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Cascading Failure Model for Power Systems With High Penetration of Wind Power

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***Abstract*—In this paper, we propose a cascading failure model to generate cascading outage data for power systems with high penetration of wind power. The proposed model considers line outages due to overloading and wind turbine tripping due to voltage violations and electromagnetic transient disturbances. The impact of the electromagnetic transient disturbance of a line outage on a wind turbine is approximately considered by the electrical distance between the wind turbine and the line. Control strategies such as under voltage load shedding and generation re-dispatch are also considered. The proposed model is applied to the modified IEEE RTS-96 system with 30% and 50% wind power penetrations. The impact of high wind power penetration on failure propagation is revealed and the interactions between line outages and wind turbine tripping are analyzed.**

***Index Terms*—Blackout, cascading failure, electrical distance, overload, simultaneous tripping, simulation model, wind turbine.**

I. Introduction

Large-scale blackouts, such as the 2003 U.S.-Canadian blackout [1], have led to serious social and economic impacts. Due to the limited amount of outage data, various cascading failure simulation models have been developed, such as hidden failure model [2] and ORNL-PSerc-Alaska (OPA) model [3]. The simulated data has been studied for extracting failure propagation properties, such as by the branching process model [4], [5] and the component interaction models including interaction network [6], [7] and influence graph [8]. Recently, real utility outage data has also been analyzed to reveal the cascading failure propagation features [9]–[11].

However, these studies only involve the outage data in traditional power systems with conventional generating sources, and do not consider the renewable energy sources related challenges. These inverter-based resources might impair system stability by lowering the system inertia, causing fluctuations in frequency and voltage [12]. For the blackouts in Australia in 2016 [13], [14] and in U.K. in 2019 [15], both systems have high renewable penetration, especially wind power. In these blackouts, wind turbines were tripped due to lightning or transmission faults, and further caused frequency drop and voltage disturbances due to the loss of generation.

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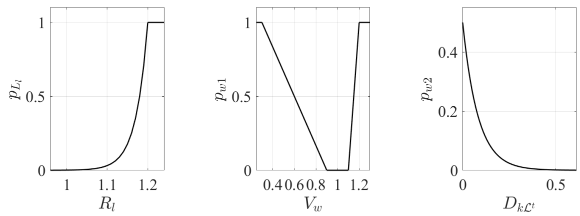
Unfortunately, the outage data with wind turbine tripping is limited. Hence, simulation models have been proposed to generate outage data for the systems with high wind power penetration. In [16], a simulation model with a fast cascading path searching method is proposed, simulating line outages under high wind generation scenarios. In [17], a stochastic simulation model based on AC power flow is used to study the failure propagation on the system with a large portion of wind power. Nonetheless, these two models do not include wind turbine tripping when failures propagate. Considering the wind power standard GB/T 19963-2021 in China, a wind turbine tripping probability function related to voltage violation is used in the simulation model in [18]. However, this model does not consider line outages in the failure propagation. Moreover, in addition to steady-state over/under-voltage, electromagnetic transients-related voltage disturbances could also contribute to wind turbine tripping [19] and should be considered.

Hence, to address the above problems, we propose a cascading failure simulation model for power systems with high penetration of wind power, aiming to generate realistic cascading failure data with both wind turbine tripping and line outages. Load shedding and operator re-dispatch strategies for overloaded lines are also considered in the proposed model.

The main contributions are summarized as follows.

1) We propose a cascading failure model to simulate cascading outages. The model considers line outages due to overloading and wind turbine tripping due to voltage violations and electromagnetic transient disturbances. The impact of the electromagnetic transient disturbance of a line outage on the wind turbine is approximately considered by the electrical distance between the wind turbine and the line. Besides, the model includes load shedding and generation re-dispatch as control strategies, making the simulation more realistic.
2) We test the proposed cascading failure model on a power system with 30% and 50% wind power penetrations. The simulated data clearly shows the impact of increased wind power penetration on more serious failure propagation, and reveals the interactions between some line outages and wind turbine tripping.

The remainder of this paper is organized as follows. Section



(a) (b) (c)

Fig. 1. Probability of (a) overloaded line tripping; (b) voltage limit violation tripping; and (c) simultaneous wind turbine tripping.

II defines tripping probabilities for lines and wind turbines based on the special operating requirements of these two components. Section III provides the control strategies of load shedding and generation re-dispatch to reflect the real operation. Section IV introduces the modified IEEE RTS-96 system and presents the result analysis of the simulated data. In the end, conclusions are drawn in Section V.

