Developing a Correlation Index to Identify Coordinated Cyber-Attacks to Power Grids

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Abstract—The large deployment of Information and Communication Technology (ICT) exposes the power grid to a large number of coordinated cyber-attacks. Thus, it is necessary to design new security policies that allow an efficient and reliable operation in such conflicted cyber-space. The detection of cyber-attacks is known to be a challenging problem, however, through the coordinated effort of defense-in-depth tools (e.g., Intrusion Detection Systems (IDSs), firewalls, etc.) together with grid context information, the grid’s real security situation can be estimated. In this paper, we derive a Correlation Index (CI) using grid context information (i.e., analytical models of attack goals and grid responses). The CI reflects the spatial correlation of cyber-attacks and the physical grid, i.e., indicates the target cyber-devices associated to attack goals. This is particularly important to identify (together with intrusion data from IDSs) coordinated cyber-attacks that aim to manipulate static power applications, and ultimately cause severe consequences on the grid. In particular, the proposed CI, its properties, and defense implications are analytically derived and numerically tested for the Security Constrained Economic Dispatch (SCED) control loop subject to measurement attacks. However, our results can be extended to other static power applications, such as Reactive Power support, Optimal Power Flow, etc.

Index Terms—Correlation Index, Intrusion Detection Systems, Data Integrity Attacks, Static Power Applications, Substations.

I. INTRODUCTION

The power grid is evolving to an increased dependency on Information and Communication Technology (ICT) to support control and monitoring applications. This trend is propagating from the transmission systems of high voltage level to lower voltage levels such as distribution systems. ICT systems enable a more efficient and reliable power grid operation. However, they can be target and entry points for a wide variety of cyber-attacks with potential catastrophic consequences.

In particular, power control applications were designed with redundancy, but not considering cyber-security as a threat. They were thought to be secure by isolation through the use of closed/proprietary communication infrastructure. However, for reasons of increased efficiency, deployment of more sophisticated devices and information technology, and migration to open standards, these critical applications are transitioning towards the use of multiple ICT systems, which creates a large number of cyber vulnerabilities.

Cyber-attacks can potentially exploit these vulnerabilities to utilize a large number of ICT systems spread over a wide geographical area. These large coordinated attacks pose a significant threat to the security of the grid, as highlighted by the famous cyber-attack to the Ukrainian power grid [1]. This massive cyber-attack triggered power outages across large areas, leaving more than ten thousand consumers and facilities without electricity. It was carried out using a malware that affected control center computers. Showing that motivated adversaries can certainly impact the power grid by compromising multiple ICT systems. Therefore, protecting the power grid from large coordinated cyber-attacks is now critical to nations’ security.

Nevertheless, protecting the grid against coordinated attacks is a challenging problem. In fact, the power grid will never be fully protected from cyber-threats. Security breaches will occur, despite the use of several defense layers. Particularly, some challenges are the following. Cyber-attacks are not constrained by geography, thus, the population of target cyber and physical devices is extremely large, making the detection of coordinated attacks difficult, since the intrusions might be spread across multiple ICT systems in a short period of time. On the other hand, cyber-attacks are fairly rare events and therefore difficult to anticipate and stop. Finally, cyber-attacks are continuously evolving. They are becoming more dangerous, sophisticated and persistent.

However, any attempt by the adversary, to gain access to a cyber-device (or ICT system) without having authorization to do so, will generate abnormal behaviors in the form of cyber-traces. We leverage on this statement to state that defense-in-depth security tools, e.g., Intrusions Detection Systems (IDSs), can be deployed to estimate the real security situation of the power grid and the strategies used by the adversary, which can be used to identify, intercept, and minimize the consequences of cyber-attacks.

IDSs are security tools deployed to monitor (by inspecting cyber-traces) ICT systems and report possible security threats. IDSs have proven to be a critical component of traditional ICT systems. However, they cannot avoid false alarms and missed detection [2], and do not provide relevant information of the adversary’s strategy. Therefore, IDSs are necessary defense-in-depth tools for the power grid’s control center and substations (depicted in Fig[1]), however, alone, they are not sufficient to detect and intercept coordinated cyber-attacks.

By correlating ex-post raw intrusion information from different grid’s IDSs, the detection and interception of coordinated attacks can be improved. A Correlation Index (CI) uses such information to provide an interpretation of the adversary’s strategy at target ICT system and the possible consequences on the physical power grid.
Prior Works.

Many CIs have been proposed in the literature; however, they differ in their principles, as summarized below.

(i) CIs based on adversaries’ cyber traces. Attack sequences of the same adversary have similar cyber-traces that can be identified as contributing to coordinated attacks. This detection principle can be utilized by IDSs to investigate the temporal correlation of intrusions in cyber-space. Anomaly matrices [3] and Time Failure Propagation Graphs (TFPG) [11] are proposed to relate intrusion time with intrusion actions. While capable of detecting coordinated attacks at the cyber-space, CIs (i) do not provide information related to the attack strategy at the physical grid.

(ii) CIs based on cyber-physical dependence. They are based on logic graphs describing the conditions that need to be fulfilled (in sequence in the cyber-space) for a physical consequence to take place [4]. The logic graphs can take forms of attack trees [5], attack graphs [6] and PetriNet [7]. Temporal correlation of attacks is derived not only in the cyber-space but also on the physical power grid (see Fig. 2 in [8] for an example). However, constructing these logic graphs usually requires great computational efforts due to the large number of cyber and physical components. The graphs’ accuracy also deteriorates as the size of the power grid under study increases.

(iii) CIs based on attack goals on the physical grid. Adversaries’ goals are described with reliability metrics or criticality of a certain target. For example, in [11], ICT systems at substations are attack targets and their criticality is first ranked. In [9], the attack goal is modeled as causing an insufficient capability of power transfer (i.e., the divergence of power flow). The work takes a numerical approach by taking off a set of substations at one time and running power flow. The substations in the set are identified as correlated if the power flow is divergent. In addition, cascading failure studies are deployed to identify spatial and temporal correlation [10].

Contributions.

