Efficient and Cooperative Failure Control in Smart Grid

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***Abstract*—Failures in the transmission network compromise the proper delivery of energy in a power grid. Control actions planned solely by a power utility (or operators) whose domain contains the failure cannot provide a strategy that guarantees the global stability of the grid. Such inappropriately addressed failures may develop a cascading behavior that can cause large-scale blackouts. In this paper we propose a distributed system to control failures based on cooperation agreements between different control domains of a Smart Grid. We design a control mechanism that generates low communication overhead and makes use of only local information (tie-lines) while providing a global stability. We also provide a guarantee for the system to cooperate to deliver as much energy as possible to meet the global demand. Our results show that our design can yield an increased amount of demand while maintaining low communications overhead compared to other distributed approaches.**

I. Introduction

The proper control of the transmission network is essential to provide reliable supply of energy. In contrast to the traditionally automatic local control, Smart Grid control is expected to be well planned, coordinated and able to quickly respond to current conditions of the power grid. Upon the occurrence of a failure, a control center will inform and control relevant grid elements for corrective actions to alleviate the effect of failures.

The power transmission grid comprises a very large number of components, including generators, various electricity loads, and power lines. If a single control center is used for managing the whole grid, it would create a single point of failure for the system and a bottleneck for the data network to transmit control messages. Moreover, the power grid is a traditionally distributed system consisting of power utilities, independent system operators (ISOs) and regional transmission organizations (RTOs), each of them with different geographical regions defining different control domains. The inherent regionalization of the power grid helps to reduce the power control complexity, and makes the overall grid management more scalable. When a failure occurs, one could expect that corrective control be performed by the control center of the corresponding region.

Due to the physical behavior of electricity, failures can affect and extend to other regions. Also, control actions within a single region can affect neighboring or even distant regions. Hence, control actions performed by different regions should be coordinated, timely communicated, and cooperative. Despite its importance, existing power grids often have very limited coordination between neighboring regions. Moreover, a power operator can be reluctant to implement new coordinated control applications that require sharing of sensitive information such as its private power system operational states.

In this paper, we propose a distributed control mechanism to efficiently alleviate the effects of failures. Our aim is to quickly bring the global transmission network back to the stable operation while delivering as much power as possible. Our proposed solution can ensure power cooperation to timely recover the transmission grid after the failure, while only requiring the information on links between 1-hop neighboring regions for low overhead coordination and restricting the access to private information.

The paper is organized as follows. In Section II, we summarize the related work on failure control and distributed networked systems for Smart Grids. Section III describes the models used. In Section IV, we present our proposed control mechanism step by step. We evaluate the performance of our work in Section V, and conclude the paper in Section VI.

II. Related Work

Power grid control based on automatic protections and adaptive systems based on local signals, e.g. AGC, PSS, VAC, have been extensively implemented and studied in the literature. However, in the recent years large-scale failures still occur, and reports show the lack of coordination of the inherent distributed power grid system to be one of the main causes for the low resiliency of the grid [1]–[3].

A centralized control has been proposed in [4], [5] to overcome failures, which demonstrates the feasibility of coordinated and planned wide-area networked control. However, such a centralized approach is not coherent with the distributed nature of power grid organization. Moreover, a centralized control would incur in a large communication overhead to exchange global information across the wide area networks.

Some distributed mechanisms have been presented in the context of power networks. In [6] the distributed estimation of power system states is robust to bad data. Also, recently in [7] the authors present a distributed energy management

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system. Both works use ADMM [8] to iteratively solve the distributed problems. However, the iterative methods taken by the two schemes require sharing a large amount of information among nodes, while our solutions are kept strictly local to a region for the system to quickly recover from a failure and reach the stability.

III. System Model

In this section, we introduce the models for the power grid, failures, and control used to design our solution. Also, in the context of inter-connected regional networks, we briefly discuss how power line failures and non cooperative control can potentially affect large sections of the power grid.