II. Transmission Line and Wind Turbine Tripping

Here we define the tripping probability functions for transmission lines and wind turbines.

A. Line Tripping

1) Initial line outage

In the proposed model, we use line outage as the trigger of a cascading failure. Each line is tripped by a small probability p_0. When there is at least one line tripping, a cascading failure is initiated and simulation continues.

2) Line tripping due to overloading

Lines have relatively high outage probabilities when they exceed their capacities. For an overloaded line l, we propose the following tripping probability function p_{L_l}:

$$p_{L_l} = \begin{cases} \epsilon_{L_l}, & R_l \leq 1 \\ a_{L_l} e^{b_{L_l} R_l}, & 1 < R_l \leq K_L \\ 1, & R_l > K_L, \end{cases} \tag{1}$$

where $R_l = F_l / \overline{F}_l$ is the loading ratio, F_l is the power flow of line l, $\overline{F}_l$ is the line capacity, K_L is a predetermined threshold, $a_{L_l} = \epsilon_{L_l} / e^{\frac{\ln \epsilon_{L_l}}{1-K_L}}$, and $b_{L_l} = \ln \epsilon_{L_l} / (1 - K_L)$. When $R_l \leq 1$, the tripping probability is a predetermined small value ϵ_{L_l}; when $R_l > K_L$, the line is heavily overloaded and we set its tripping probability as 1; when $1 < R_l \leq K_L$, the line tripping probability is described by the exponential function in (1). In Fig. 1(a) we show the p_{L_l} function with $\epsilon_{L_l} = 0.001$ and $K_L = 1.2$.

B. Wind Turbine Tripping

1) Tripping due to high/low voltage violation

According to high/low voltage ride-through standards, the tripping probability for a wind turbine is formulated as [18]:

$$p_{w1} = \begin{cases} 1, & V_w > 1.2 \\ (V_w - 1.1)/0.1, & 1.1 < V_w \leq 1.2 \\ 0, & 0.9 < V_w \leq 1.1 \\ (0.9 - V_w)/0.6, & 0.3 < V_w \leq 0.9 \\ 1, & V_w \leq 0.3, \end{cases} \tag{2}$$

where V_w is the voltage of the bus to which the wind turbine is connected. The curve of (2) is shown in Fig. 1(b). Though the wind turbines that are connected to the same bus share the same voltage, each wind turbine is tripped independently by probability p_{w1}. In this way, the wind turbines connected to the same bus may trip successively during the simulation.

Note that the V_w in (2) is obtained from the power flow calculation. It is rare to have a very severe voltage violation for a steady state calculated from power flow. Consequently, wind turbine tripping may not be easy to be triggered. To more realistically model wind turbine tripping, we also consider the simultaneous wind turbine tripping below.

2) Simultaneous tripping due to electromagnetic transients

Simultaneous tripping refers to wind turbines tripping off from the grid when they are under large voltage disturbances through electromagnetic transients [19]. Since performing electromagnetic transient simulation is time-consuming, in this paper the impact of the electromagnetic transient on wind turbines is approximately considered by using the distance between the failed line and the bus with wind turbines. We assume that the shorter the distance between the failed line and the bus with wind turbines is, the larger the voltage disturbance the wind turbine will experience and thus the higher the simultaneous tripping probability for the wind turbine is.

Consider the power network as a weighted graph where the buses are nodes and the lines are edges. The weight of an edge (line l) is defined as the electrical distance between its two buses, i.e., $w_l = \sqrt{r^2 + x^2}$ where r and x are, respectively, the resistance and reactance of line l in per unit. The distance between any two buses i and j, denoted by d_{ij}, is defined as the shortest path between them considering the weight of the edges. Then, the electrical distance between a bus k and a line $l : s_l$–t_l is defined as $D_{kl} = \min\{d_{ks_l}, d_{kt_l}\}$.

