Threat Scenarios and Monitoring Requirements for Cyber-Physical Systems of Energy Flexibility Markets

Nils Müller, Kai Heussen
Department of Electrical Engineering
Technical University of Denmark
Lyngby, Denmark
{nilmu; kh}@elektro.dtu.dk

Zeeshan Afzal, Mathias Ekstedt
Department of Computer Science
KTH Royal Institute of Technology
Stockholm, Sweden
{zafzal; mekstedt}@kth.se

Per Eliasson
Foreseeti AB
Stockholm, Sweden
per.eliasson@foreseeti.com

Abstract—The ongoing integration of renewable generation and distributed energy resources introduces new challenges to distribution grid operation. Due to the increasing volatility and uncertainty, distribution system operators are seeking concepts to enable more active management and control. Flexibility markets offer a platform for economically efficient trading of electricity flexibility between distribution system operators and other participants. The integration of cyber, physical and market domains of multiple participants makes flexibility markets a system of cyber-physical systems. While cross-domain integration sets the foundation for efficient deployment of flexibility, it introduces new physical and cyber vulnerabilities to participants. This work provides a systematic overview of threat scenarios for the cyber-physical systems of flexibility markets. Results reveal several remaining security challenges across all domains, that require more attention. Based on the threat scenarios and a novel generic monitoring requirements model, monitoring concepts for secure participation of distribution system operators in flexibility markets are proposed. By highlighting approaches to tackle identified challenges, this work provides new directions for further investigations, and takes important steps towards secure implementation of flexibility markets.

Index Terms—distribution grids, flexibility markets, threat scenarios, monitoring requirements, cyber-physical power systems

I. INTRODUCTION

To reach the European goal of carbon neutrality in 2050, electricity generation and consumption must undergo radical changes. While the share of renewable generation needs to increase, electrification of other sectors through devices such as electric vehicles (EVs) and heat pumps (HPs) will drive up and reshape electricity demand. This extensive installation of distributed energy resources (DERs) on end user level will introduce more uncertainty and volatility, and thus radically change the requirements to the operation of distribution grids. Originally designed for the supply of consumers based on centralized generation, distribution grids will increasingly be used as carriers of volatile and often bi-directional power flows [1]. Thus, the active management of distribution grids based on the emerging smart grid technologies for monitoring, control, and communication is seen as a requirement for distribution system operators (DSOs) [2]. With the improving capability and affordability of information and communication technology (ICT), the utilization of end user flexibility, commonly referred to as demand response, is becoming more attractive. By reducing equipment loading during peak hours, DSOs can use local flexibility to delay or avoid investments for reinforcement of transformers and power lines [3].

As a framework for the integration of local flexibility, a widely discussed approach are flexibility markets (FMs) [4]–[6]. FMs constitute a competitive trading platform for electricity flexibility, typically in a geographically restricted area such as neighborhoods or towns [7]. There exist a variety of market designs and new concepts are still under development [4]. However, a typical setup of market participants consists of a DSO, a balance responsible party (BRP), several aggregators and a market operator. Aggregators pool and manage multiple small residential flexibility assets. In this way, aggregators enable end users to participate in the FM. Larger flexibility assets, such as industrial loads, can potentially also directly participate in the market. In FMs, DSOs and BRPs typically are flexibility buyers, while aggregators constitute flexibility sellers. DSOs procure flexibility for operational purposes, such as congestion management or voltage control. BRPs buy flexibility for portfolio optimization. By adjusting the power demand of the aggregated residential flexibility assets, aggregators make profits according to flexibility contracts. The owners of flexibility assets make profits by providing a DER, such as a HP or an EV, as a flexibility asset to an aggregator. FMs are promoted by EU legislators [8]. Reasons include (i) FMs resolve potential conflicts of interest between system operators, (ii) FMs require only minor adjustments in the legislative framework, allowing to maintain the current wholesale markets structure, and (iii) market competition ensures efficient allocation of resources and accurate pricing for market participants.

