An Enhanced OPA Model: Incorporating Dynamically Induced Cascading Failures

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***Abstract*—The OPA (ORNL-PSERC-Alaska) model has been widely used in cascading failure simulations to predict likely and plausible sequences of cascading failures. This letter focuses on an algorithmic approach to enhance the OPA model whose main engine is based on quasi-steady-state models without considering the impact of collective transient dynamics of the entire system on the sequence of cascading failures. In particular, the enhanced OPA model incorporates dynamically induced cascading failures in fast time scales, which allows it to capture more realistic and detailed cascading scenarios. In this work, we outline the enhanced OPA model and provide simulation results to illustrate its feasibility with the realistic test network.**

***Index Terms*—Cascading failures, OPA model, power system dynamic simulation, power system protection.**

I. Introduction

THE growing significance of studying cascading failures has been recognized in the power industry and research community. However, the study of cascading failures is a challenging task because many mechanisms in different time scales involved in cascading failures complicate cascading modeling and mitigation strategies.

One key approach to evaluate cascading failure risk is the modeling and simulation of cascading failures, which can capture plausible sequences of cascading failures. In this aspect, a wide range of cascading failure modeling approaches have been proposed.

Among many of these models, the OPA[1] model [1], [2] is a commonly used tool to simulate the patterns of cascading failures under complex power system evolutions and engineering responses to failures. An OPA model can contain an inner, fast dynamics loop that simulates a cascade of overloads and outages together with remedial actions and an outer, slow dynamics loop that simulates complex system dynamics with a slowly evolving power network over years. Most of existing works that apply the fast dynamics loop of the OPA model for cascading failures simulation are based on only quasi-steady-state power flow models without taking into account any transient dynamic effects such as rotating machines and relevant control devices. Indeed, the collective nonlinear transient dynamics of the grid in fast time scales play an important part in determining the failures of network components during the severe failures and thus the overall cascading failures happening on time scales of minutes. The importance of linking nonlinear transient dynamics to cascading failure events has been emphasized in [3], [4].

For a more credible simulation of cascading failures, this letter focuses on enhancing the fast dynamics loop of the OPA model based on a given fixed power system without considering slow evolving of the power network. Compared to [5] whose main engine utilizes power-flow based quasi-dynamic models in different timescales, this letter integrates the fast transient dynamics modeling of cascading failures and protections in fast time scales. Specifically, we propose an advanced cascading failure simulation framework, which incorporates the effect of fast nonlinear transient dynamics and discrete protection events into the OPA model. In case studies, the enhanced OPA model is examined with the realistic test network, and then is used to form the graph of interactions between failed components [6] for evaluating cascading risk.

II. Enhanced OPA Model

A. Dynamic Simulation Model of Cascading Failures

Power system dynamics are typically modeled as a set of nonlinear differential-algebraic equations (DAEs):

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{y}) \tag{1a}$$

$$0 = g(\mathbf{x}, \mathbf{y}) \tag{1b}$$

where $\mathbf{x}$ and $\mathbf{y}$ represent the vectors of state variables and other algebraic, non-state variables, respectively. This work employs IEEE Model 2.2, and the modeling details and its extensive validation can be found in [7].

1) Relay Modeling: During cascading failures, the power systems encounter many different discrete events (e.g., interior events such as automatic protective relay actions), which consequently change the system state and thus may result in a more widespread and large blackout. To consider such dynamic changes resulting from the discrete events of protective relays,

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[1]OPA stands for Oak Ridge National Laboratory, Power Systems Engineering Research Center at the University of Wisconsin, University of Alaska to indicate the institutions collaborating to devise the simulation.

one may introduce an additional set of equations for each protective relay i to (1) as follows:

$$d_i = \begin{cases} \text{Active}(\text{i.e., } d_i > 0) & h_i(\mathbf{x},\mathbf{y}) \geq h_i^{\max} \text{ or} \\ & h_i(\mathbf{x},\mathbf{y}) \leq h_i^{\min} \\ \text{Inactive}(\text{i.e., } d_i = 0) & h_i^{\min} < h_i(\mathbf{x},\mathbf{y}) < h_i^{\max} \end{cases} \tag{2}$$

where the function h_i evaluates the monitoring signal for the relay i to activate an associated counter function d_i. When d_i reaches its limit, it triggers the protective relay (i.e., relay trips) and thus changes its state (e.g., from "on" to "off").

The usage of the counter function $\mathbf{d}$ is to add time delays to each protective relay for preventing unnecessary relay trips due to brief transient oscillations. This work considers two counter functions: the fixed-time delay and time-inverse delay. For the fixed-time delay, $\mathbf{d}$ starts to count down from 0 as soon as the monitored signal (i.e., $\mathbf{h}$) associated with that protective relay exceeds its threshold (i.e., $\mathbf{h}^{\max}$ or $\mathbf{h}^{\min}$) and continues its timer until the associated relay takes actions. If the signal becomes less than its threshold, $\mathbf{d}$ is reset to 0. For the time-inverse delay, it evaluates the area over the threshold to consider both how much and how long the signal exceeds its threshold.