Given the great-size of power grids, the combined deployment of CIs in (i) and (iii) promise better computation performance and higher accuracy than (ii). The existing CIs based on physical consequences (iii), however, are limited to few attack goals achieved by corrupting control commands. Other cyber-attacks, such as measurement attacks, present much higher threats in coordination (as a rich body of literature has shown their impact in electricity markets and security constrained power flows [11]–[14]) though they are likely to be overlooked in isolation.

In this paper, we focus on deriving CIs (iii) for static power applications, i.e., power applications with dynamics settled at steady state, while the integration of CIs (i) and (iii) will be formally presented in a different paper. In particular, we make the following contributions:

- We derive CIs for static applications based on analytical models and methods of attack goals and grid response. The CIs provide the spatial correlation between critical cyber-devices and goals on the physical power grid.
- We characterize the CIs’ properties that relate coordinated attacks with attack goals on the physical power grid.
- We describe some defense implications based on CIs. For example, we define the risk of not securing critical ICT systems and their cyber-devices.

We use Security Constrained Economic Dispatch (SCED) subject to measurement attacks as an example to demonstrate how to derive the CIs. We assume the SCED control loop is executed by collecting measurements from remote substations, thus, the CI describes the spatial correlation between multiple target substations’ ICT systems and attack goals on the physical grid. Finally, the results are validated through numerical examples. We want to recall, however, that such derivation is not limited to SCED and can be generalized to any static application, e.g., Emergency Control, Optimal Power Flow, Reactive Power Support etc., subject to measurement and control attacks. The development of CIs for dynamic power applications is part of our future work.

The rest of the paper is organized as follows: in Section II, we introduce the problem by describing the power grid operation subject to cyber-attacks, the IDS, and the CI. In Section III, we model the SCED control loop. The attack
template is presented in Section IV. In Section V, we derive the CI and characterize some of its properties. In Section VI, we discuss defense implications based on CIs. Numerical experiments are provided in Section VII. Finally, Section VIII concludes the paper.

II. BACKGROUND

A. Power Grid Operation under Cyber-Attacks.

The power grid must continuously operate efficiently and reliably. To ensure such operation, power control applications (or power applications) are implemented. Power applications are control loops designed (usually independently) to enable remote control based on real-time measurements collected at substations over a large geographical area. In this paper, we focus on static power applications, which analyze the grid at its equilibrium conditions, i.e., the grid is considered to be operating in sinusoidal quasi steady-state. Examples of Static applications are: Electricity Markets, Emergency Dispatch, Optimal Reactive Power Support, etc.

A general abstraction of a static application (e.g., SCED) is illustrated in Fig. 2. In general, static applications have state estimation (SE) capabilities to best track the grid’s current operating point given real-time measurements and accurate models; and the optimization algorithm (triggered by the grid’s operator), which selects a control command, by optimizing a performance function while ensuring that security constraints are met. Both, estimation and optimization algorithms, rely heavily on observed measurements. Thus, Bad Data Detection (BDD) algorithms are implemented to verify the integrity of measurements collected at substations [15].

The role of substations: Transmission and distribution substations are critical for the power grid operation. Substations collect measurements and have important physical devices, such as transformer, capacitors, circuit-breakers, Intelligent Electronic Devices (IEDs), etc. The current trend is to deploy modern ICT systems to enhance the efficiency and reliability of substation operation, monitoring, and control. However, ICTs expose substations to cyber-attacks.

Cyber-attacks can originate from remote access points, used by operators to get collected measurements or send supervisory control commands to substations, with potential catastrophic consequences. For example, the adversary might be able to access the Human Machine Interface (HMI), which provides the operation and supervision of the substation [16]. Using the HIM, the adversary can send trip commands to circuit-breakers or change the output of reactive power devices. The adversary, on the other hand, might be able to corrupt measurements by accessing the communication links or by corrupting them at the substation’s data collector. In the worst case scenario, simultaneous intrusions to multiple substations can lead to catastrophic events, including cascading blackouts and/or voltage collapse [17]. As a result, the defense of substations to coordinated attacks is top priority.

By exploiting the vulnerabilities at the substation’s ICT system, an adversary can launch a Data Integrity Attack (DIA). In DIAs, adversaries manipulate power applications (to achieve a goal on the physical power grid) by fabricating measurements (Fig. 3a), and/or by directly altering control commands (Fig. 3b). Such attacks require access to critical resources, i.e., adversaries need to have knowledge of the system models, and be capable of disclosing and altering the information content at substations [18]. To prevent DIAs, recent studies have proposed eliminating bad data in the first place by enhancing SE techniques and/or optimization algorithms [19]. However, these techniques cannot detect control DIAs [20], and, under certain conditions [15], measurement DIAs.

B. Intrusion Detection Systems

An attempt by the adversary to gain access to ICT systems without having authorization to do so will generate abnormal behaviors that can be identified and recorded as log files. An Intrusion Detection System (IDS) is a security tool deployed to monitor the power grid’s ICT systems and report these security threats. IDSs are inherently reactive, i.e., the cyber-attack has already begun when the IDS acts. The main goal of the IDS is to find out whether or not the system is operating normally. Abnormality or anomaly in the ICT systems behavior may indicate the occurrence of malicious intrusions that are the consequences of successful exploitation of system vulnerabilities.

Based on the information sources analyzed to detect possible intrusions, IDSs can be classified into two main categories [21]: (i) Network-based Intrusion Detection Systems (N-IDS), and (ii) Host-based Intrusion Detection Systems.
Anomaly detection, on the other hand, has the potential to
of false alarms, but is designed to detect predefined attacks.
nesses. For instance, signature-based detection has a lower rate
possible intrusions. Thus, a repository of normal behaviors is
reference against which deviations are detected and alerted as
individual attacks, however, coordinated attacks
necessary. A H-IDS identifies abnormal behavior by analyzing these information with user-defined-rules. Therefore, the detection performance of a H-IDS is independent of the packets’ content. For DIs that can that bypass BDD, an H-IDS can still catch their intrusion attempts within the ICT systems. Recent development of IDS shows that host-based and network-based IDSs can be used together to provide additional context for improved intrusion detection at substations [1]. This merge is called Hybrid IDS and it is illustrated in Fig. 1 for the case of substations.

