - T_0 = 2\text{h}$ and $\tau_D = 0.5\text{h}$. The reliability parameters of generators and branches are generated based on literatures [2][35][39][44].

Fig. 18 shows one of the cascading outage processes simulated using the proposed cascading outage model. The result indicates that the cascading outage process lasts for around 1.5 hours. It starts by the outage of Erie-Perry 345kV line, and then develops with the loss of East lake generation and three more Ohio area lines in 1 hour. Till then, transmission paths along the south of Lake Erie have been cut, following which the outages then accelerate. The loss of several lines at Ohio-Pennsylvania border further narrows channels of power supply to Lake Erie south shore area. The outages also develop westward, forcing power flow to detour, causing more outages in Michigan and power flow reverse from Ontario. Such a pattern of transitions in power flow under cascading outages resembles that during the August 14th, 2003 blackout just before the final fast cascades stage, as illustrated in Fig. 19(a). The simulated outages develop quickly at 1.5 hours after initial outages, finally separate Michigan from Ontario and cut off almost all channels to Michigan but a shallow neck at west Michigan. The power supply to the Lake Erie south shore is also limited to only a few branches from southwest. The Michigan and Lake Erie south areas then experience severe stress, with high risk facing fast outages and blackout. The pattern of power flow is also similar to that before the 2003

blackout (Fig. 19(b)) and the stressed areas in simulation have large overlaps with the areas affected by the 2003 blackout.
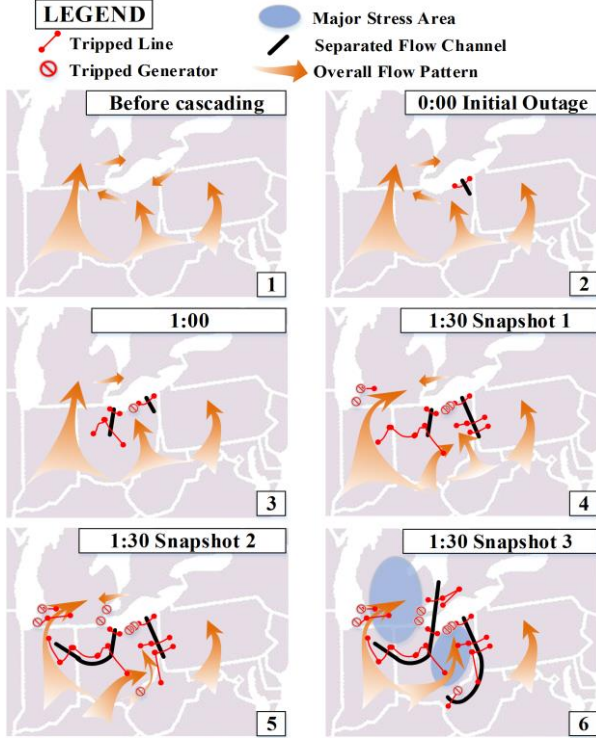

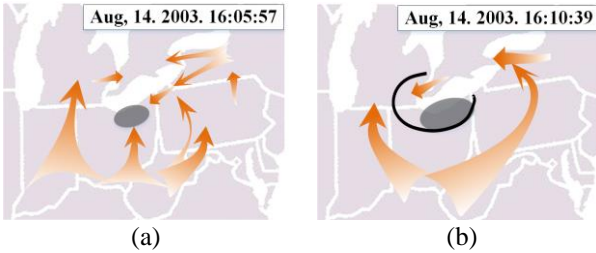Fig. 18. Cascading process in US-Canada Northeast System

(a)   (b)

Fig. 19. Actual flow patterns in Aug. 2003 blackout [2]

B. Evaluation of Control Measures

The proposed model also has potentials in assessing the performance of control measures against cascading outages. In practice, power flow re-dispatch is one of the systematic defensive measures against cascading outages, especially in the earlier stages of cascading outages. In this model, the maximum re-dispatch round N_C represents operations that can be taken by human, thus reflecting the speed of re-dispatch operations. Different N_C's are used in simulations to compare the impact from re-dispatch speed on the risk of cascading outages.

Fig. 20 compares load losses in three stages with N_C =3, 5 and 7. (Note there is a break on the vertical axis.) Comparing the cases of different re-dispatch speeds, the conclusion is that faster re-dispatch tends to shed more load at early stages of cascading outages, which better relieves stress on the system and largely decreases the load loss in the final stage of cascading outages, contributing to major decrease of the overall load loss risk.

Besides the re-dispatch speed, the branch flow constraint coefficient λ_{li} is also an important parameter which reflects operator risk preference.
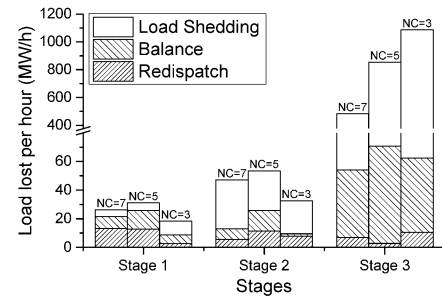