A. Power Grid Model

Consider a graph representation of the transmission network $\mathcal{T}(\mathcal{N}, \mathcal{E})$, where the set of nodes $\mathcal{N}$ represents power substations, and the set of edges $\mathcal{E}$ the power lines connecting substations. Each $n \in \mathcal{N}$ has an associated power level $p \in \mathbb{R}$. Based on the values of p, substations in $\mathcal{N}$ can be classified into three categories: generators ($p > 0$, power supply), loads ($p < 0$, customers demand) or neutral ($p = 0$).

Each edge (link) in $\mathcal{E}$ represents a power line in the transmission network. Lines have an associated power flow $f_{i,j}$, which is not expected to exceed the physical capacity limit $C_{i,j}$ associated with the power line.

The normal (stable) operation of the power grid is maintained when the network is power balanced, i.e. $\sum_{i \in \mathcal{N}} p_i = 0$, and all the lines operate safely under their capacity limits. Moreover, the dynamics of the transmission grid depend on the topology and physical characteristics of $\mathcal{T}(\mathcal{N}, \mathcal{E})$, and can be captured by a *power flow model* [9]. We overload the symbol $\mathcal{T}$ to also indicate the set (equations) that define the used power flow model.

Failures in the power grid model correspond to modifications of the graph $\mathcal{T}$ in such a way that the normal operation described before is compromised. Failures can cause power imbalance or drive power flows to exceed their capacity limits. In practice a failure can be triggered by the disconnection of a power line (or several lines), i.e. a removal of an edge in $\mathcal{E}$, which may be caused by intentional attacks, natural phenomena or the automatic equipment protections that trip faulty lines. Hence, in our distributed control model, once a failure occurs in a region, control actions should be performed in this *affected* region, and possibly in other regions as well, in order to prevent the development of consequent failures, e.g. cascading failures.

B. Region-based Control Model

Consider a communication network $\mathcal{C}$ whose topology follows that of $\mathcal{T}$ to control the transmission grid, i.e. $\mathcal{C}(\mathcal{N}, \mathcal{E})$. If the network has only one control center, it can be located at one of the $n \in \mathcal{N}$ nodes. As in principle $\mathcal{T}$ is a connected graph, the control center can transmit messages to any node that needs to modify a state parameter as part of the control strategy to achieve the normal operation.

For more scalable grid management and also due to the geographical regional constraint, a power system is generally divided into K regions. Each region has a control center to manage its local set of nodes, and edges that includes "tie-lines" i.e. the edges that connect a region-k with other regions. The subscript k will be used to represent the variables or parameters related to a specific region $k \in \{1 \dots K\}$. We use $\mathcal{T}_k(\mathcal{N}_k, \mathcal{E}_k)$ to represent a region k with all its local power nodes and power lines, $\cup_{k=1}^{K} \mathcal{N}_k = \mathcal{N}, \cup_{k=1}^{K} \mathcal{E}_k = \mathcal{E}$, including its tie-lines which are shared with other regions.

Using the notation and models established, in the next section we present the design of the proposed failure control mechanism with low communication overhead.

IV. Cooperative Failure Control with Low Communication Overhead

In this section, we develop our proposed control mechanism in two steps. We start with the design of a distributed solution that can be directly extended from an ideal centralized control; without considering the communication overhead or cooperation guarantees. Then, we propose a control mechanism with cooperation guarantees, based only on the local parameters of a region-k and its 1-hop neighbor information for low communication overhead.

A. Distributed Control of Power Grid Failure

To control a failure, the loads of the power grid can be modified so that the grid becomes balanced to meet the power flow requirements. With the goal of minimizing the total changes of power to loads, the control mechanism can be represented by the following optimization problem:

$$\begin{aligned} \underset{D}{\text{minimize}} \quad & \sum_{k} \sum_{i} |D_{k,i} - D_{k,i}^{0}| && \text{(1a)} \\ \text{subject to} \quad & D_{k,i}^{0} < D_{k,i} < 0, \qquad \forall i \in D_k && \text{(1b)} \\ & V, P, F \in \mathcal{T} && \text{(1c)} \\ & |f_{i,j}| < C_{i,j}^{max}, \qquad \forall e_{i,j} \in \mathcal{E} && \text{(1d)} \end{aligned}$$