Assume the set of lines that are tripped in the current loop of simulation is $\mathcal{L}^{\mathrm{t}} = \{l_1, \cdots, l_L\}$. The simultaneous tripping probability of a wind turbine connected to bus k is:

$$p_{w2} = \begin{cases} \epsilon_{w_2}, & D_{k\mathcal{L}^{\mathrm{t}}} > K_D \\ a_w e^{b_w D_{k\mathcal{L}^{\mathrm{t}}}}, & 0 < D_{k\mathcal{L}^{\mathrm{t}}} \leq K_D \\ p^{\mathrm{high}}, & D_{k\mathcal{L}^{\mathrm{t}}} = 0, \end{cases} \tag{3}$$

where $D_{k\mathcal{L}^{\mathrm{t}}} = \min\{D_{il_1}, \cdots, D_{il_L}\}$, K_D is a predetermined threshold, $a_w = p^{\mathrm{high}}$, and $b_w = (\ln \epsilon_{w_2} - \ln p^{\mathrm{high}})/K_D$. If a line outage happens and a wind turbine connects to one of its buses, then $D_{k\mathcal{L}^{\mathrm{t}}} = 0$ and p_{w2} is set as a high probability p^{high}; when $D_{k\mathcal{L}^{\mathrm{t}}} > K_D$, the voltage disturbance on the wind turbine due to the line outage is small enough to be ignored, and we set p_{w2} to be a predetermined value ϵ_{w_2}. When $D_{k\mathcal{L}^{\mathrm{t}}}$ is between these two values, the wind turbine tripping probability

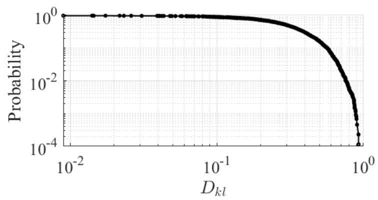


Fig. 2. CCD of the distances between a bus and a line in the IEEE RTS-96 system.

is described by the exponential function in (3), which is shown in Fig. 1(c). In this paper, we set $\epsilon_{w_2} = 0.001$ and $p^{\text{high}} = 0.5$. For the IEEE RTS-96 system [20], the complementary cumulative distribution (CCD) of all D_{kl}'s is shown in Fig. 2. With the calculated D_{kl} between each pair of bus and line, we choose $K_D = 0.51$ as the 85th percentile of all values.

III. Control Strategy and Model Flowchart

Cascading failure can be suppressed by various control strategies during failure propagation. These strategies include load shedding that maintains voltage stability and generation re-dispatch by the operator to avoid further line outages caused by overloading. In this paper we consider both strategies.

A. Under Voltage Load Shedding

The very low voltage of a bus may active under voltage load shedding. In the simulation, when the voltage of a load bus i, V_i, is below a threshold V_{th}, the system starts to shed active load $\Delta P_{\text{sh},i}$ as:

$$\Delta P_{\text{sh},i} = \min\left(K_{\text{sh}} \Delta V_i, P_i^d\right), \tag{4}$$

where P_i^d is the active load of bus i and K_{sh} is a load shedding constant [21]. we choose $V_{\text{th}} = 0.9$ p.u. for every bus and $K_{\text{sh}} = 600$.

Besides, the reactive power to be shed at load bus i, $Q_{\text{sh},i}$, is calculated as:

$$\Delta Q_{\text{sh},i} = Q_i^d \frac{\Delta P_{\text{sh},i}}{P_i^d}, \tag{5}$$

where Q_i^d is the reactive load of bus i.

B. Generator Re-Dispatch by Operator

When a cascading blackout starts, the operators can monitor the power flow and re-dispatch the generators when there are overloaded lines. The re-dispatch sequence is decided based on R_l and the operator first adjusts generation to eliminate the overloading of the line with the highest R_l.

For a chosen line l, the generators are ranked by the power transfer distribution factor (PTDF) defined in (6):

$$\text{PTDF}_{g,l} = \frac{\Delta f_l}{\Delta P_g}, \tag{6}$$

where Δf_l is the change in active flow on line l when a power injection change ΔP_g is made at a bus g with a generator. When adjusting generation, we prioritize the generators with the largest positive PTDF values, followed by the generators

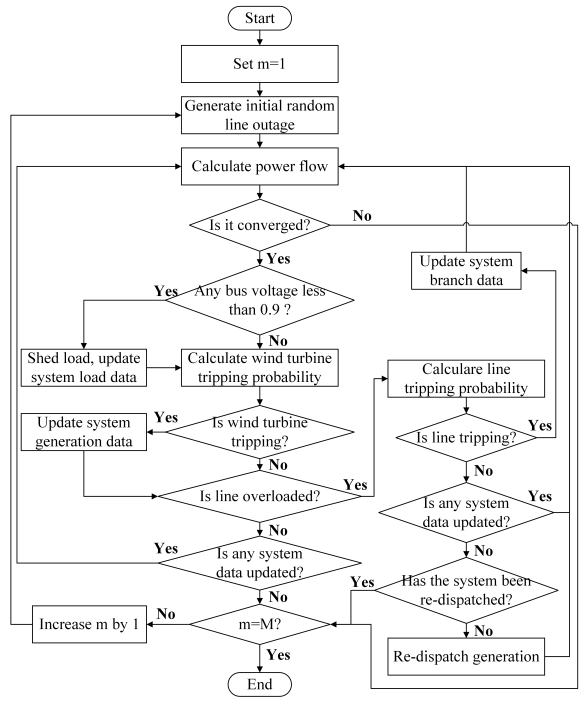


Fig. 3. The flowchart of the proposed cascading failure model.