The foundation of a FM is a strong integration of cyber, physical and market domains of multiple actors, making it a system of cyber-physical systems. While this cross-domain integration sets the foundation for efficient deployment of flexibility assets, it also introduces new vulnerabilities to the involved participants and their systems. By applying end user flexibility to avoid critical grid states, DSO grid operation becomes partly dependent on third parties. Moreover, the

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required use of ICT, including less secure public networks, and the strong coupling with the physical and market domain opens doors for cyber criminals, aiming at social or financial damage. In addition, incorporating home devices of end users as flexibility assets also requires transmission, storage and processing of sensitive data.

To alleviate the above-mentioned concerns, possible risks first must be identified and security requirements formulated. In this context, understanding requirements for holistic monitoring of involved cyber-physical systems is a mainstay.

This work provides an overview of possible threat scenarios for the cyber-physical systems of FMs. Based on the threat scenarios and a novel generic monitoring requirements model, monitoring concepts for secure participation of DSOs in FMs are proposed.

A. Related work

As highlighted by [9] and [10], the influence of flexibility on power system security constitutes a research gap, since most existing works only focus on benefits of flexibility utilization. Some works shed light on specific physical threats, such as uncertain customer behavior [11]–[13] or financial threats, for instance the financial risk of aggregators due to the intermittent nature of flexibility assets [14]. Other works investigate cyber threats which are introduced by the application of new smart grid technologies, such as smart meters (SMs) and advanced metering infrastructure [15]–[18]. In [19], a number of cyber threats (divided into different groups) are identified and mapped to grid assets and threat agents. The work also addresses possible security controls to reduce exposure to threats.

All listed works only focus on specific threats or threat categories. Moreover, no work specifically addresses FMs, but rather consider a more generic smart grid infrastructure.

In [10], Sperstad et al. discuss possible positive and negative impacts of flexibility on the security of supply from a physical and a cyber perspective. A major physical threat is seen in the rebound effect of flexibility activations that may shift load peaks, and result in even more severe situations than without flexibility activation. A flexibility-induced cyber threat is seen in load-altering attacks that may impact the bulk power system without compromising better protected assets on transmission level.

To the best of the authors knowledge, the work of Sperstad et al. is the only work that provides cyber and physical threat scenarios in the context of flexibility. However, since threat scenarios are no major concern of the work, it does not provide a comprehensive and systematic overview. Moreover, it does not take characteristics of FMs into account and does not derive required security concepts from the described threat scenarios.

B. Contribution and paper structure

The contribution of this paper is threefold:

- Systematic formulation and description of threat scenarios for the cyber-physical systems of FMs. Scenarios consider threat origins in various domains and emphasize the interaction among the cyber, physical and market domain.
- Introduction of a generic monitoring requirements model for DSOs, developed for identification of missing monitoring concepts.
- Identification of required monitoring concepts of DSOs for participation in FMs based on a mapping of threat scenarios onto the developed generic monitoring requirements model.

The remainder of this paper is structured as follows. Section II provides a systematic overview of threat scenarios for the cyber-physical systems of FMs. Section III begins with the description of the proposed generic monitoring requirements model, followed by a proposal of monitoring concepts for participation of DSOs in FMs. Finally, Section IV concludes the paper and motivates future work.

II. THREAT SCENARIOS

This section is concerned with the systematic formulation and categorization of threat scenarios for the cyber-physical systems of FMs. Subsection II-A presents the scenario formulation approach, followed by scenario descriptions in Subsections II-B to II-J.

A. Threat scenario formulation

In order to describe and compare scenarios with various backgrounds, a domain-neutral formulation is required, which still captures key information. In Fig. 1 the applied formulation concept is schematically represented. Threat origin, affected component and threat impact are selected as domain-independent key information.

The threat origin comprises two groups, namely external and internal. In Table I the considered origins are listed and allocated to one of the two groups, supplemented by information on their background. Table I indicates that a broad spectrum of origins is considered, allowing for a holistic investigation of threat scenarios.