IDSs can also be classified based on detection techniques [22]. The most common detection techniques used by IDSs are: (i) Misuse or signature-based detection, and (ii) Anomaly detection. Signature-based detection uses a blacklist approach, that is, a set of rules or attack patterns are used to decide if analyzed intrusion data matches the signature of a known attack. Therefore, a database of all known attack patterns or intrusive scenarios is necessary. On the other hand, Anomaly detection uses a whitelist approach, i.e., model of normal system (network or cyber-device) behavior is used as reference against which deviations are detected and alerted as possible intrusions. Thus, a repository of normal behaviors is usually necessary. Both techniques have strengths and weaknesses. For instance, signature-based detection has a lower rate of false alarms, but is designed to detect predefined attacks. Anomaly detection, on the other hand, has the potential to detect zero-day attacks, but it suffers from high alarm rate [23].

Intrusion detection systems have proven to be a critical component of traditional ICT architectures. For the power grid, however, IDSs, alone, are not sufficient to satisfy its security needs. IDSs cannot avoid false alarms and missed detections [2], and they do not provide relevant information related to the adversary’s strategy. Finally, IDS do not consider the physical process and how this knowledge can be used to identify compromised cyber-devices.

**Coordinated Cyber-attacks**

The power grid current and future reliability standards (e.g., N-k criteria) will likely to provide resiliency against individual attacks, however, coordinated attacks (i.e., organized simultaneous cyber-disruptions targeting multiple substations and their cyber-devices) might be able to cause major failures with possible catastrophic consequences. Such attacks are difficult to detect using individual substations’ IDS. Therefore, a collaborative approach among the IDS at multiple substations is necessary.

**Correlation Index**

The correlation and interpretation of intrusion data from different IDSs have been extensively studied by the Computer Science community [23]. However, for the power grid, it is also necessary to consider grid context information and models of cyber-attacks and power applications. These are particularly important for coordinated attacks, since their individual attacks share not only similar attack sequences (cyber-traces), but the same goal on the physical power grid. Therefore, by interpreting the ex-post raw intrusion data from multiple IDSs’ outputs together with grid context information, CIs can provide a high-level description of the attempted intrusions to multiple cyber-devices, i.e., the CIs attempt to identify the adversary’s strategy at the cyber-space and the goals on the physical power grid.

This can be leveraged to realize a defense strategy which: (i) identifies coordinated attacks based on their cyber-traces (CI based on adversaries’ cyber-traces), and (ii) estimates instantaneous impact of coordinated attacks with grid context information (CI based on attack goals on the physical grid). The integration of the two CIs will allow to: (i) track coordinated cyber-attacks, (ii) predict their consequences on the physical power grid, (iii) improve the detection capability (rate of false alarms) from individual IDSs, and (iv) execute mitigation actions that will stop the attack or minimize the consequences on the physical grid.

The CI based on adversaries’ cyber-traces determines temporally correlated attacks based on cyber-traces extracted from multiple cyber-devices. To relate intrusion time with intrusion attempts, we use a Time Failure Propagation Graph (TFPG) model (depicted in Fig. 4), which contains the cause-effect relationship between (i) attack modes, (ii) ICT system behavior discrepancies, and (iii) attack propagation [1]. Since each attack step can create a specific path to the final attack goal at the ICT system, the attack sequence can be regarded as the propagation path. Coordinated attacks follow similar attack sequences at multiple ICT systems. Thus, a coordinated attack can be identified by analyzing these attack sequences at multiple IDSs. Note that temporal correlation is required, since the adversary might switch targets, so they can probe cyber-vulnerabilities and hide from detection.

The CI based on attack goals on the physical power grid, on the other hand, links the attack’s spatial characteristics with the attack goal on the physical grid, i.e., the CI is an indicator of target cyber-devices associated with a particular goal on the physical grid. This CI is obtained with grid context information (e.g., models of cyber-attacks and power applications.)

In this paper, we focus on deriving the CI based on attack goals for static power applications. In a different paper, we...
will formally describe how to integrate both CIs using a decision layer based on the Fuzzy Cognitive Map (FCM) algorithm [24]. FCM defines a state variable that incorporates both CIs. When the state variable of the decision layer exceeds a pre-defined threshold, the attack event can be identified as a coordinated attack. The rest of the paper is devoted to illustrate the analytic derivation of CI based on attack goals on the physical power grid for the case of SCED.

III. MODELING

In this section, we model the Security Constrained Economic Dispatch (SCED) loop for a power grid at the sub-transmission level.

A. Mathematical Notation

Throughout this paper we use the following notation. The sets \( \mathbb{R} \) and \( \mathbb{R}_+ \) denote the fields of real numbers and non-negative real numbers. For \( n > 1 \), we let \( I_n \) denote the \( n \)-dimensional identity matrix. \( \mathbf{1} \) and \( \mathbf{0} \) denote the vectors or matrices of appropriate dimensions with all components equal to one and zero, respectively. Given a finite set \( \mathcal{V} \), we let \( |\mathcal{V}| \) denote its cardinality, that is, the number of elements of the set.

For a matrix \( A \in \mathbb{R}^{n \times m} \), \([A]_i\) and \([A]_{ij}\) denote its \( i \)th row and its \( (i,j) \)th element. Given a vector \( x \in \mathbb{R}^n \), \( x_i \) denotes the \( i \)th element and \( \text{diag}(x) \) denotes the diagonal matrix of \( x \). Furthermore, we let \( ||x||_0 \) denote the zero norm of \( x \), that is, the number of non-zero elements of \( x \). We let \( ||x||_{\infty} \) denote the infinity norm defined as \( ||x||_{\infty} := \max\{|x_i|; i = 1, \ldots, n\} \). Finally, for two vectors \( x, y \in \mathbb{R}^n \), \( x \circ y = z \in \mathbb{R}^n \) denotes the Hadamard or element-wise product, i.e., \( z_i = x_i y_i \), and \( x \preceq y \) denotes the element-wise inequality, i.e., \( x_i \leq y_i \) for all \( i \).