The control strategy is defined by the changed $D_{k,i}$ loads, where $D_{k,i}$ corresponds to the load of the node i in the region k that has power $p < 0$. D_k is a vector that represents all loads of the region k and the superscript 0 in $D_{k,i}^{0}$ represents a load value before the control is applied. The vectors $P, V \in \mathbb{R}^{|\mathcal{N}|}$ represent the power and voltages associated with all the $\mathcal{N}$ nodes in the grid. The vector $F \in \mathbb{R}^{|\mathcal{E}|}$ contains the power flows and $C_{i,j}^{max}$ is the maximum capacity of the power line. The constraint in (1c) enforces the power flow model represented by $\mathcal{T}$ on all grid variables.

The distributed model to be designed is shown in figure 1. To achieve a truly distributed control, define the set of power flows of the tie-lines of area k as $\widetilde{F_k} = \{f_{i,j} \in F_k | i \in \mathcal{N}_k, j \in \widetilde{\mathcal{N}_k}\}$, where $\widetilde{\mathcal{N}_k}$ is the set of nodes in the neighboring

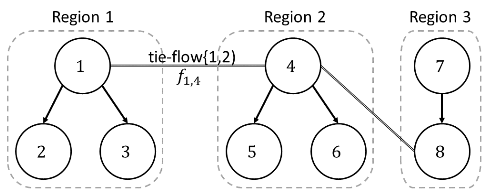


Fig. 1: Distributed model: control regions share only tie-lines.

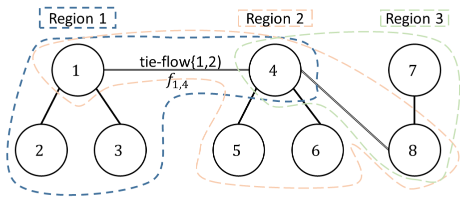


Fig. 2: Control regions due to the inherent power model.

regions of k. We can formulate a local version of (1) that maintains the tie-lines connected and the corresponding flows coherent among areas:

$$\underset{D_k}{\text{minimize}} \quad \sum_i |D_{k,i} - D^0_{k,i}| \tag{2a}$$
$$\text{subject to} \quad D^0_{k,i} < D_{k,i} < 0, \qquad \forall i \in D_k \tag{2b}$$
$$\widetilde{F}_k = Z_k, \tag{2c}$$
$$V_k, P_k, F_k \in \mathcal{T}_k \tag{2d}$$
$$|f_{i,j}| < C^{max}_{i,j}, \qquad \forall e_{i,j} \in \mathcal{E}_k \tag{2e}$$
$$\widetilde{\mathcal{V}}_k \in \mathcal{T}_k \tag{2f}$$

The vector Z_k represents the consensus of tie-flows that $\widetilde{F}_k$ should reach with all its neighboring regions, shown with the consensus constraint (2c). Similarly, $\widetilde{V}_k$ contains the voltages of nodes in the neighboring regions that are connected to $\widetilde{F}_k$, which are added to $\mathcal{T}_k$ based on the power flow model. Comparing this formulation with our K-region distributed model in figure 1, we observe that although, with (2), region-k does not intend to control other regions, it has to do so indirectly when looking for optimal $\widetilde{V}_k$. In Figure 2, regions are lassoed as they are considered in practice due to (2f). If a region-k needs 1-hop information of its neighbor region, which in turn requires its own 1-hop information, region-k would need 2-hop information. Moreover, If we restrict (2) to work only with 1-hop information, the local solutions will converge to make the tie-flows become 0, which would practically disconnect the tie-lines and go against our cooperation goal. In the next subsection we address these issues.

B. Distributed Failure Control with 1-Hop Information

Our goal is to design a distributed control system where each region will determine its shared tie-flows $\widetilde{F}_k$ by controlling only its local parameters, P_k and V_k, based on the information of itself and its 1-hop neighboring regions. We define a *"tie-node"* as a *virtual power node* that represents

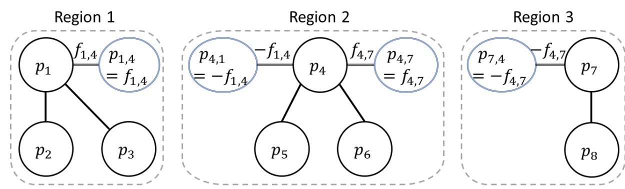


Fig. 3: Distributed Control regions as desired for Fig. 1.