Typically, a critical situation develops around a specific component or component type in a system, independent of the threat origin. A cyber attacker will most likely try to manipulate a specific data stream or device to launch the

| Nr. | Threat origin         | Group  | Background          |
|-----|-----------------------|--------|---------------------|
| 1   | Device failure        | Internal | accidentally        |
| 2   | Human error           | Internal | accidentally        |
| 3   | Market actors         | Internal | financial gain      |
| 4   | Insiders              | Internal | dissatisfaction     |
| 5   | Consumer behavior     | Internal | randomness           |
| 6   | Weather               | External | volatility, political |
| 7   | Price signals         | External | volatility          |
| 8   | Organized cyber-criminals | External | randomness |
| 9   | State-sponsored actors | External | financial gain       |
A famous example is the Industroyer malware attack on the Ukrainian power system, which targeted the control of circuit breakers in substations [20]. An aggregator who falsely determines the flexibility potential of its portfolio will affect a flexibility service traded in the market. At the same time, the affected components in most cases constitute interface components between the different domains. As a result, threat scenarios typically have an impact on multiple domains. As an example, flexibility services that are not provided according to the contract will affect both the power system and market operation. This dependency can be explained by the strong cross-domain integration of FMs.

At the end of every scenario there is a potential negative impact, which typically is of social or financial nature. However, other impact, such as a loss of private information, are taken into account. To allow for a better overview and to demonstrate how fundamentally different threat origins can result in similar critical situations, scenarios are grouped by the affected component. Table II summarizes the scenarios, including probable impacts and threat origins, which are given as numbers referring to Table I.

B. SM-based scenarios

End users are increasingly equipped with SMs. Depending on the FM architecture, SMs may provide data to aggregators for flexibility planning and verification. Meters typically use a programmable logic controller (PLC) interface to communicate with the utility and have capability to remotely switch power on or off.

1) Unauthorized access and modification of SM data: Cyber-criminals could gain access to sensitive meter data such as consumption, credentials (including keying material), and firmware information by exploiting known software vulnerabilities or by decrypting PLC communication that uses weak encryption. Additionally, if cyber-criminals can take over the meter communication with the aggregator (e.g., by using the encryption key), they can send wrong consumption data. The asset owner could be fined for not fulfilling flexibility agreements and eventually be removed from the portfolio. Having a hold of private data and options for financial damage, cyber-criminals may aim at blackmailing flexibility asset owners.

2) Accessing and controlling multiple SMs: As an extension of Scenario [II-B1] cyber-criminals or state-sponsored actors may aim at accessing and controlling multiple SMs. Attackers may use common weaknesses of SMs, such as static encryption keys. Typically, SMs deployed by a DSO share the same encryption key. Thus, if attackers gain access to the encryption key of one SM, they are also able to extract useful information, such as the energy consumption behavior, of entire neighborhoods. At this stage, attackers can also take over SMs remote on/off switching. In [21], it is demonstrated how attackers can cause line trips by exploiting the switching capability of multiple SMs on a load bus to introduce load oscillations. The result may be power outages, resulting in high social and financial cost. Another attack path to target multiple SMs is to launch a remote or physical attack on meter data concentrators.

C. Local controller-based scenarios

Various actors of FMs rely on local controllers. By interfacing the cyber and physical domain, they constitute critical system components, introducing potential threats.
1) **Modification of substation controller:** Primary and often secondary substations are equipped with local controllers, such as PLCs, remote terminal units (RTUs) and intelligent electronic devices (IEDs). State-sponsored actors could place infected rootkits onto one or multiple local controllers. By sending malicious control signals to circuit breakers and protection relays the attackers could damage grid facility and disconnect customers. To hide the attack from the central control room, normal operation values could be returned back. In [22], it is demonstrated that attackers can create such false data that will not raise an alarm by existing algorithms for bad data detection.

2) **Modification of flexibility asset controller:** Small flexibility assets such as EVs or HPs are typically controlled by home energy management systems (HEMS) [23]. These are internet-connected systems that typically have remote control capability and are based on off-the-shelf soft- and hardware, making them vulnerable to cyber attacks and asset owner modification. Flexibility asset owners may modify setpoint boundaries or increase setpoints before a service is activated. In both scenarios they could make financial gain and would manipulate the flexibility service of the aggregator. Organized cyber-criminals could make use of weak password security and encryption to gain access to individual HEMS. Attackers may collect sensitive data, change setpoints to impair customer comfort and degrade flexibility assets, or increase costs by raising consumption or mitigating flexibility activation, resulting in non-compliance with flexibility contracts. Hence, organized cyber-criminals could blackmail customers for financial gain. State-sponsored actors could infiltrate the local controllers of multiple small or individual large flexibility assets. By changing the setpoints or switching assets on or off, they could introduce load peaks or oscillations that trigger transformer protection, resulting in customer disconnection. A coordinated attack affecting both flexibility assets and grid protection mechanisms simultaneously could result in severe physical damage of grid facilities and blackouts.