B. Power Grid Modeling

The power grid at the sub-transmission [25] level is modeled as the graph \( G = (\mathcal{V}, E) \), where \( \mathcal{V} \) and \( E \subset \mathcal{V} \times \mathcal{V} \) are the sets of \( n := |\mathcal{V}| \) buses and \( m := |E| \) transmission lines. The grid is considered to have \( N \) substations associated to the index set \( \mathcal{S} = \{1, 2, \ldots, N\} \). At the \( k \)th substation, the grid within its service area is represented by the sub-graph \( G_k = (\mathcal{V}_k, E_k) \). The sub-graphs have the following properties:

1) All the substation service areas compose the power grid, i.e., \( \cup_{k \in \mathcal{S}} G_k = G \).

2) Substation service areas may overlap, i.e., \( G_j \cap G_k \) may not be empty for any \( j, k \in \mathcal{S} \).

3) The overlapped areas do not contain generator buses, i.e., for any \( j, k \in \mathcal{S} \), we have \( \mathcal{V}_j \cap (\mathcal{V}_j \cap \mathcal{V}_k) = \emptyset \), where \( \mathcal{V}_g \) denotes the set of generator buses.

To each bus \( i \in \mathcal{V} \), we associate the active power injection \( P_i := P_{g,i} - P_{d,i} \in \mathbb{R} \), where \( P_{g,i} \in \mathbb{R}_+ \) (resp. \( P_{d,i} \in \mathbb{R}_+ \)) denotes the generation (resp. demand) at the bus. Similarly, to each transmission line \( e := (i, j) \in E \) connecting buses \( i, j \in \mathcal{V} \), we associate the power flow \( P_{f,e} \in \mathbb{R} \). In vector form, the generation, demand and power flows are respectively \( P_g = [P_{g,1}, \ldots, P_{g,n}]^\top \), \( P_d = [P_{d,1}, \ldots, P_{d,n}]^\top \), and \( P_f = [P_{f,1}, \ldots, P_{f,m}]^\top \).

C. Security Constrained Economic Dispatch

At sub-transmission level, the SCED control loop collects demand measurements \( \bar{P}_d \) from substations and computes the optimal generation dispatch \( P_g^* \) by solving an optimization problem based on the solution of the power flow equations.

The AC power flow model is the basic mathematical tool to operate the grid. It considers both real and reactive power and is formulated by a set of nonlinear equations. However, for large power grids, SCED using the AC power flow model is computationally expensive and even infeasible. Thus, it is approximated by a linearized power flow model that decouples real and reactive power, the DC power flow model. DC power flow is simpler and more robust due to sparsity and linearity; however, it is only accurate in a small neighborhood of the current operating point. We refer the interested reader to [Citation] and [Citation] for more information and current practice on DC power flow in utilities.

The power grid’s DC-SCED optimization problem minimizes the total generation cost \( (1a) \) subject to the following security constraints: (i) generation-demand balance, (ii) operation limits of the generators \( (1b) \); and (iii) transmission limits on power flows \( (1c) \). Formally, it can be formulated as the following convex optimization problem

\[
\begin{align}
\min_{P_g} \quad & \frac{1}{2} P_g^\top \Gamma P_g + \beta^\top P_g + \alpha, \\
\text{s.t.} \quad & P_g \in [0, \bar{P}_g], \\
& H(P_g - \bar{P}_d) \subseteq [-\bar{P}_f, \bar{P}_f],
\end{align}
\]

where \( \gamma, \beta, \alpha \in \mathbb{R}_+^n \) are the cost coefficients associated with each generator, \( \Gamma = \text{diag}(\gamma) \), \( \bar{P}_g \in \mathbb{R}_+^n \) is the rated power from generators, and \( \bar{P}_f \in \mathbb{R}_+^n \) is the thermal capacity of transmission lines. Note that \( (1c) \) can be written equivalently for each substation as follows:

\[
P_{g,i} \in [0, \bar{P}_{g,i}], \quad \forall i \in \mathcal{V}_k, \quad \forall k \in \mathcal{S}.
\]

IV. ATTACK TEMPLATE: MEASUREMENT DIAS TO SCED

In this section, we model measurement DIAs to SCED. The adversary’s goal and stealthy conditions to bypass BDD are provided. Finally, bilevel optimization is used to describe an adversary that aims to maximize the impact on the grid by manipulating SCED, while minimizing the number of attacked substations.

A. Measurement DIAs

We assume the adversary fabricates the attack vector \( a \in \mathbb{R}^n \) to modify the integrity of transmitted measurements to \( \tilde{P}_d = P_d + a \), (2) and manipulate the output of SCED, which impacts the grid by modifying the flows on transmission lines.

Stealthy Conditions. DIAs to SCED must first bypass BDD and SE [15] as depicted in Fig. 2. The attack vector \( a \) remains stealthy/undetected by BDD if one of the following conditions is satisfied:
1) **Conforming DIA** [15]. The attack vector \(a\) has the same statistics as the measurements \(P_d\).

2) **Blind DIA**. The elements of \(a\) are smaller than the tolerance of the BDD (\(\epsilon\)), i.e., if \(||a||_\infty \leq \epsilon\).

In the reminder of this paper, we assume that the attacks are Blind DIAs. Blind DIAs are less restrictive than Conforming DIAs. They are not constrained to a specific subspace.

**The role of substations (Attack Region)**. DIAs are launched at substations’ data collector as illustrated in Fig. 2. Thus, if the adversary hacks into the \(k\)th substation, then (s)he can corrupt all its measurements. Similarly, if the \(k\)th substation is protected, then (s)he cannot falsify any measurement. This constrains the stealthy attack vectors \(a\) within a compact region, i.e.,

\[
a_i \in \delta_k[-\epsilon, \epsilon], \quad \forall i \in \mathcal{V}_k, \forall k \in \mathcal{S},
\]

where

\[
\delta_k = \begin{cases} 1, & \text{if the adversary can attack the } k\text{th substation,} \\ 0, & \text{otherwise.} \end{cases}
\]

We collect all such \(\delta_k\) in the vector \(\Delta(e) = [\delta_1, \ldots, \delta_N] \in \{0, 1\}^N\). With some abuse of notation, \(\Delta(e)\) describes the target substations during the attack.