(i.e., whose value is equal to) the power flow a region supplies or consumes through a tie-line. Then the information a region k will share with its 1-hop neighbors can be represented by defining $\hat{N}_k$ a vector of size $|\widetilde{F}_k|$, which contains all the power flows that region k shares through its tie-lines. This is illustrated in Figure (3).

These added tie-nodes are local to the region-k. We treat each tie-node as a regular node within the region it is added and describe the node by its power and voltage parameters $(\hat{P}_k, \hat{V}_k)$. We can reformulate the local control mechanism as follows:

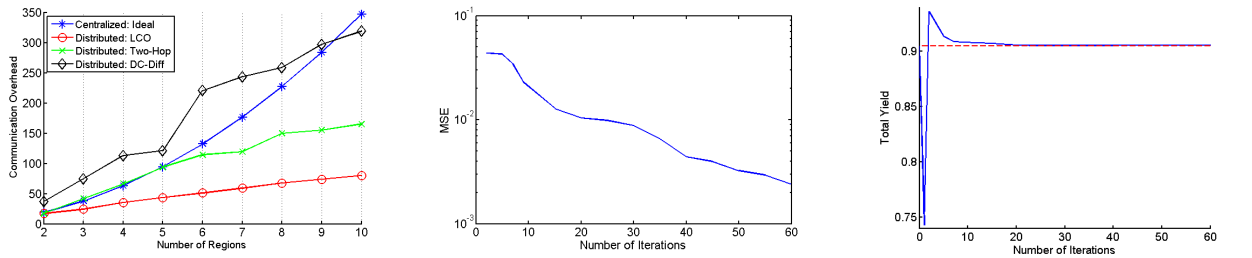
$$\underset{D_k}{\text{minimize}} \quad \sum_i |D_{k,i} - D^0_{k,i}| \tag{3a}$$
$$\text{subject to} \quad D^0_{k,i} < D_{k,i} < 0, \qquad \forall i \in D_k \tag{3b}$$
$$\hat{P}_k = Z_k, \tag{3c}$$
$$V_k, P_k, F_k \in \mathcal{T}_k \tag{3d}$$
$$\hat{P}_k \in \mathcal{T}_k, \tag{3e}$$
$$\hat{F}_k \in \mathcal{T}_k \tag{3f}$$
$$|f_{i,j}| < C^{max}_{i,j}, \qquad \forall e_{i,j} \in \mathcal{E}_k \tag{3g}$$

In this control mechanism, we add tie-nodes' powers $\hat{P}_k$ to the power flow model $\mathcal{T}_k$ in (3e) and add $\hat{F}_k$ in (3f) to represent edges for tie-flows connecting the tie-nodes to their corresponding local nodes in the region. Different from (2), our formulation does not include any parameters of the nodes in $\widetilde{\mathcal{N}}_k$ which would require the non-strictly local information from neighbors of the region k. Instead, the global consensus among regions is kept through the constraint in (3c). Also, as shown in Figure 3, each added tie-node has a degree of 1 and the flow associated with it equals its power value, hence $\hat{P}_k = \hat{F}_k = \widetilde{F}_k$ are virtually one variable. Thus, in our proposed (3), we reduce the complexity compared to the case of (2) and also only need to use the local parameters and 1-hop information.

Now, we will exploit ADMM [8] to provide an iterative solution for Equation 3. We start with the augmented lagrangian for each region-k:

$$L_\rho(P_k \cup \hat{P}_k, V_k, Z_k, \mu_k) = 1^T D_k + \mu_k^T(\hat{P}_k - Z_k) + \rho/2\|\hat{P}_k - Z_k\|^2 \tag{4}$$

where ρ is a positive scalar for the augmented penalty. The primal variables are updated as follows:



(a) Communication Overhead.

(b) Convergence rate.