2) Solution Approach: In power system simulation packages, the commonly used method for solving DAEs is partitioned-explicit (PE) method, which separately solves the succession of the ordinary differential equations and the algebraic equations. To address the difficulties of relay modeling across a large test system appropriate for cascading failure analysis, the proposed dynamic simulation of cascading failures uses and leverages this PE method to reflect the impact of (2) on the solution of (1). The PE method obtains the solution of the state and algebraic variables at the end of each time step. This solution can then be used to evaluate the function $\mathbf{h}$ and thus either activate or deactivate the counter function $\mathbf{d}$. That is, it first solves (1) using the PE method with known initial conditions. Then, it evaluates (2), triggers the protective relay if $\mathbf{d}$ reaches its limit, and reflect the corresponding discrete changes on (1). Next, it resolves (1), and the same process repeats until the end of the whole simulation period.

Note that the PE method is able to incorporate the modeling of protective relays into dynamic simulations of large-scale test networks since the protective relay modeling only increases the size of equations (2), and it just needs to explicitly evaluate (2), which is computationally very fast. In addition, it is straightforward in incorporating any form of relay modeling into the PE method.

As an example with the over-current relay, consider the simulation time $[t_0, \ldots, t_N]$ with $t_n = t_0 + n\Delta t$. Then, given the solution of state variables $\mathbf{x}^*$ and complex voltage phasors $\mathbf{V}^*$ at the end of each time step t_n, one can evaluate the vector of current flows along the line as:

$$\mathbf{i_f} = Y_f \mathbf{V}^*, \quad \mathbf{i_t} = Y_t \mathbf{V}^* \tag{3a}$$

$$\mathbf{h} = \max(|\mathbf{i}_f|, |\mathbf{i}_t|) \tag{3b}$$

where Y_f and Y_t represent the admittance matrices which yield the vectors of current flows from the "from" bus ($\mathbf{i_f}$) and "to" bus ($\mathbf{i_t}$), respectively of each line. Here, the function $\mathbf{h}$ compares the magnitudes of two current vectors element by element and returns larger elements. If the i^{th} component of $\mathbf{h}$ is greater than or equal to $h_i^{\max}$, the corresponding component of $\mathbf{d}$ becomes active and starts to count down (e.g., its value becomes Δt from 0 in the fixed-time delay). Other relays can be implemented similarly; for example, the function $\mathbf{h}$ can be defined as $\mathbf{h} = |\mathbf{V}^*|$ and $\mathbf{h} = \omega^*$ (rotor speed from $\mathbf{x}^*$) for voltage-related relay and generator-related relay, respectively

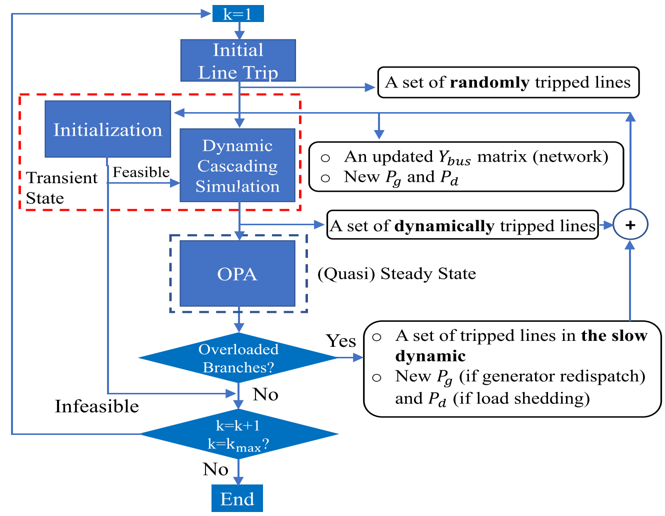

Fig. 1. Flowchart of the enhanced OPA model.

B. OPA Model With Dynamically Induced Cascading Failures

This section proposes an enhanced OPA model consisting of two main engines. It combines the previously described dynamic simulation of cascading failures with the existing fast dynamics loop of the OPA model that includes the quasi-steady-state modeling of the cascade with simulation of the complex system dynamics omitted. Therefore, the enhanced OPA model from the proposed method upgrades the fast dynamics loop (i.e., inner loop) of the OPA model that has been validated on large test systems. Using this approach, the enhanced OPA model can consider the effects of extra mechanisms such as automatic control and relay protection on cascading failures and thus reflect more realistic and detailed failures. Its flowchart is shown in Fig. 1.

