Causal Network Analysis using Markov Chain

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Abstract- When components of a power grid fail, due to a storm, malfunction or cyber-attack, a cascading sequence of subsequent component failures may occur, which may lead to a very large blackouts. Hence, a timely prediction of the components that are most likely to fail next, given a list of a few components that have failed, may enable operators to take mitigating actions such as shutting down sections of the power grid before a large-scale blackout occurs. The proposed model can determine a large number of possible cascading failure chains in IEEE 118 bus system through causal network analysis using Markov chain.

Index Terms- Cascading failure, Causal Network, Markov Chain

1. INTRODUCTION

Power system, one of the most complex networks in modern society, plays a major role in our daily life. The fast growth of its size and diversity, as well as the rise of the smart grid, has brought many challenges involving stability issues and the following occurrence of blackouts. Blackouts are not so frequent, but extensively risky due to their catastrophic effects. For example, a large blackout happened on November 1, 2014 where 100 million people in Bangladesh, out of a total of 160 million, were without electricity for about 10 hours [7]. A summary of major blackouts occurred in recent years is presented in Table 1 [1].

These blackouts draw wide attention from both academia and industry. Such large blackouts are more complex than normal electric outages which are caused by small disturbances. Actually, these major blackouts are due to complex mechanisms rather than simple component failures. From the reports of those blackouts, cascading failure is found to be the key factor leading to a large blackout. According to North American Electric Reliability Corporation (NERC), a cascading failure is "the uncontrolled successive loss of system elements triggered by an incident at any location [1]." In fact, sometimes the cascading failure is initiated by more than one disturbance. In reality, most electric power grids are using N-1 secure criterion, which means the system could keep working under normal status with a single failure. However, other likely failures, such as hidden failures in relays or errors during operating procedures, may amplify the failure and trigger more components, finally lead to a cascading failure. In general, the failure of components can cause the redistribution of the power flow in the power system, and then lead to the overload of other transmission lines or dynamic instability problems of generation units, thus forming the cascading failure and ultimately affect a very large area.

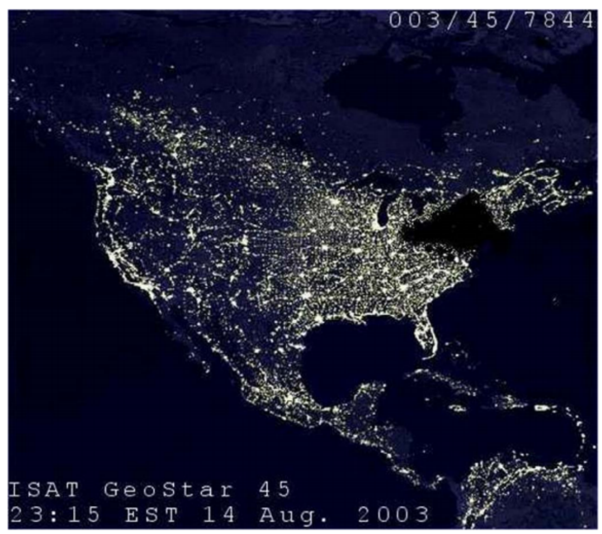

Fig. 1. The satellite photograph shows a totally black zone in the northeast of North America due to blackout [1].

There are various causes for a cascading failure [2]. External factors that initiate the event, and internal events that trigger the components can be commonly classified as four groups:

• **Nature disasters:** Lightening strike, strong winds (hurricane, tornado), and earthquakes.
• **Human activity**: Errors made by human mis-operations, incorrect setting for protection devices, intentional physical or cyber-attacks on power grids.

• **Unexpected component failures:** Hidden failures which is exposed during changing operation status, transmission line that contact plants.

• **System failures:** Distance relays trigger the transmission line due to overcurrent or undervoltage, voltage collapse, generators tripped by under-frequency, abnormal excitation in generators, abnormal speed in generators, generators tripped by out-of-step, generators tripped by under-voltage, insufficient reactive power, small signal instability etc.