(c) Effect of convergence in the total yield.

Fig. 4: Effect of communication overhead in control.

$$\{P_k^{t+1} \cup \hat{P}_k^{t+1}, V_k^{t+1}\} = \underset{P_k \cup \hat{P}_k \in \mathcal{T}_k}{\operatorname{argmin}} \; L_\rho(P_k \cup \hat{P}_k, V_k, Z_k^t, \mu_k^t) \tag{5a}$$

$$\{Z_k^{t+1}\} = \underset{Z_k}{\operatorname{argmin}} L_\rho(P_k^{t+1} \cup \hat{P}_k^{t+1}, V_k^{t+1}, Z_k, \mu_k^t) \tag{5b}$$

where the variables optimized in (5a) correspond to the parameters to be controlled by the region k and should follow the conditions and limits defined by (3d)-(3g) and represented by the feasibility set $\mathcal{T}_k$. The dual variable μ_k is updated as follows: $\mu_k^{t+1} = \mu_k^t - \rho(\hat{P}_k^{t+1} - Z_k^{t+1})$.

With some simple manipulations, we can see that Z_k^{t+1} is the average of the $\hat{P}_k^{t+1}$ for every two regions that share Z_k^{t+1}. Also, the multipliers μ_k can be updated based on the difference between the $\hat{P}_k^{t+1}$ values updated by (5a) and the corresponding $\hat{P}_{k*}^{t+1}$ received as the 1-hop information from the neighbors of k.

Furthermore, if an affected region k has become overloaded after the failure, it can communicate with neighboring healthy regions to cooperate with them. To model a cooperation guarantee, let us denote $\hat{P}_{k*}^{commit}$ as a vector containing the power cooperation requests received by k from all its neighboring control centers. Defining an auxiliary vector A_k that handles the updates of the multipliers, replacing Z_k and μ_k, and including $\hat{P}_{k*}^{commit}$ as a regularization term that enforces cooperation, the updates become:

$$(P_k^{t+1} \cup \hat{P}_k^{t+1}, V_k^{t+1}) = \underset{P_k \cup \hat{P}_k, V_k}{\operatorname{argmin}} \left[1^T D_k + \rho 1^T (\hat{P}_k^T I \hat{P}_k - (A_k^t + \hat{P}_{k*}^{commit})\hat{P}_k) \right] \tag{6a}$$

$$A_k^{t+1} = A_k^t + \hat{P}_{k^*}^{t+1} - (\hat{P}_k^t + \hat{P}_{k*}^t)/2 \tag{6b}$$

where each element of $\hat{P}_{k*}^{commit} \in \mathbb{R}^{|\tilde{N}_k|}$ has the proper sign to determine if each neighbor region is providing or requesting power from region-k. In this new control mechanism, even if the *requested* power from a neighboring region of k is 0, the local control will treat all its tie-nodes as local nodes that can be either generators or loads, hence guaranteeing the cooperation.

V. Performance Evaluation

In this section we evaluate the performance of the proposed control mechanism. First, we test the required iterations, i.e. communicated messages between regions, to converge to a global control strategy along with the total number of transmitted messages to apply the controls strategy, i.e. communication overhead. Then, we evaluate the yield of demand after control strategies are applied to alleviate failures.

A. Simulation setup

We use the IEEE 118-bus test case [10] to define the local topologies of each region of the global interconnected power grid. We employ the DC power model to define $\mathcal{T}_k$s, which due to its reduced complexity is often used for grid reliability analysis [5]. Regions are connected through random realizations of *Small World* [11] topologies with an average of two tie-lines per region. For each scenario, we take an average of 100 realizations of the described random interconnection topologies.

For the evaluations we implemented an ideal *Centralized* failure control such as the one described in [5]. For comparison with other distributed solutions we implemented *Two-hop* and *DC-Diff*. *Two-Hop* corresponds to the distributed control outlined in (2) that requires 2-hop messages and attempts to use non-strictly local power node parameters. The reference scheme *DC-Diff* is an intuitive distributed solution that works as follows: define the shared variables as the flow in the DC model [9]: $f_{i,j} = b_{i,j}(\theta_i - \theta_j)$. Then, each region-$k$ will optimize this difference while treating θ_i and θ_j as local. We label our solution in the plots as *LCO* (Low Communication Overhead).