3) **Failure of large flexibility asset controller:** The activation of a large flexibility asset could fail due to software or hardware failures. Compared to activation failures of small assets, the impact may be severe. An industrial plant could provide flexibility services by reducing production capacity during times when many EVs are simultaneously charging to benefit from low prices. Under these conditions, an activation failure could lead to congestion at the transformer.

**D. Flexibility activation signal-based scenarios**

Flexibility activation signals comprise activation requests from flexibility buyers to sellers, and activation signals from aggregators to small flexibility assets. The transmission is typically conducted via public networks.

1) **Tamper or disrupt flexibility activation signals:** Aggregator employees may launch insider attacks, such as sending activation signals at wrong times or preventing required flexibility activations. Insiders of DSOs may send wrong activation requests. Flexibility activation signals could also be manipulated by cyber-criminals or state-sponsored actors through false data injection attacks by exploiting insecure authentication or weak encryption. Attackers could also flood flexibility assets with activation signals to disrupt the activation process. In all these scenarios, attackers could prevent or temper required flexibility activations to leave congestions or voltage violations unresolved or even intensify them. Moreover, attackers could initiate critical situations by activation of flexibility assets. In both cases high social and financial costs are likely.

2) **Unintentional wrong activation of flexibility assets:** Besides intentional attacks on flexibility activation signals, wrong activation may occur accidentally. Human errors from various actors, such as DSOs or aggregators, and in different process steps, from determining required or available flexibility to preparing and sending activation requests, could result in wrong flexibility activations. Equivalent to intentional attacks, damage could be of social and financial nature.

3) **Parallel flexibility activation with opposing or reinforcing effects:** Flexibility services can be requested by different actors with distinct purposes. While a DSO may intend to prevent congestion, a BRP may aim at portfolio optimization. Therefore, flexibility could be activated simultaneously from different FM actors and with opposing effects. Such scenarios can result in financial damage, since services may be procured without achieving the desired outcome. At the same time, price-based demand response introduces additional flexibility activations in distribution grids. DSOs might be unaware of future behavior of price-driven loads during flexibility planning. Thus, a risk for network violations exists if the service procured by a DSO results in over-activation of flexible loads.

**E. Historical data-based scenarios**

Historical data is of high importance for several actors in FMs. Threats emerge from potential data loss or manipulation.

1) **Compromised data on DSO or aggregator data historian:** Historical data provide necessary information for flexibility planning, activation and verification. Typically, they are not checked for integrity, after being stored. However, integrity could be affected by human and transfer errors, compromised hardware, and attacks. Model development based on compromised data will weaken performance or might make the model useless [24]. Financial damage for market participants may result due to imprecise flexibility planning and verification. In severe cases, techniques for power system monitoring may fail, leaving critical grid conditions unresolved.

**F. Flexibility request-based scenarios**

To procure flexibility, DSOs and BRPs need to submit flexibility requests to the FM. Depending on the market concept, requests can be formulated from intraday to months ahead.

1) **High uncertainty in the determination of flexibility needs:** Distribution grids face increasing volatility due to the dependency of distributed energy resources on weather, consumer behavior and price signals. At the same time, low-voltage
(LV) distribution grid states are highly underdetermined due to low real-time meter device coverage (low observability). The resulting uncertainty complicates forecasting of flexibility needs and requires DSOs to request larger flexibility capacities, which increases costs.

2) Uncertainty about power system states due to frequent flexibility activations: DSOs want to request and activate flexibility to avoid or postpone expensive grid extensions. However, frequent activations may break correlation between the few available measurements (e.g., primary substation and weather data) and power system states at the end of LV feeders \[25\]. Thus, the implementation of FMs might deteriorate the accuracy of LV state estimation, making critical states potentially unobservable to DSOs. Based on inaccurate state estimations a DSO might also activate unnecessary or even counteracting flexibility, resulting in financial costs. In severe cases, the triggering of protection mechanisms might cause disconnection of customers.