Reference [3] provided a comprehensive overview of all current methodologies to discuss cascading failures in power systems, and it concluded six types of research methodologies: 1) from security to resilience, 2) critical components and high risk multiple contingencies, 3) network theory approaches, 4) probabilistic and deterministic approaches, 5) conventional reliability methods [12], and 6) high-level probabilistic models.

In this paper, the proposed model can determine a large number of possible cascading failure chains in IEEE 118 bus system for any transmission line failure through causal network analysis using Markov chain.

The remainder of this paper is organized as follows. In section 2, the basics of causal network and event precedence model has been explained. In section 3, the model was tested on IEEE 118 bus system as a case study. Finally, section 4 concluded merits and demerits of the methodology.

2. PRELIMINARIES

In this section, we introduce the concepts that are central to the techniques explained in the paper.

2.1 CAUSAL NETWORK

A causal network is a directed acyclic graph G = (V, E) to represent causality, where V is the set of nodes representing event types i.e. transmission lines and E is the set of edges between nodes and the weights are the conditional probability of the failure of the transmission lines. For each directed edge, the parent node indicates the cause, and the child node means the effect.

2.2 EVENT PRECEDENCE MODEL

The proposed evet precedence model (EPM) is a first-order absorbing Markov chain [5]. As a required condition for causality, EPM models the temporal precedence relationship between events as a first order Markov chain which is independent of all previous observations except the most recent one, the probability [4] of occurrence of an effect event given past cause events is

$$w = \sum_{m}^{M} P(A|B_m)P(B_m)\,;[\mathrm{d} > 1]$$

$$s.t.\ P(A|B) = FP(A)_d$$

$$P(B) = FP(B)_{d-1}$$

$$FP = \frac{FC}{N}$$

FP = Failure Probability

FC = Number of failure occurrence

N = total number of sample space

Table 1. List of major blackouts since 2003

Blackout Llocation	Date	People affected (Millions)	Loss of load (MW)	Estimated cost (Million Dollars)	Time duration	Improvements after blackout
Kenya	7 June 2016	44	N.A.	N.A.	< 3 h	N.A.
Sri Lanka	13 March 2016	21	800	N.A.	> 4 h	Adopting 'must run units'
Turkey	31 March 2015	70	32.2	700	> 7 h	Improve overload monitoring and protection of transmission lines
India	30–31 July 2012	670	48	6000	2–8 h	New load shedding strategies
Brazil	4 February 2011	40	8.884	N.A.	> 3 h	Implement new islanding protection scheme
Brazil and Paraguay	10–11 November 2009	87	24,436	N.A.	4–6 h	Introduce House Load Operation (HLO) and new restoration strategies
Colombia	26 April 2007	41	6.644	130	> 4 h	Improvements of communication channels among the control centres
Europe	4 November 2006	45	14.5	N.A.	2 h	Amendments UCTE Operation Handbook
Pakistan	24 September 2006	160	11.16	N.A.	5–6 h	N.A.
Italy	28 September 2003	57	24	1200	5–9 h	Implement Day-Ahead Congestion Forecast (DACF)
London	28 August 2003	0.5	724	N.A.	> 30 mins	Enhance cooperation between utility companies
North America	14–15 August 2003	50	61.8	Over 10,000	5–72 h	Introduce higher reliability standards for North American electricity industry

3. RESULTS AND DISCUSSION

The methodology was applied to IEEE 118 bus systems, 186 transmission lines and the experiment was done in MATLAB® R2017b. Fig 2 and Fig 3 represents the failure occurrences (FC) and failure probabilities (FP) of 186 transmission lines in the 16430 cascade sequences. In Fig 4, the Event Precedence Network (EPN) is shown. The EPN was constructed by considering each transmission line as a node V where the degree of each node is 5. That means for each node, next top five events are considered in order to make the causal network acyclic. The weights colored from blue to red means the highest to lowest of the conditional probability between two nodes