with the smallest negative PTDF values. Specifically, the real power output of a generator at bus g is re-dispatched as:

$$\text{P}_g = \text{P}_g^0 + \frac{\overline{F}_l - F_l}{\text{PTDF}_{g,l}}, \tag{7}$$

where P_g^0 is the initial power injection at bus g.

C. Flowchart of the Proposed Simulation Model

The flowchart of the proposed simulation model is shown in Fig. 3. The simulation model is used to generate M cascades to make sure there is enough data for analysis. The major steps for simulating one cascade are summarized as follows.

1) For each cascade m, initial line outages are generated as in Section II-A1.
2) Update system data after initial outages and calculate power flow. Check if there is any wind turbine tripping or load shedding based on (2)–(3) and (4)–(5). If yes, update the system data.
3) The calculated power flow after initial line outages helps decide the overloading situation of each line, based on which the following steps will be performed.
   - 3.1) If there is no overloaded line, go to the next cascade if the system data is not updated from the last step; otherwise, calculate power flow based on updated system data.
   - 3.2) If there is an overloaded line, calculate line tripping probability by (1) and trip the line according to this probability. If at least one line trips, update the system data and calculate power flow for the updated system; if there are overloaded lines but no system update, go to re-dispatch.

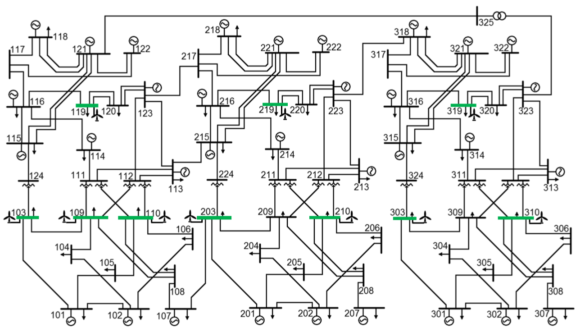


Fig. 4. IEEE RTS-96 system.

- 3.2.1) Since the time left for the operators to do re-dispatch is limited during cascading failure, we allow operators to do generation re-dispatch up to three times in each cascade, and power flow is calculated for further propagation.
- 3.2.2) If there are still overloaded lines but no system data update after the re-dispatch, go to the next cascade, assuming the overloading situation can be eliminated by other techniques such as optimal power flow.

IV. Simulation Results

A. *Modified IEEE RTS-96 System*

The IEEE RTS-96 system, as shown in Fig. 4, has 120 transmission lines and 73 buses, among which one is the slack bus and 32 are PV buses [20]. In this paper, we connect wind turbines with a capacity of 1.5 MW to 10 buses (buses 103, 109, 110, 119, 203, 210, 219, 303, 310, and 319), which are the PQ buses with the top ten heaviest active loads. These 10 buses are highlighted in green in Fig. 4.

The numbers of wind turbines connected to each bus are 170 and 286, with a real power generation of 255 MW and 429 MW, respectively for 30% and 50% wind power penetration. With the load in the system unchanged, the active powers of the original generators are reduced to 70% and 50%.

B. *Simulation Result Summary*

The proposed cascading failure simulation model is applied to the modified RTS-96 system to generate $M = 3000$ cascades. The power flow calculation in the proposed model is performed by MATPOWER [22]. A summary of the simulated data for both scenarios is listed in Table I.

In this paper, an outage can be a line outage or a wind turbine tripping event. Anytime when at least one wind turbine connected to a bus trips, it is counted as a wind turbine tripping event. As seen in Table I, with the wind penetration level increased by 20%, the number of total outages increases by 9.4%. The CCDs of the total number of outages in each cascade are shown in Fig. 5. Under higher wind power penetration, the number of outages is larger and the probability for the same size of cascade is higher, compared to that for the system with 30% wind power penetration. Higher wind power penetration leads to more serious failure propagation.