3) Parallel events resulting in sudden change of flexibility needs: In distribution grids a variety of events, including line failures or shut down of large industrial loads, can lead to a sudden change of the grid condition. Additionally, new events, such as load peaks due to simultaneous charging of EVs, will be introduced to distribution grids in the upcoming years. If they occur during an activation period, such events may change grid condition in a way that flexibility activation is not required or even critical. Moreover, state-sponsored actors could launch attacks on other systems, e.g., large battery energy storage systems or industrial plants during flexibility activation periods to modify the grid condition. Due to the low observability of distribution grids, the detection of such events may be challenging.

G. Flexibility offer-based scenarios

To sell flexibility, aggregators need to submit flexibility offers to the FM. Depending on the market scheme, flexibility can be offered for time frames reaching from intraday to months ahead.

1) Place wrong flexibility offers on the FM: Flexibility offers are placed on the market by either aggregators or large flexibility asset owners. If flexibility offers on the market do not reflect the actual flexibility potential, flexibility activation will likely not match the problem to solve. State-sponsored actors or insiders could tamper flexibility offers or place offers on the market in the name of verified market participants. In less serious cases aggregators will have to pay a refund. However, in severe cases critical grid conditions might not be solved by a DSO due to dependency on a wrong flexibility offer.

2) High uncertainty in the determination of flexibility offers: Aggregator determination of flexibility potential is subject to uncertainties. The capacity of an aggregator portfolio is dependent on the comfort requirements of customers, weather, customer behavior and other portfolio changes. In particular, weather and customer behavior uncertainties directly translate into uncertainty of flexibility offers. Moreover, in most cases the demand of small flexibility assets can only be controlled indirectly, by adjusting e.g., a temperature setpoint. As the translation of temperature setpoints to power consumption is dependent on external factors, additional uncertainties are introduced during activation. Unreliable flexibility offers mainly result in reduced financial profit for aggregators. However, severe uncertainties might make the use of flexibility for DSOs unreliable, and lead to more expensive but reliable alternatives, such as grid extensions. In case a DSO relies on a flexibility offer to solve a critical condition, high uncertainty might result in disconnection of end users.

H. Flexibility measurement or schedule-based scenarios

Reliable measurements of flexibility assets are required for service planning, activation and verification. Besides SM readings, additional data may come from devices such as
photovoltaic (PV) meters. To define the activation process, aggregators and flexibility asset owners typically agree on flexibility schedules.

1) Disrupt or manipulate flexibility measurements and schedules: Several actors might have an interest in manipulating flexibility measurements and schedules either by gaming or data tampering. Market actors such as aggregators or flexibility asset owners could manipulate flexibility activation recordings for financial gain. EXEMPLARY, for baseline services an asset owner could increase consumption before an activation period, to imitate a service by just returning to normal consumption level. Also cyber-criminals that can sniff and modify data in networks of aggregators or a service verification responsible party could compromise measurements, e.g. for blackmailing. One way is the modification of flexibility portfolio recordings to disrupt the service verification process. As a result, aggregators might receive fines for not fulfilling contractual agreements. Attackers could also modify the flexibility schedules which aggregators send to the assets, resulting in wrong flexibility activations. In mild cases, aggregators will be fined. In severe cases, wrong activations might trigger grid protection, resulting in disconnection of customers and thus high social costs.

I. Flexibility asset-based scenarios

Flexibility assets constitute a heterogeneous group of DERs, owned by multiple end users or companies. They can reach from small loads such as refrigerators to large loads, including industrial processes.

1) Unavailability of flexibility assets: During an activation period flexibility assets may not be available for reasons such as software failures, manual changes in the setpoint limitations by the asset owner or unforeseeable changes in the physical process of industrial flexibility assets. Moreover, cyber-criminals or state-sponsored actors could disturb communication by denial-of-service attacks. Since flexibility asset owners break the contract in cases of a failed activation, such scenarios would result in a financial penalty. Especially in case of large flexibility assets, unavailability could also lead to unresolved congestions and voltage violations.