Finally, note that \(a\) constrained as in (3) implies that the adversary might need to target more than one substation to impact the grid, i.e., launch a coordinated DIA to multiple substations.

B. Adversary’s Goal (\(\tau\))

We consider the following adversary’s goal: to increase the power flow on a single target transmission line \(e \in \mathcal{E}\), which occurs at

\[
|P_{f,e}| = |[H]_e(P_g^*(a) - P_d)| \geq (1 + \tau)|P_{f,e}^*|
\]

where \(P_{f,e}^* \in \mathbb{R}\) is the flow on \(e\) without attack, and \(\tau \geq 0\) quantifies the increase of the flow. Therefore, in the worst case scenario, the adversary will try to maximize \(\tau\) by manipulating SCED. Note that, with some abuse of notation, we have used \(P_g^*(a)\) to state the fact that \(P_g^*\) is being manipulated by \(a\) through SCED.

C. Minimizing Target Substations (\(\kappa\))

To achieve (4), the adversary might need to launch a coordinated attack to multiple substations. However, due to limited resources, the number of target substations is also limited, i.e.,

\[
||\Delta(e)||_0 \leq \kappa,
\]

where \(\kappa \in \mathcal{S}\) quantifies the maximum number of target substations. Indeed, an optimal adversary will try to achieve (4) while minimizing \(\kappa\), i.e., minimize the number of target substations.

Remark 1. The adversary faces two opposing objectives: (i) maximize \(\tau\); while, at the same time, (ii) minimize \(\kappa\). The interaction \(\tau - \kappa\) describes the spatial correlation between target substations (\(\kappa\)) and adversary’s goal (\(\tau\)).

D. Attack Template in Bilevel Form

The attack template for measurement DIA to manipulate SCED (worst case scenario), can be written as the following Bilevel optimization program:

\[
\begin{aligned}
\max_a \quad & \tau - \kappa, \\
\text{s.t.} \quad & \text{Eqs. (3) - (5)}, \\
\end{aligned}
\]

and \(P_g^*(a)\) is the optimal solution of the SCED optimization problem, parametrized by the attack vector \(a\), i.e.,

\[
\begin{aligned}
P_g^*(a) = \arg\min_{P_g} \quad & \frac{1}{2}P_g^\top \Gamma P_g + \beta^\top P_g + \alpha, \\
\text{s.t.} \quad & 1^\top P_g - 1^\top a - 1^\top P_d = 0, \\
& A_1 P_g + A_2 a - b \leq 0.
\end{aligned}
\]

To simplify our notation, the SCED problem subject to measurement DIA (7) was written in compact form by defining the following matrices:

\[
\begin{bmatrix}
-I_n \\
I_n \\
H
\end{bmatrix}, \quad \begin{bmatrix}
0 \\
0 \\
-H
\end{bmatrix}, \quad \begin{bmatrix}
\bar{P}_f \\
\hat{P}_f
\end{bmatrix}, \quad \begin{bmatrix}
0 \\
\bar{P}_f \\
\hat{P}_f
\end{bmatrix} - A_2 P_d.
\]

Remark 2. We interpret the bilevel form as follows. The upper level (6) models the adversary’s goal and constraints, and the lower level (7) models the operator’s decision being manipulated by the adversary through \(a\). Finally, notice that the bilevel form (6)-(7) depends on the actual value of the measurements \(P_d\). Thus, for defense purposes the attack template can be modeled for the worst case of \(P_d\), i.e., in heavy loaded situations.

Bilevel optimization is a hierarchical mathematical program that has proven very useful in the modeling of hierarchical decision making process among agents (e.g., adversary vs the grid’s operator) [26]. It has been used to model cyber and physical attacks to power grids. For instance, in [27], [28], attack conditions are derived by solving bilevel forms that model cyber-attacks to static power applications. On the other hand, bilevel forms have been applied in [29] to characterize physical attacks on the grid.

V. CORRELATION INDEX BASED ON ATTACK GOALS

In this section, we describe how to derive the CI in the context of a SCED control loop subject to measurement DIAs. Moreover, we provide some of the CI’s properties that can be leveraged for defense purposes.

A. Attack Template in Mathematical Programming Form.

Since the SCED subject to DIAs (7) is strictly convex on \(P_g\) for a fixed \(a\), then its KKT conditions are necessary and sufficient for optimality [30]. Therefore, the bilevel form (6)-(7) can be equivalently transformed into a Mathematical
Program with Equilibrium Constraints (MPEC), i.e., a single-level optimization problem \([31]\), by replacing (7) with its KKT system. As a result the attack template becomes

\[
\begin{align*}
\max_a &\quad \tau - \kappa, \\
\text{s.t.} &\quad \text{Eqs. } (3) - (5), \\
&\quad 1^T P_g^* - 1^T a - 1^T P_l = 0, \quad (8a) \\
&\quad \Gamma P_g^* + \beta - 1 v^* + A_1^T \lambda^* = 0, \quad (8b) \\
&\quad A_1 P_g^* + A_2 a - b \leq 0, \quad (8c) \\
&\quad \lambda^* \geq 0, \quad (8d) \\
&\quad \lambda^* \circ (A_1 P_g^* + A_2 a - b) = 0. \quad (8e)
\end{align*}
\]

In the above, \((8a)-(8e)\) is the KKT system of (7), where \(v^*\) and \(\lambda^*\) are respectively the Lagrange multipliers of the equality constraint and inequality constraints of (7).

**Remark 3.** Physically, \(\lambda^* = 0\) implies that the generator and deceived power flows are at the operational limits. Consequently, alarms might be triggered. A positive \(\lambda^*\), in turn, will deceive the operator, by depicting a "false" secure economic dispatch.