We will evaluate *communication overhead* in terms of the total number of messages: transmitted to generate the control strategy, between regions, and to communicate the control actions planned to all nodes. Also, we evaluate the *yield of demand* which corresponds to the fraction of the original demand (before the failure) that is supplied to the customers after the failure is controlled.

B. Centralized vs. Distributed: Communication Overhead

In Figure 4a we present the amount of communication overhead incurred by our proposed design and compare

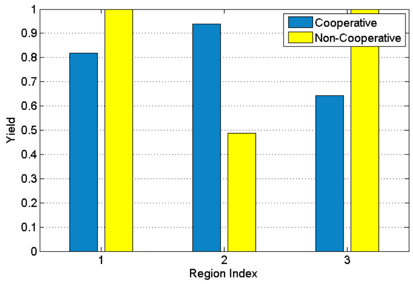


Fig. 5: Cooperation effect on yield.

it against peer centralized and distributed solutions. We evaluate the impact of the number of regions in the power grid, which can reflect the scalability of the algorithms. Particularly, as we limited the information exchange to 1-hop neighboring regions in our design, LCO has the lowest communication overhead. On the other hand, the length of the paths that control messages need to traverse to reach the power nodes grows with the grid size, which significantly increases the overhead of an ideal centralized solution as shown in the figure. In comparison, the overhead needed by Two-hop becomes significantly larger than that of LCO as the requests of information past 1-hop grow with the number of regions. This becomes more evident for larger grid sizes where LCO can reduce the overhead by a factor of 3 compared to Two-hop. DC-Diff also uses only 1-hop information, however the number of messages required to reach the consensus is very large, as an agreement on $\theta_1 - \theta_2$ can be reached with several combinations of θ_1 and θ_2.

Now, we are interested in inspecting the performance degradation we incur with our distributed proposal. Using the *Centralized* solution as reference, in Figure 4b we show the mean square error of the distributed tie-flows for a grid with 10 regions. In Figure 4c we show the yield comparison between the centralized and our proposed distributed scheme. The centralized solution, being ideal, shows the optimal value of yield of demand supplied to the loads. From these two figures we can see that our proposed distributed control can yield almost the same demand as the centralized scheme after only a few iterations. Moreover, the distributed performance does not improve significantly in terms of the amount of yield gained by setting a stricter convergence criteria, i.e. setting a tie-flow consensus threshold of as little as 10^{-2} results in near optimal yield.

C. Cooperative vs. Greedy Performance

Now we will test the cooperative feature of our solution introduced in Section IV-B. We set up the power grid with 3 regions so we can clearly keep track of the healthy and affected regions. For the scenario shown in Figure 5, failures are generated in Region 2 in a way that only $\sim$5% of the total load is supplied locally. Also, we have supplied Region 1 with extra generation capacity. Consider that customers served by region 2 are of (global) importance, then, region 2 requests for cooperation through $\hat{P}_{k*}^{commit}$.

Without cooperation (in yellow), regions 1 and 3 satisfy all their corresponding demand. The yield at region 2 reaches 50% thanks to the power contribution from the extra capacity of region 1. Instead, when the *Cooperative* algorithm is used, region 2 can meet almost all its demand. Because of the regularization term we have in our cooperative solution, regions 1 and 3 are forced to cooperate with region 2 for the "global benefit" of all customers. Moreover, given that region 1 has extra power, its final demand supplied is greater than that of region 3.

VI. Conclusion

We have defined a failure control system in a region-based fashion, where the regions share only information and control of the tie-lines. The presented solution distributes control between neighboring regions while maintaining faulty and healthy regions connected when possible. With the distributed model presented, the number of messages exchanged to achieve the coordinated control is maintained to be low, even though the inherent power flow model may require additional information across regions. Also, as shown in our results, our proposed control mechanism can guarantee that regions cooperate to yield as much demand as possible according to their capabilities or desire to share power.

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