Considering k cascading failure scenarios, the process of the enhanced OPA model starts with a set of randomly tripped lines as an initial line trip. This initial line failure firstly induces the transient dynamics of the power system that can be captured by the dynamic simulation, which may result in some protective action due to the violation of a transient reliability standard, (e.g., over-current line tripping) and thus provides a set of dynamically tripped lines in the transient dynamic. Then, the next line failures (i.e., the initial line failure and dynamically tripped lines) may trigger other line failures in the OPA model, which considers such remedial actions as generator redispatch and load shedding to mitigate the impact of line failures. If there are no overloaded lines, exit the loop and go to the next cascading scenario. If

TABLE I
ARRANGEMENT OF CASCADING FAILURES

	generation 0	generation 1	generation 2	$\cdots$
cascade 1	R_0^1	F_1^1	S_2^1	$\cdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
cascade $k_{\max}$	$R_0^{k_{\max}}$	$F_1^{k_{\max}}$	$S_2^{k_{\max}}$	$\cdots$

Algorithm 1: Enhanced OPA model.

Input: Determine the value for the number of cascading scenarios $k_{\max}$; obtain the initial line trips R_0^k; set $j = 1$.

1: Set $R^k = R_0^k$. While $k \le k_{\max}$,
2: With R^k, run the dynamic simulation of cascading failures and obtain F_j^k.
3: With $R^k \cup F_j^k$, run the OPA model and obtain S_{j+1}^k.
4: If $S_{j+1}^k \neq \emptyset$, go to step 2 and augment the previous cascading failures with $R^k = R^k \cup F_j^k \cup S_{j+1}^k$. Then, update $j = j + 2$, reinitialize the system, and rerun the dynamic simulation to obtain F_j^k. If not, exit the loop.
5: Update $k = k + 1$.

there are overloaded lines, these become a set of tripped lines in the slow dynamic, and it returns to the dynamic simulation of cascading failures with all previously tripped lines (i.e., all tripped lines change the Y_{bus} matrix accordingly as an updated network).

Note that the governor power flow (G-PF) model, more relevant in the face of component failures, is utilized for the initialization step of dynamic simulation. If the G-PF model results in infeasible power flow solution due to multiple line outages, exit the loop and go to the next cascading scenario. To stop time-domain simulation, the time delays are used as a criterion; that is, over the long enough time period, if the over-current relays for any un-tripped lines do not take tripping actions for more than the fixed-time/time-inverse delay without increasing oscillation pattern, then it assumes no more tripped lines and switches to the OPA model.

For each cascading scenario, resulting cascading failures are arranged as shown in Table I. As an example with cascade 1, the initial random line trips are grouped in generation 0 as R_0^1. Similarly, the next dynamically tripped lines are grouped in generation 1 as F_1^1. Then, the next tripped lines from the OPA model are grouped in generation 2 as S_2^1. Note that the dynamically tripped lines after S_2^1 are grouped in generation 3 as F_3^1. Algorithm 1 describes the pseudocode for the enhanced OPA model. Note that R^k in step 2 is constantly increasing with all previously tripped lines in a recursive manner.

III. NUMERICAL CASE STUDIES

This section presents case studies to illustrate the cascading failures resulting from the enhanced OPA model using the reduced NPCC (the Northeastern Power Coordinating Council) 140-bus system, which represents the northeast region of the Eastern Interconnection involved in the 2003 blackout [8].

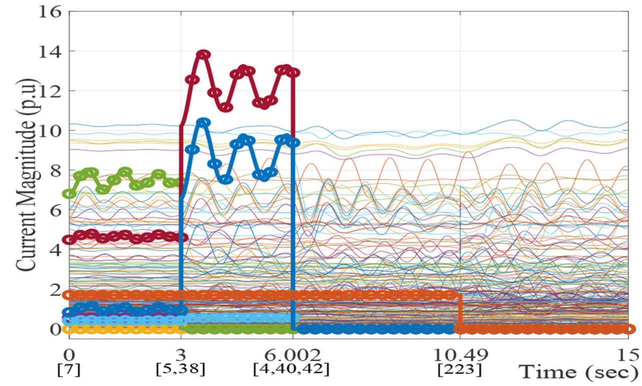

Fig. 2. Current magnitudes and cascading failures due to the line 7 failure.

A. Validation of Dynamic Simulation of Cascading Simulation

To validate the dynamic simulation of cascading failures, we first show the sequence of relay actions and resulting system dynamic behaviors as depicted in Fig. 2. For this particular example, the initial event was a single-line failure (i.e., line 7). The count-down timer of the fixed-time delay was set to $3s$. As illustrated, the system experiences the oscillation, and two lines become overloaded due to the one-line failure. Right after $3s$, the relay takes actions and trips those lines (i.e., line 5, 38). After this, other three lines (i.e., line 4, 40, 42) become overloaded and are tripped around $6s$. Then, one more line (i.e., line 223) is tripped at $10.49s$. The numbers below each time indicate the set of tripped lines at that time, and these dynamically tripped lines are highlighted with thicker plots.