J. Vendor soft- and hardware-based scenarios

All actors of FMs are dependent on services of third-parties, such as vendors. An often inherent need for trust between suppliers and users introduces potential threats.

1) Compromise vendor provided software and systems: State-sponsored actors could install malicious code in the software or hardware provided by a vendor. For example, an attacker could install a backdoor in a PLC that is provided by a vendor to the DSO. This backdoor can later be used to manipulate DSO operation in many ways. The impact of such an event may go beyond a single end user, as vendors of EVs or HPs provide software or hardware to multiple flexibility asset owners. A real-world example of the severity of such a threat comes from the recent SolarWinds hack [26].
execution and protocol delay, and resistance to attacks and failures.

3) Internal communication network monitoring: Internal communication networks of DSOs transmit critical operational data between the perceptual execution layer and higher layers. Due to new data sources, such as SMs and microphases measurement units (μPMUs), communication steadily increases. A disruption of data transmission can result from natural causes, device errors or attacks, and might provoke system unobservability, leading to inadequate control actions. Additionally, cyber attackers may observe, hide, create, or change process data. Communication networks are protected by several security measures, such as firewalls, authentication, and encryption [32]. However, these security measures might not prevent insider attacks or new attacks. Moreover, attackers increasingly use encryption to hide attacks from security measures [33]. To detect attacks at an early stage and reconstruct attack paths, intrusion detection systems should be located across the communication network and its components. To avoid delays in the face of increasing communication, and since both DSOs and attackers increasingly use encryption, intrusion detection mechanisms might need to be based on network flow data instead of the packet payload. However, some attacks might be invisible by only observing the network flow [34].

4) Historical data integrity checking: With the deployment of data-driven techniques for distribution system operation, historical process data will play a more important role than today. Based on historical data, models for critical applications, such as state estimation, fault detection or load forecasting, can be developed. As outlined in Subsection II-E1, compromised historical data might arise for several reasons, leading to varying degrees of model performance deterioration. Cloud storage and computing may further increase these risks for the DSO, as third parties are involved in data management [35]. Therefore, the integrity of historical data should be monitored throughout the process of uploading, storing and retrieving.
5) Power system monitoring: Due to the ongoing integration of DERs, DSOs are increasingly concerned with improving awareness of the system condition through techniques such as state estimation or topology identification. Low observability in distribution grids sets specific requirements. Techniques must be applied which maximize information extraction from available data sources. This includes data fusion as well as using historical data for real-time monitoring. The lack of observability also sets high requirements on robustness against cyber attacks and failures, as model results cannot be validated based on redundant measurements.

6) Decision support verification: Under certain conditions, decision support tools for distribution system operation may generate inaccurate or even wrong results. Reasons can be outdated model parameters, new or unseen power system states, and cyber attacks. Some recent works have demonstrated that already small input perturbations let several well-trained and accurate machine learning models predict incorrect answers with high confidence. Misleading decision support can result in critical control actions. Therefore, the possibility of model verification is desirable. To enable verification, a requirement is interpretability, which implies that human operators can retrace the cause of model decisions. However, especially in machine learning, models often constitute black boxes, which is a major barrier for use in critical applications such as power system operation. Potential directions to improve interpretability are seen in physics-aware models, specialized verification frameworks, and uncertainty quantification.

7) Multi-domain system-wide condition and risk monitoring: The cyber-physical system of a DSO is becoming more complex due to the increasing dependency between different system domains, the ongoing distribution and automation of control functions, and continuous installation of DERs. Thus, retrace the cause of an anomaly or critical condition might require correlation of multiple individual monitoring reports. In this context, an example of increasing importance are coordinated attacks. However, manually correlating multiple reports for assessing the system-wide condition becomes impractical. For this reason, a requirement is seen in the automated correlation of individual reports in a system-wide multi-domain condition analysis, as e.g. promoted in. Ideally, external information, such as weather conditions or states of adjacent energy systems, are incorporated. This would enable identification of potential risks, introduced by critical co-occurrence of specific system and external conditions.

