Controlling Cascaded Failures in Interdependent Networks.

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***Abstract*—Vulnability due to interconnectivity of multiple networks has been obsereved in many complex networks. While many failure resilient network designs have been proposed in the literature; the transient state of the system or failure/attack mitigation strategies has not been studied extensively when the system is still in transient state. This paper studies the problem of controlling interdependent networks from both the attackers view and the mitigation view. We propose a mitigation strategy in two steps: 1)Once the cascaded is detected in the system, we prevent further disruption by reducing the load or increasing the generator's power. 2)we propose a recovery plan to maximize the total inoperability of the network during recovery time.**

***Index Terms*—Interdependent networks; Cascaded failures; Optimization**

I. Problem Definition

Many man-made or natural systems can be modeled as an interconnection of multiple networks, where the nodes are the system components and the edges show the interaction or dependency between different components. Because of the dependency between different components in multiple networks, perturbations caused by physical attacks or natural disasters in one node can cascade and affect other nodes in the sysetm. The cascaded failure can repeat multiple times and result in a total failure of the whole system. Cascaded failures in interdependent networks have been studies in several works [1, 2, 3, 4, 5, 6, 7]. The existing works on interdependent networks are mainly divided into three categories: 1) those which study the interaction through percolation/epidemic theory [4, 5, 6, 7] 2) the works which try to identify most vulnerable nodes and design failure resilient networks [1, 8, 9], 3) and the works which try to find the root cause of failures [10, 11]. But to the best of our knowledge, the transient state of the system or failure/attack mitigation strategies has not been studied extensively when the system is still in transient state. Percolation/epidemic-based approaches depend on having a prior knowledge about the probabilistic model of failure propagation which is hard to realize. In addition, real systems usually have a deterministic failure propagation. For example, if a power line fails, certain number of communication routers will certainly stop working. Finding root cause of failure which is shown to be NP-Hard [10] is the key to design restoration algorithms. Identifying most vulnerable nodes and root cause of failures help to design failure-resilient systems but does not provide a mitigation solution when the failure happens in the system.

We aim to study the system under attack/failure to control the system such that the attack/failure is detected while the system is in transient state. We propose mitigation strategy to avoid further cascade and propose a recovery plan to maximize the total operability of all network components during K steps of recovery.

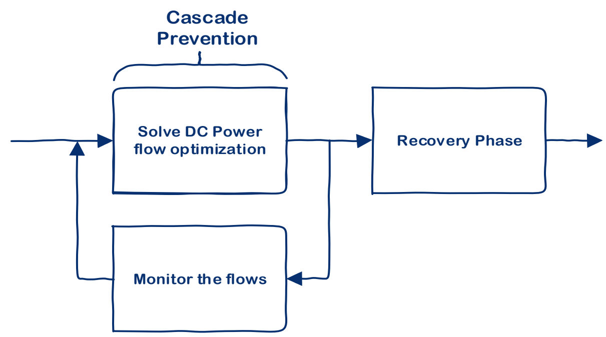

Fig. 1: Recovery Process: 1) Re-distribution of power, 2) Recovery phase.

II. 2-phase Recovery approach: Power network case study

In this section, we study recovery process for a cascaded failure in power network. Figure 1 shows the recovery process in two phases: 1) preventing the cascade using a combination of load shedding and adjusting the generated power, and 2) Recovery phase.

A. Preventing the cascade (Min-CFA)

We model the cascaded failures in a power system using a DC load flow model [12]. The DC power flow model provide a linear relationship between the active power flowing through the lines and the power generated/consumed in the nodes, which can be formulated as follows:

$$F_{ij} = \frac{V_i - V_j}{x_{ij}} \tag{1}$$

Where, F_{ij} is the power flow in line (ij), x_{ij} is the series reactance of line (ij) and V_i and V_j are the voltage of node i and j. The power flow of node i can be found by summing up the power flow of all its adjacent power lines:

$$P_i = \sum_j F_{ij} \tag{2}$$

We can re-write the power flow model as a linear system of equations as follows:

$$F = XP \tag{3}$$

Where $x_{ij} = -\frac{1}{x_{ij}}$ for $i \neq j$ and $x_{ii} = \sum_k \frac{1}{x_{ik}}$.
Once a transmission line trips, the power is redistributed according to equation 3 and if the power exceeds the maximum threshold on another line (ij), the transmission line (ij) will also disconnect unless we reduce the total load or re-distribute the generated power. Once we detect an outage of the transmission line, we run an optimization to avoid cascaded failure.
Minimum Cost Flow Assignment (*Min-CFA*) optimization problem tries to minimize the total cost of increasing the generated power and reducing the load. Let w_{g_i} be the weighted cost of increasing the power in generator g_i and w_{L_i} be the weighted cost of decreasing the power of load L_i.

$$\begin{aligned}
\text{minimize} \quad & \sum_{g_i \in G, L_j \in L} w_{g_i} P_{g_i} - w_{L_j} P_{L_j} \\
\text{subject to} \quad & 0 \leqslant P_{g_i} \leqslant P_{g_i}^{max}, \ \forall g_i \in G \\
& 0 \leqslant P_{L_j} \leqslant P_{L_j}^{demand}, \ \forall L_j \in L \\
& -F_{ij}^{max} \leqslant F_{ij} \leqslant F_{ij}^{max}, \ \forall (ij) \in E \\
& \sum_{g_i \in G, L_j \in L} P_{g_i} + P_{L_j} = 0. \\
& F = XP
\end{aligned} \tag{4}$$

The first constraint indicates that the generated power of each generator can not exceed a maximum threshold. The second constraint shows that the reduced load can not exceed the demand. The third constraint shows that the power flowing each line can not exceed the maximum capacity of the line. The fourth constraint is the power conservation condition, i.e the total power generated in the generators should be equal to the total power consumed in the loads; and the last constraint is the DC power flow model.

B. Recovery Phase (Max-R)

In the general cascaded model, suppose that recovery of each failed network component n_i lead to the recovery of a set of nodes S_{n_i}. Also, suppose that at each iteration of the recovery R_k resources is available and repairing n_i needs r_{n_i} resources. The maximum recovery (*Max-R*) optimization can be modeled as a mixed integer programming where we want to maximize the coverage of the repaired nodes over K steps of the algorithm. Let N_k^R be the set of nodes which have been restored up to time step k and let S_{k,n_i} be the coverage of node n_i in the kth time step of the algorithm:

$$\begin{aligned}
\text{maximize} \quad & \sum_{k=1}^{K} \Big| \bigcup_{n_i \in N_k^R} S_{k,n_i} \Big| \\
\text{subject to} \quad & \sum_{j=1}^{k} \sum_{n_i \in N_k^R} \delta_{n_i j}.r_{n_i} \leq \sum_{j=1}^{k} R_j \ \ k = 1, ..., K \\
& \sum_{k=1}^{K} \delta_{n_i k} \leq 1, \ \forall n_i \in N_k^R \ \ k = 1, ..., K. \\
& \delta_{n_i,k} \in \{0,1\}, \ \forall n_i \in N_k^R \ \ k = 1, ..., K.
\end{aligned} \tag{5}$$

Where $\delta_{n_i,k}$ is the decision variable to repair n_i at the kth iteration of the algorithm.

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