This simulation result is then compared with the result from the G-PF model to validate its adequacy [9]. With the same initial failure, the G-PF model is solved to obtain a set of overloaded lines and is continuously resolved with the updated line failures with previously overloaded lines until either no overloaded lines or the divergence. Using this process, the sequence of line failures and simulation outputs between the G-PF model and the dynamic model are compared; the dynamic simulation can yield three different outputs in general: 1) unstable trajectory, 2) sustained oscillatory behavior, and 3) stable trajectory. The divergence in the G-PF model (i.e., infeasible PF solution) may correspond to output 1), and the convergence in the G-PF model (i.e., feasible PF solution) may correspond to output 2) and 3). We have checked this consistency with all single lines as well as hundreds of randomly selected two lines as the initial line failures and checked about 80% match between these two simulations.

B. Comparison With the OPA Model

This section presents the comparison between the OPA model and the enhanced OPA model. Table II summarizes the statistical difference with 1000 cascading scenarios. Here, type 2 cascading represents cascading scenarios whose cascading failures stop in generation 2 with no failures in generation 3 or higher. One may observe that the enhanced OPA model has more line failures

TABLE II
CASCADING FAILURES BETWEEN THE OPA AND ENHANCED OPA

	OPA	Enhanced OPA
Number of scenarios	1000	1000
Total number of line failures	2640	4024
Type 2 cascading	85%	74%
Type 2+ cascading	15%	26%

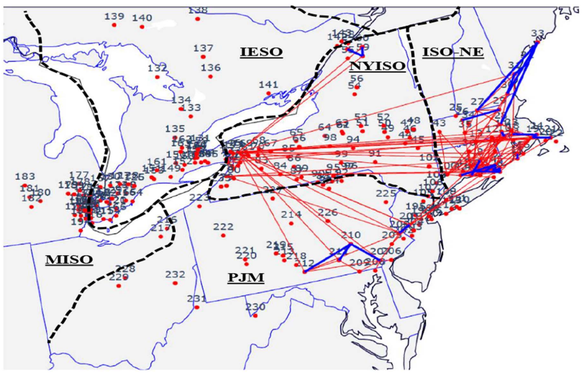

Fig. 3. Interaction graph with the OPA model.

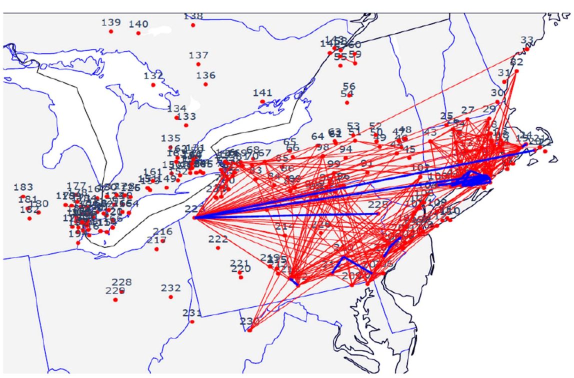

Fig. 4. Interaction graph with the enhanced OPA model.

and type 2+ cascading due to the incorporation of dynamically induced line trips.

With these cascading scenarios, we also compare the corresponding interaction graph, shown in Figs. 3–4 where the nodes denote lines in the NPCC system, the edges denote the links (representing that the failure of the source line causes the failure of the destination line) between lines, and the blue edges indicate 30 key links. As expected, the interaction graph with the enhanced OPA model in Fig. 4 shows more detailed cascading information and has a few key links over a long distance (about 10%) due to the collective dynamic effects, which are only captured with the enhanced OPA model. Note that about 80% of the 30 key links from the OPA model can be identified from the enhanced OPA model; in particular, around 60% of them are within 50 key links of the enhanced OPA. In the context of weak areas, the similarity is also shown; ISO-NE, NYISO, and PJM area are weak areas in both models.

IV. CONCLUSION

In the context of cascading failure simulation, the conventional dynamic model seldom considers outages of network components under control actions of operators, and the OPA model only considers quasi-steady-state behaviors and the slow evolving of the network in the form of the complex system dynamics without considering the fast transient dynamics. To this end, this letter has proposed the enhanced OPA model incorporating dynamically induced cascading failures to consider the effects of extra mechanisms associated with nonlinear transient dynamics and thus capture more realistic and detailed scenarios in simulating cascading failures. For future work, it is important to consider a wide range of protective relay models and quasi-dynamic models covering in mid- and long-term timescales to capture a more complete picture of cascading failure scenarios.

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