**Mathematical Challenges.** The MPEC (6) and (8) is a difficult optimization problem. The geometric properties of MPECs are far more complex than traditional mathematical programming problems, and therefore, the standard nonlinear programming approach cannot be immediately applied \([31]\). The difficulty of (6) and (8) arises due to the following:

(i) Lack of convexity due to complementary slackness (8e).

(ii) Local optima might exist. We linearize the complementary constraints as follows \([31]\). Let \(M > 0\) be a sufficiently large constant; then, (8c) is equivalent to

\[
\lambda^* \leq M(1 - \omega), \quad -(A_1 P_g^* + A_2 a - b) \leq M\omega,
\]

where \(\omega \in \{0,1\}^{2(n+m)}\) is a binary decision variable, which transforms the MPEC into a mixed integer problem. Note that if the solution of the MPEC exists, then for different \(M\) there might be different local optimal solutions. Therefore, \(M\) is a parameter in our derivation.

(iii) MPEC (6) and (8) is non-differentiable due to (4). Note that \(P_{f,e}^p\) is the optimal solution of the SED without DIA. Thus, \(f_{f,e}\) is known before solving the MPEC (6) and (8). Therefore, (4) (for a single target line \(e\)) is equivalent to

\[
\begin{pmatrix}
[H]_e (P_g^p(a) - P_d) \\
[H]_e (P_g^p(a) - P_d)
\end{pmatrix} \geq (1 + \tau) P_{f,e}^p, \quad \text{if } P_{f,e}^p \geq 0,
\]

\[
\begin{pmatrix}
[H]_e (P_g^p(a) - P_d) \\
[H]_e (P_g^p(a) - P_d)
\end{pmatrix} \leq (1 + \tau) P_{f,e}^p, \quad \text{if } P_{f,e}^p < 0.
\]

(iv) MPEC (6) and (8) is a hard combinatorial problem due to (5) with dual objectives \(\tau - \kappa\). To deal with the combinatorial nature of \(|\Delta(e)|_0\) and the adversary’s dual objectives \((\tau - \kappa)\), we develop the following algorithm.

**Algorithm.** Let \(\bar{k} \in S\) denote the maximum number of targeted substations. Then, the following mixed integer linear optimization problem computes the optimal attack vector \(a^*\) for an adversary constrained to attack up to \(\bar{k}\) substations:

\[
\begin{align*}
\max_a &\quad \tau, \\
\text{s.t.} &\quad \sum_{k \in S} \delta_k \leq \bar{k}, \\
&\quad \text{Eqs. } (3), (8a)-(8d), (9) \text{ and } (10).
\end{align*}
\]

By increasing \(\bar{k}\), Algorithm \([11]\) finds the optimal vector of attacked substations \(\Delta^*(e)\), targeting a single line \(e\), which changes the flow of \(e\) larger than a pre-defined target congestion, i.e., \(\tau^* > \bar{\tau}\).

**Remark 4. Implementation:** Algorithm \([11]\) requires to solve the mixed integer linear problem \([11]\) for at most \(N\) times. Mixed integer programming is NP-hard \([\text{Citation}]\). The rest of the operations have complexity \(O(1)\).

**Remark 5.** In Algorithm \([11]\) we choose to manipulate \(\kappa\). Nevertheless, we can obtain the same result, if instead, we define a finite set \(\bar{\tau}\) of targeted congestion, while minimizing \(\kappa\). This is a consequence of the Pareto nature from the dual opposing objectives \((\tau - \kappa)\).

**B. The Correlation Index**

In this subsection, we characterize the Correlation Index for the SCED problem. We remark that the CI provides the spatial correlation between the adversary’s goal and vulnerable cyber-devices. However, since the vulnerable cyber-devices are located within substations, we will simply state that the CI correlates the adversary’s goal with multiple target substations during a coordinated cyber-attack. Formally, the CI is defined as follows.

**Definition 1. The Correlation Index.** Let \(\Delta^*(e)\) be a solution of Algorithm \([11]\) for a given \(\bar{\tau}\). Then, the CI \(I_e \subseteq S\), associated with the target line \(e\), is the set that identifies targeted substations from \(\Delta^*(e)\). Hence, there exists a relation between \(I_e\) and \(\Delta^*(e)\), i.e., \(\Delta^*(e) \leftrightarrow I_e\), given by

\[
I_e := \{k \in S \mid [\Delta^*(e)]_k \neq 0\}.
\]

In the rest of the paper, with some abuse of notation, we will denote the relation between a single target line \(e\) and its corresponding CI \(I_e\) as: \(e \mapsto I_e\). Moreover, since the CI describes target substations, we will interchangeably use CI
and optimal coordinated attack. Some properties of the CIs are described next.

C. Properties of the Correlation Index

Uniqueness of $I_e$. Since the original problem (6) and (7) is non-convex (31), the CI $I_e$ might not be unique. However, for fixed values of $M > 0$ and $\bar{r} > 0$, the CI has always minimum cardinality. Some properties of the CI are described next.

The following lemma shows that for a coordinated attack $I'$, if it cannot inflict impact on a transmission line $e$, then $e$ is also secured under all subordinated coordinated attacks $I \subset I'$. 

Lemma 1. If $e \not\in I'$, then $e \not\in I \subset I'$.

Proof. Appendix.

Due to Lemma 1 we know that security is guaranteed for subordinated coordinated attacks of the CI $I_e$. However, any coordinated attack containing $I_e$ can inflict impact on $e$. This is generalized in the following lemma.

Lemma 2. Let $e \mapsto I_e$ denote the target line and associated coordinated attack. Suppose there exists another coordinated attack $I \subset S$, then $e \mapsto I_e \cup I$.

Proof. Appendix.

Lemma 2 implies that large coordinated attack could be targeting a finite number of transmission lines. Formally, we state this in the following theorem.

Theorem 1. Suppose the coordinated attacks $I_e$ can impact transmission lines $e$, for $e \in \mathcal{E}$, i.e., $e \mapsto I_e$, for $e \in \mathcal{E}$. Suppose there exists a large coordinated attack $I^*$ such that $I_e \subseteq I^*$, for all $e \in \mathcal{E}$. Then, $I^*$ can inflict impact on any transmission line $e \in \mathcal{E}$, that is, $e \mapsto I^*$, for any $e \in \mathcal{E}$.