Fig. 20. Stage load loss comparison under different re-dispatch speeds

Fig. 21 is the comparison of stage load losses under different λ_{li} as 0.9, 0.95 and 1.0, corresponding to columns respectively from left to right in the figure. Lower λ_{li} means more conservative operation and causes more loads shed by re-dispatch. However in the last stage, more conservative re-dispatch achieves much lower loss.
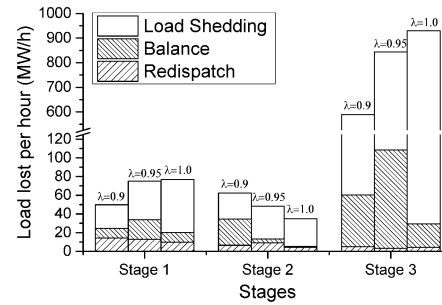

Fig. 21. Stage load loss comparison under different risk preferences

By comparing cases of different operation speeds and risk preferences, the effects of re-dispatch can be quantitatively evaluated, especially with time and speed analysis which is of vital importance in application yet has not been discussed in cascading outage study.
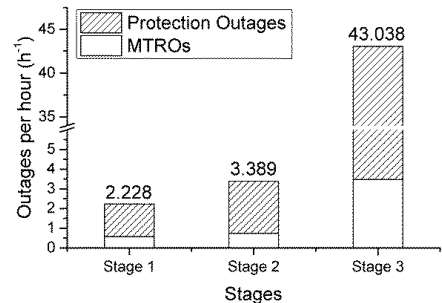

Fig. 22. Average outage speeds by stage in US-Canada Northeast system

The proposed model can be utilized to evaluate the effectiveness of control measures. In general, the control actions may be effective if no outages occur before control is finished; otherwise the goal of the control is not achieved and further actions are required. Therefore effective control should be fast enough to "win the race" against outages. For example, Fig. 22 illustrates the average outage speed in each stage, which is useful in evaluation and selection of control measures in different stages. In the first two stages, the outages occur at 2-4 times per hour, which indicate 15-30 minutes on average for taking a control action. In this stage the human re-dispatch actions can satisfy the requirement. But in the last stage the outage speed increases drastically to nearly one outage per

minute, far exceeding the capability of human-involved control schemes. Actually, in the fast cascade stage in real systems, human operators will be overwhelmed by floods of messages and alerts but cannot take any effective actions [2], and automatic emergency controls should take effects.

The proposed model is expected to provide quantitative risk assessment of control measures with time information, which is more comprehensive and practical for the industry to evaluate and invest control measures along with economic cost/benefit analysis.

Similar evaluations can also be applied in voltage control. Voltage stability is a major issue in cascading outages since voltage drop and branch/generator outages contribute to each other, making local outages spread towards system-wide blackouts. Therefore providing sufficient and timely voltage support is beneficial to relieving system stress and mitigating cascades. In practice, there are some requirements for voltage support [45]:

1) Speed of decision-making and action-taking.
2) Solution optimality in wide-area system.
3) Flexibility to various operational preferences.
4) Ability to address uncertainties.

In different time horizons, the requirements for control actions have different biases. In planning or scheduling stage, addressing uncertainties, flexibility and coordination of areas are more important. The major objectives include minimum investment cost, minimum operation cost, least possible voltage deviation, etc. [46]. In the normal operation or a slow cascade stage, the computation efficiency should be considered. The analysis approaches include metric-based methods [47], [48], continuation/QSS methods [49] and security region [50], etc. Wide-area synchronous measurements are useful in system-wide coordinated control [51], [52]. When cascades mature and accelerate, since the time is rather limited and transients are prominent, the speed of decision-making and control is at the high priority. Current industrial solutions are rarely implemented in a proactive manner, such as relay actions, UVLS, system separation, etc. Coordinated emergency control is desirable but hard, which requires fast simulation/analysis, highly efficient communication and control infrastructures.

VI. CONCLUSION

This paper proposes a multi-timescale quasi-dynamic model for simulation of cascading outages. In this model, cascading outages related dynamics are categorized according to their time scales, and a multi-timescale framework based on quasi-dynamic method is established to realize more accurate simulation of interactions among dynamics in various timescales with explicit representation of time. The model overcomes the ambiguity of timescales in conventional quasi-static models, and time-consuming full-dynamic cascading outage simulation is avoided. Besides, this model also provides flexibility incorporation of dynamic simulation of short-term processes as needed. The proposed model improves simulation on reactive power related dynamics as well as dispatcher actions.

This paper uses the IEEE-30 bus system to study the influence of the loading level, generator outage and reactive power capacity on cascading outage processes and risk metrics.

The significance of considering these factors in cascading outage simulation is verified. Case studies also demonstrate the roles and interactions of dynamics in different timescales during the complete processes of cascading outages. Moreover, since this model can simulate cascading outages with time information, stage characteristics of cascading outages are verified and analyzed. To discuss the potential of application use, the proposed model is utilized in case study of US-Canada Northeast system, with demonstration of cascading outage stage characteristics and analysis of how system control measures have impact on cascading outage risk. The proposed multi-timescale cascading model provides more accurate cascading outage simulation and risk assessment with time information, and has potentials to be utilized in industry for evaluation and selection of control schemes against cascading outages.

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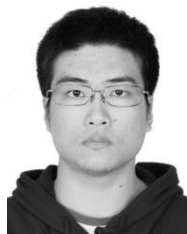
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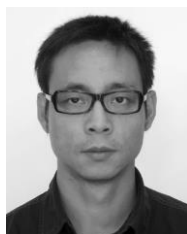
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