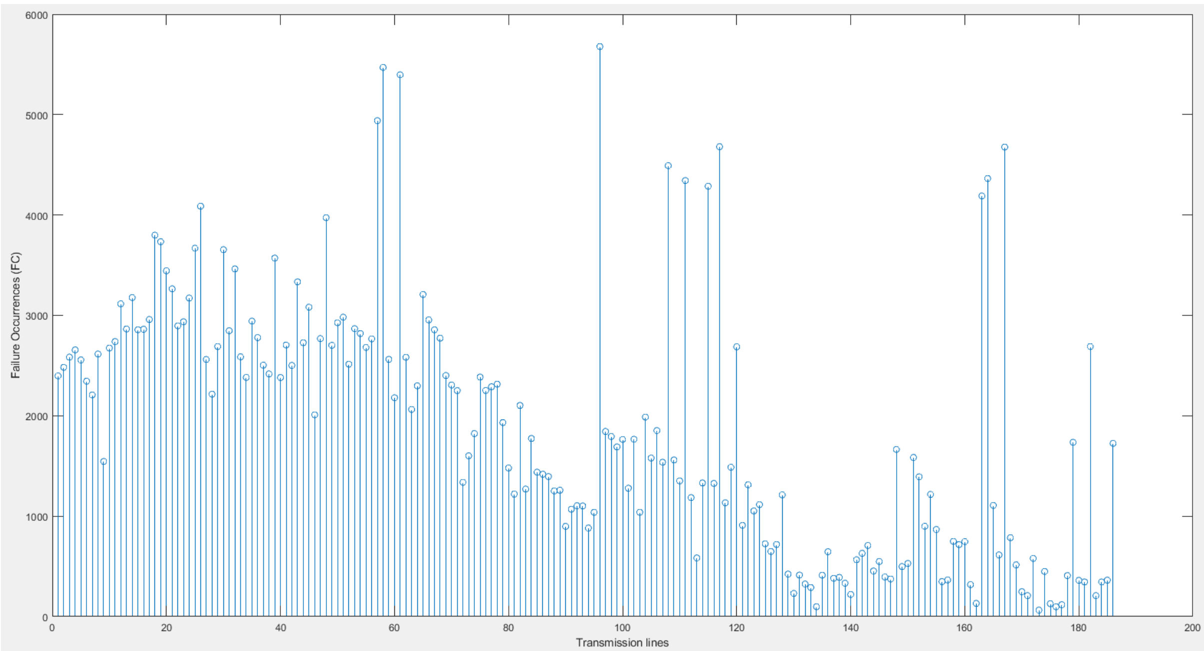

Fig 2. Failure occurrences of 186 transmission lines in the 16430 cascade sequences