Proof. Appendix.

Due to Theorem 1 we know that multiple (individual) target lines might have common target substations. The following theorem leverages on this fact to describe individual protection of substations.

Theorem 2. Let $\mathcal{L} \subset \mathcal{E}$ be a set of target lines. For any $e \in \mathcal{L}$, let $I_e$ be the associated CI (coordinated attack). Suppose the coordinated attacks, for the set of target lines $\mathcal{L}$, satisfy $\cap_{e \in \mathcal{L}} I_e \neq \emptyset$. If the grid’s operator protects measurements at substation $k^*$, with $k^* \in \cap_{e \in \mathcal{L}} I_e$, then one of the following occurs to each target line $e \in \mathcal{L}$:

(i) If $I_e$ is the only coordinated attack with cardinality $|I_e|$ that can inflict impact on $e$, then the new coordinated attack $I_e^{new}$, with the $k^*$th substation protected, will require to target more substations, i.e., $|I_e^{new}| > |I_e|$.

(ii) If $I_e$ is not the only coordinated attack with cardinality $|I_e|$, then the new attack will inflict less or equal impact (congestion) to the target line, i.e., $\tau'(e) \geq \tau_{new}(e) > \bar{r}$.

(iii) The attack is not longer feasible.

Proof. Appendix.

In the next section, we will leverage on Theorem 2 to derive the best defense on substations. Intuitively, Theorem 2 suggests that a target substation is more critical when is associated to more target substations during coordinated attacks.

D. Multiple Target Lines

The study of coordinated attacks to a set of multiple target lines $\mathcal{L}^*$ is important in the analysis of the attack’s final consequences. For instance, $\mathcal{L}^*$ might be the set of lines that the adversary needs to congest in order to cause a cascading blackout. However, we will potentially be analyzing $|2^{\mathcal{E}}|$ combinations of multiple target lines. Similarly, if we choose to analyze from target lines to physical consequences, we will need to study $|2^{S}|$. For large scale power grids, both approaches are computationally prohibitive.

Therefore, we show that the simultaneous attack to multiple lines, from the defense viewpoint, does not differ from the single line attack, if the attack is still feasible. We justify this statement through the following proposition.

Proposition 1. Let $\mathcal{L}^*$ denote the set of multiple target lines ($|\mathcal{L}^*| > 1$) and let $I_\mathcal{L}^*$ denote the corresponding CI. Moreover, to each individual target line $\{e\}$ with $e \in \mathcal{L}^*$, we associate the individual CI $I_e$. Then, $I_\mathcal{L}^*$ satisfies

$$| I_\mathcal{L}^* | \geq \max \{| I_e | \mid e \in \mathcal{L}^* \}. $$

Remark 6. In fact, under the same assumptions of Proposition 1 the following statement holds (except in some pathological cases):

$$\cup_{e \in \mathcal{L}^*} I_e \subseteq I_\mathcal{L}^*. \quad (13)$$

Proposition 1 and (13) implies that by protecting $e$, we also protect against coordinated attacks that target a set $\mathcal{L}$ containing $e$.

VI. DEFENSE IMPLICATIONS

In this section, we leverage on the CI’s properties to derive: (i) the best defense for a target line $e \in \mathcal{E}$, and (ii) the best defense on substations.

The best defense for a target line $e \in \mathcal{E}$

Suppose the coordinated attack $I_e$ can impact the target line $e$. Then, the best defense for the transmission line $e$ is to protect the set $\mathcal{D}_e \subseteq I_e$ of substations, with minimum cardinality, such that the coordinated attack $I^* = I_e \setminus \mathcal{D}_e$ cannot longer inflict impact on $e$. The set $\mathcal{D}_e$ is called the minimal attack set, i.e., the minimal set of exploits (substations) whose protection prevents the adversary from reaching the goal on the physical grid.

On the other hand, there is no guarantee that cyber-attacks taking place at substations will remain static. For instance, let $I_e$ and $I'$ be two coordinated attacks that can impact $e (|I_e| \leq |I'|)$. Then, the adversary can switch from $I_e$ to $I'$ to identify vulnerabilities and hide from detection. However, if there is common substations between attacks, i.e., $k^* \in I_e \cap I'$, then, the best defense for $e$ is to protect the $k^*$th substation.
The best defense of substations

To describe the best defense on the grid, i.e., the most critical substation to protect, we define the risk of not protecting the kth substation as follows.

**Definition 2.** Given a target congestion \( \bar{\tau} \), the risk of not protecting the kth substation is

\[
R_k(\bar{\tau}) := \frac{1}{m} \sum_{e \in E} (|I_e^k| - |I_e^*|),
\]

where \( I_e^k \) denotes the CI after protecting the kth substation.

Notice that Theorem 2 implies that the risk is non-negative, i.e., \( R_k(\bar{\tau}) \geq 0 \), for all \( k \in S \). Therefore, based on this risk quantifier, the best defense strategy for the grid is to protect substation(s) \( k^* \), such that \( R_{k^*} \in \arg \max_{k \in S} \{ R_k \} \). We interpret this as follows. By protecting substation \( k^* \), the operator forces the adversary to target (on average) more substations during coordinated attacks to any transmission line \( e \in E \).

**VII. Numerical Experiments**

In this section, we provide numerical examples to illustrate the CI (correlated attacks to multiple substations), its properties, and the best defense on the grid. We use the New England 39 bus system, depicted in Fig. 5, to model a power grid composed with \( N = 6 \) substations implementing SCED. Given target congestion \( \bar{\tau} \), we compute the CI, by solving Algorithm 1. In particular, to solve (11), we used CVX, a package for specifying and solving convex programs [32], [33].