TABLE I
RESULT SUMMARY

Wind power penetration	30%	50%
# of total outages	31,625	34,606
# of line outages	6,192	6,479
Line with most frequent outages	208–209	203–209
# of times that line 208-209 and 203–209 fail	99	147
# of wind turbine tripping	25,434	28,127
Bus with most frequent wind turbine tripping	219	219
# of times that bus 219 has wind turbine tripping	2876	3100

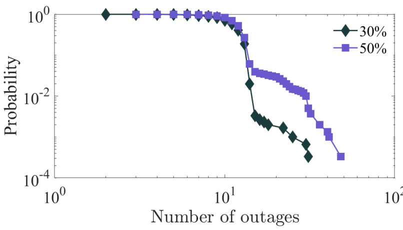


Fig. 5. CCDs of the total number of outages.

TABLE II
INTERACTION BETWEEN LINE OUTAGES AND WIND TURBINE TRIPPING

Wind power penetration	30%	50%
Top 3 line outages following which there are the most wind turbine tripping	**316-319** 113-215 119-120	**203-209** 201-203 216-217
# of wind turbine tripping following the top 1 line outage	678	1078

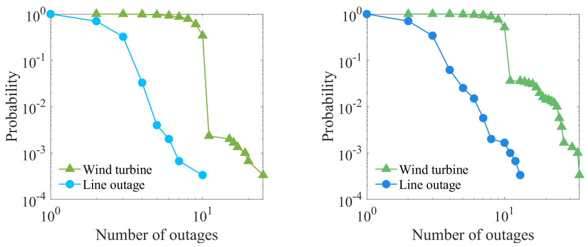
When wind power penetration increases from 30% to 50%, the number of line outages increases by about 9% and the line that outages most frequently changes from line 208–209 to line 203–209, respectively with the corresponding number of outages as 99 and 147.

With the increased wind power penetration, the number of wind turbine tripping also increases by 10%. The wind turbines at bus 219 trip most frequently. This can be explained by the fact that it has the smallest average distance between this bus and all lines among all buses with wind turbines. According to the proposed wind turbine tripping probability in Section II-B2, it has a high chance to trip.

Fig. 6 shows the CCDs of the number of wind turbine tripping and line outages under different levels of wind power penetration. The number of wind turbine tripping is larger than that of line outages.

C. *Analysis of the Interactions Between Line Outages and Wind Turbine Tripping*

The interactions between line outages and wind turbine tripping are analyzed, and the results are listed in Table II. We rank the line outages according to the number of times that wind turbines trip after them and list the top 3 of them in Table II. For the two wind power penetration levels, the top 1 line outage is, respectively, line 316–319 and line 203–209. With a 20% increase of the wind power penetration, the number of



(a) (b)

Fig. 6. CCDs of the number of wind turbine tripping and line outages in the system with (a) 30% wind power penetration and (b) 50% wind power penetration.

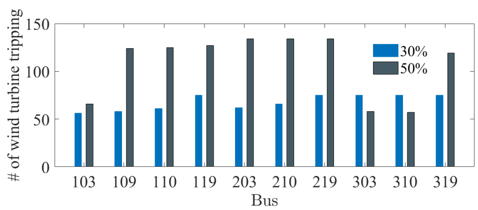


Fig. 7. Number of wind turbine tripping following the Top 1 line outage in Table II.

involved wind turbine tripping increases significantly from 678 to 1078, indicating that the interaction between line outages and wind turbine tripping becomes stronger. Also, under 50% wind power penetration, the most frequency line outage in Table I happens to be the top 1 line outage in Table II.

In Fig. 7 we show the number of wind turbine tripping for the ten buses with wind turbines after the outage of the Top 1 line in Table II. This can help identify the lines and the buses that have strong interactions. For example, under 50% wind power penetration, buses 203, 210, and 219 have the strongest coupling with the outage of line 203–209. Based on this useful information, mitigation strategies can be developed to suppress the failure propagation and reduce the risk of cascading.

V. Conclusion

In this paper, a cascading failure model is proposed for power systems with high penetration of wind power. This model considers line outages and wind turbine tripping, together with control strategies such as load shedding and generation re-dispatch by the operator. The proposed model is applied to the modified IEEE RTS-96 system. The results show that higher wind power penetration can lead to more serious failure propagation. The simulated data is also used to analyze the interactions between line outages and the buses with wind turbine tripping and identify the components with strong coupling. In our future work, more detailed analysis of those interactions will be performed.

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