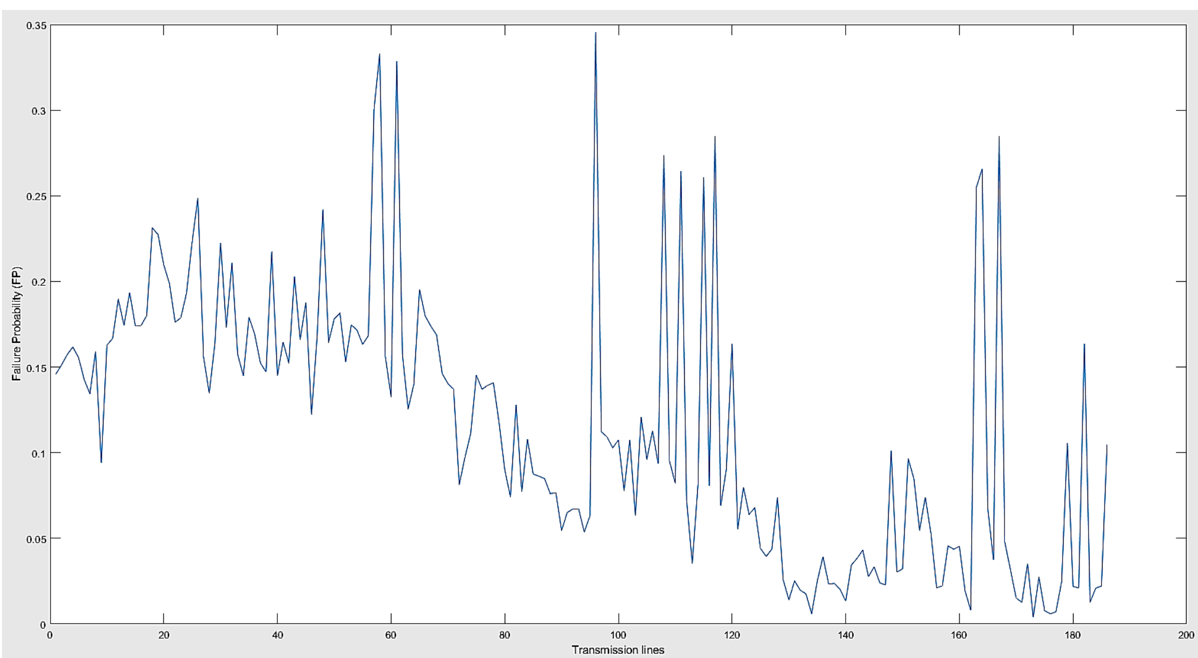

Fig 3. Failure probabilities of 186 transmission lines in the 16430 cascade sequences

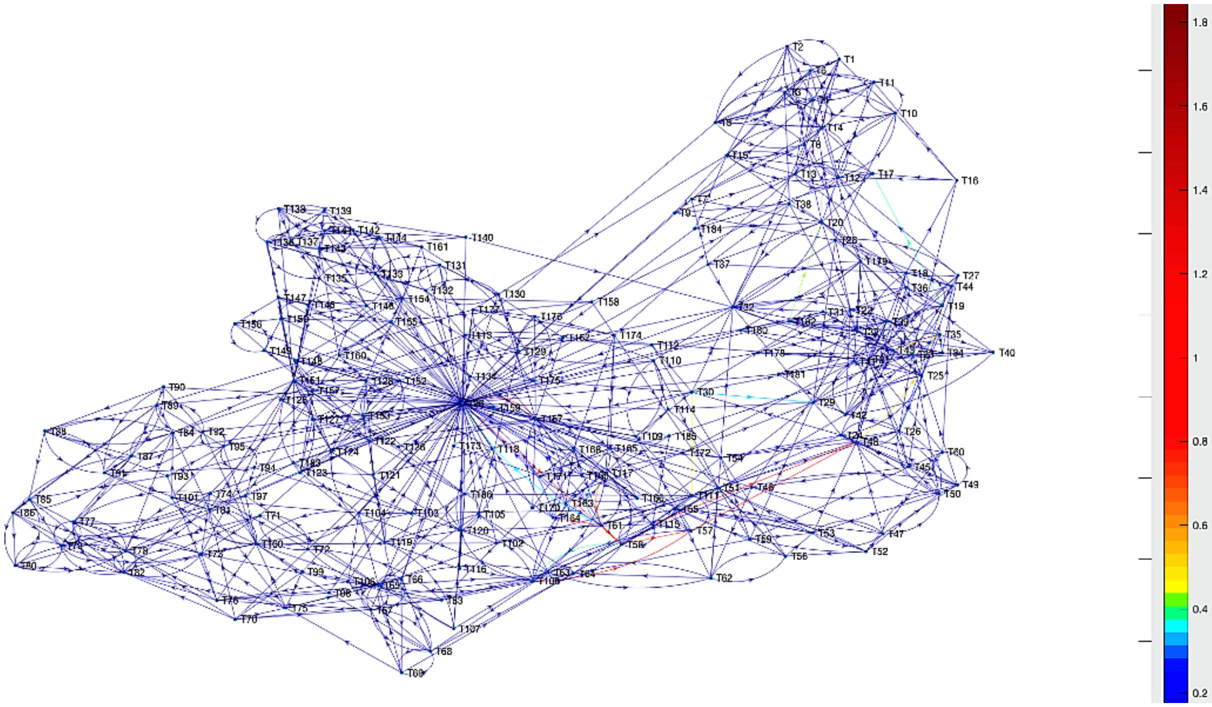

Fig 4. Event Precedence Network (EPN)

Table 2. Five examples for the initial failure of transmission line 96, 58, 61, 57, 117 respectively and their corresponding sequence and weights. The weight represents the conditional probability of failure between two stages. For each initial transmission failure, the runtime from stage 1 to stage 6 is 40 seconds.