**Experiment 1. Computing the CI**

Consider two target lines \( e = (2, 25) \) and \( e' = (16, 21) \). We solve Algorithm 1 to compute the CIs (coordinated attack) for the target congestion \( \tau \in (2.5\%, 5\%, 7.5\%, 10\%, 12.5\%) \), and maximum number of attacked substations \( \kappa \in S \). The results are illustrated in Fig. 6 and Fig. 7 respectively. It can be seen that by fixing \( \kappa \), we find the maximum target congestion achieved, e.g., for \( e \) and \( \kappa = 2 \), the maximum congestion achieved is \( \tau = 2.5\% \). Similarly, by fixing \( \tau \) we find the CI of the line, for instance, given \( \tau(e') = 5\% \), the CI is \( I_{e'} = \{4, 5, 6\} \). Finally, we have used \( S \) to denote coordinated attacks to all substations (e.g., \( \tau(e) = 10\% \)), and \( \emptyset \) to denote attacks that are not feasible (e.g., \( \tau(e') = 10\% \)).

**Experiment 2. Protecting a single substation**

Properties of coordinated attacks to \( e \) and \( e' \) are described next. Fig. 6 shows that for \( \tau(e) = 5\% \), any subordinated attack to \( I_e = \{2, 5, 6\} \) will not inflict impact on the grid (Lemma 1). Similarly, for \( \tau(e) = \tau(e') = 2.5\% \), Fig. 6 and Fig. 7 show that a coordinated attack \( I^{**} = \{1, 2\} \) might be targeting both \( e \) and \( e' \) (Lemma 2 and Theorem 1). Finally, suppose the operator has protected substation \( k = 2 \). As a result, the CIs for \( e \) and \( e' \) have changed as illustrated in Fig. 8 and Fig. 9. For example, Fig. 9 shows that the new CI for \( \tau(e) = 2.5\% \) has a larger cardinality (Theorem 2 (a) implies \(|\{5, 6\}| > |\{2\}|\)). Moreover, Fig. 8 illustrates that the new CI for \( \tau(e) = 5\% \) will achieve less congestion \( \tau^* \) (Theorem 2 (b)). Finally, coordinated attacks for \( \tau(e) > 7.5\% \) are not longer feasible (Theorem 2 (c)).

**Experiment 3. The Risk of not protecting substations**

In this final experiment, we implement the best defense on substations by analyzing the risk \( R_k(\bar{\tau}) \), for all \( k \in S \). Note that the risk depends on the target congestion. The congestion selected for the experiment was \( \bar{\tau} \in \{5\%, 7.5\%\} \). The results are depicted in Fig 10 and Fig. 11. They imply that the best defense at a single substation is achieved by protecting \( k^* = 2 \).

**VIII. Conclusion**

In this paper, we derive a Static Correlation Index based on the adversary’s goal for static power applications. The CI
provides the spatial correlation between the physical consequences of a cyber-attack and target cyber-devices, i.e., the set of target cyber-devices associated to a goal on the physical power grid. The CIs are derived based on analytical models of static applications subject to coordinated attacks. Despite being described for the case of measurement DIAs to SCED, our proposed framework is applicable to other static power control applications and cyber-attacks. Defense implications based on the CIs’ properties were also discussed. In our ongoing work, we leverage on these results together with Intrusion Detection Systems to identify coordinated attacks. Finally, the real-time interception of coordinated attacks for static and dynamic power applications is part of our future work.

**APPENDIX A
PROOFS**

**Proof.** (Lemma 1) Suppose, to get a contradiction, \( e \mapsto I_e \), then from the CI’s definition, any super-set \( I_e^* \) of \( I_e \), i.e., \( I_e \subseteq I_e^* \), is also a CI for \( e \). In particular, \( I_e^* \equiv I_e \) is a CI of \( e \), which contradicts \( e \not\mapsto I_e^* \).

**Proof.** (Lemma 2) We prove the lemma by cases. (i) Suppose \( I_e^* \) is a super-set of \( I_e \), i.e., \( I_e \supseteq I_e^* \). It follows that \( e \mapsto I_e \cup I_e^* \). Similarly, (ii) suppose that \( I_e \subseteq I_e^* \). Then, it follows that \( e \mapsto I_e \cup I_e^* \). Finally, (iii) suppose the CI \( I_e^* \) is neither a subset or super-set of \( I_e \). Assume, to get a contradiction, that \( e \not\mapsto I_e \cup I_e^* \). Then, Lemma 1 implies that any CI \( I_j \subseteq I_e \cup I_e^* \) is not a CI of \( e \). In particular, \( I_j \equiv I_e \cup I_e^* \) is not a CI of \( e \). This yields the contradiction.

**Proof.** (Theorem 1) The CI \( I_e^* \) can be partitioned into the union of two disjoint sets, i.e., \( I_e^* = I_e \cup (I_e^* \setminus I_e) \), for \( e \in \mathcal{L} \). Then, by Lemma 2 we have \( e \mapsto I_e^* \), for \( e \in \mathcal{L} \), which proves the theorem.

**Proof.** (Theorem 2) If the operator protects measurements at station \( k^* \) and the attack remains feasible, Lemma 1 implies that the new CI \( I_e^{\text{new}} \subseteq S \) satisfies \( |I_e^{\text{new}}| \geq |I_e| \). Suppose the original CI \( I_e \) is the only one with cardinality \( |I_e| \), then \( |I_e^{\text{new}}| > |I_e| \). This proves (a). On the other hand, suppose the new CI \( I_e^{\text{new}} \) has the same cardinality, i.e., \( |I_e^{\text{new}}| = |I_e| \). Then the new congestion associated with \( I_e^{\text{new}} \) satisfies \( \tau_e > \tau_e^{\text{new}}(e) > \bar{\tau} \); otherwise, the original \( I_e \) would have not been optimal. The equality follows from the non-uniqueness argument. This proves (b). Finally, (c) follows trivially.

**Proof.** (Proposition 1) Suppose there exists some \( e \in \mathcal{L}^* \) such that \( |I_e| > |I_e^*| \). Then \( I_{e^*} \) cannot be a CI for \( e \) or any set containing \( e \) (by definition, the CI has minimum cardinality), which contradicts \( \mathcal{L}^* \mapsto I_{e^*} \).
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