Stages	Stage 1: Initial Failure	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Transmission line	96	61	58	117	108	115
Weight		$W_{1,2}$	$W_{2,3}$	$W_{3,4}$	$W_{4,5}$	$W_{5,6}$
		0.05595	0.0071819	0.00064957	3.4596e-05	1.8605e-06
Transmission line	58	117	108	115	57	111
Weight		$W_{1,2}$	$W_{2,3}$	$W_{3,4}$	$W_{4,5}$	$W_{5,6}$
		0.039433	0.0028848	0.00021835	1.9954e-05	1.8447e-06
Transmission line	61	58	117	108	115	57
Weight		$W_{1,2}$	$W_{2,3}$	$W_{3,4}$	$W_{4,5}$	$W_{5,6}$
		0.076913	0.0085807	0.00079525	7.1517e-05	7.4419e-06
Transmission line	57	111	30	167	164	163
Weight		$W_{1,2}$	$W_{2,3}$	$W_{3,4}$	$W_{4,5}$	$W_{5,6}$
		0.052356	0.0038399	0.00027839	2.4117e-05	2.4253e-06
Transmission line	117	108	115	57	111	167
Weight		$W_{1,2}$	$W_{2,3}$	$W_{3,4}$	$W_{4,5}$	$W_{5,6}$
		0.03156	0.0023876	0.00020091	1.7639e-05	4.5936e-07

For example, if the initial transmission line failure is 96, then the failure occurrences of transmission line 96, FC (96) = 5678. The Failure probability of transmission line 96, FP (96) = FC (96) / total number of cascade sequences = 5678 / 16430 = 0.346

The initial failure of transmission line 96 leads to the failure of 170 transmission lines among 186 lines. Among these 170 failed transmission lines, transmission line 61 has the highest number of failure occurrences which is FC (61|96) = 2660. Thus, from stage 1 to stage 2, the conditional probability of failure or weight, FP (61|96) = $w_{1,2}$ = [FC (61|96) / (total number of sample space)]*FP (96) = [2660 / (total number of pairs between stage 1 to stage 2)] * 0.346 = [2660 / 16430] * 0.346 = 0.05595

After the failure of transmission line 61, next the transmission 58 has the highest number of failure occurrences which is FC (58|61←96) = 2109. Thus, from stage 2 to stage 3, the conditional probability of failure or weight, FP (58|61←96), $w_{2,3}$ = [FC (58|61←96) / (total number of sample space)]*FP(61|96) = [2109 / (total number of pairs between stage 2 to stage 3)]* 0.05595 = [2109 / 16430]* 0.05595 = 0.0071819.

4. CONCLUSIONS AND FUTURE WORK

The proposed model can determine the cascade sequence due to the failure of any transmission line Event precedence mechanism allows to automatically build a tractable probabilistic graphical model from the events and discovers the existing dependencies among the event types in the event stream. Storing conditional probabilities in the edges facilitates computing the probability of an effect given the occurrence of a cause effect. Event Precedence Network makes the probability model visualized, so that the failure sequence of transmission lines can be easily observed from the graph. The proposed model can determine a large number of possible cascading failure chains in IEEE 118 bus system as ‘‘experience’’ which can be further used to predict the cascading failure propagation with the highest possibility obtained from the ‘‘experience’’. The proposed model can also be implemented on the Web-based online systems in which they display the same content for everyone. However, the user experience can be more productive with a dynamic system where content is displayed based on real-time prediction of users’ most likely activities, given historical data. One can use the results (i.e. the web pages/links most likely to be visited next) to display the most relevant links, content and advertisements at each step of the user activity.

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