8) Verification of manual control and supervision: In many systems the human factor is seen as the greatest uncertainty and threat. Although distribution system operation increasingly becomes automated, human operators will not disappear from control rooms in the foreseeable future. As humans by fault or on purpose can initiate or overlook critical control actions, verification is desirable. Risks in the supervisory control layer include unauthorized accessing e.g. through outdated passwords, presence of externals, social engineering, new or disgruntled employees, and the out-of-the-loop syndrome. Requirements for verification of manual control and supervision include authentication and authorization of operators, as well as verification of taken control decisions. Manual control decisions that are not consistent with the decision support results should be identified. For future DSO systems with a high degree of automation, manual decisions will mainly be necessary in extreme situations where decision support applications fail. Under these conditions, verification of manual control decisions becomes difficult, as decision support tools cannot provide information for the verification process.

B. Identification of required monitoring concepts for DSO participation in FMs

This Subsection proposes monitoring concepts for DSOs participating in FMs. For this purpose, threat scenarios from Section II are mapped onto the generic monitoring requirements model (Subsection III-A).

1) Quantifying flexibility-induced uncertainty: Threat scenario II-F2 discusses that frequent flexibility activations could introduce uncertainty to LV state estimation. At the same time, flexibility is used to operate power systems closer to their capacity limits. Under these conditions, point estimation-based monitoring might fail silently, affecting the DSO decision-making process and potentially impacting critical decisions. Thus, for power system monitoring III-A5 quantifying flexibility-induced uncertainty is an important concept to lower the risk of frequent triggering of protection mechanisms.

Uncertainty quantification also improves verification and security of decision support tools III-A6. Models that increase uncertainty under appearance of unseen flexibility activation events or system states provide human operators requirement indicators for retraining models or including additional input features. Moreover, models that provide uncertainty quantification, such as Bayesian neural networks, have shown robustness against adversarial attacks.

Finally, uncertainty quantification is beneficial for analysing the condition of the cyber-physical system III-A7. If a critical power system state is reported to the system-wide condition monitor, the probability of its occurrence could be included. By improving interpretability, the number of false alarms could be reduced, enabling more reliable system-wide monitoring of the cyber-physical system.

2) Flexibility activation detection: Several threat scenarios II-C2 II-D2 II-D3 demonstrate that flexibility activations can occur without the DSO being aware of it. Such activations might occur intentionally by cyber attackers, unintentionally due to human errors, or just by activation through other market participants. However, especially flexibility activations which are not planned by the DSO have a risk of exceeding load and voltage limitations. To allow for immediate counteractions in case of critical activations, early detection is required. Thus, for power system monitoring III-A5 automated detection of flexibility activations is seen as an important monitoring concept.
3) **Flexibility scenario monitoring:** In threat scenario [II-F1] and [II-F2] respectively, the difficulty of determining flexibility needs and flexibility activation demand is described. Especially under the aforementioned uncertainty and low observability of distribution grids, flexibility planning becomes a challenging task for DSOs. Thus, tools providing power system state scenarios under various flexibility services are considered important concepts for power system monitoring (III-A3). Depending on the market concept, tool requirements may look different. For day or week-ahead procurement, tools will be required to provide state forecasts under various flexibility services. Market concepts that include real-time procurement of flexibility require tools for mapping available flexibility offers onto the current grid state. Both scenarios involve uncertainties, such as uncertainty about the exact location of flexibility assets and their effect on a specific critical grid state. Thus, models capable of quantifying such uncertainty should be developed.

4) **Integration of multi-domain information:** Many threat scenarios demonstrate the strong dependence among the cyber, physical and market domains introduced by FMs. Cyber attackers may intend to cause physical damage ([II-C2] [II-D1] [II-E1]) or disturb market actions ([I-B1] [I-G1] [I-H1]), while insufficient coordination on the FM platform may result in physical impact due to parallel activations ([II-D2]). In such scenarios, underlying events are likely to leave traces in multiple domains. Moreover, the origin of a particular threat scenario may be in different domains. As an example, failed activation of a large flexibility asset might be caused by a hardware failure, cyber attack or end user manipulation. Thus, a required monitoring concept is seen in the integration of information from multiple domains and sources to i) improve information extraction by incorporating all available traces and ii) take possible threat origins in various domains into account. This somewhat general concept could facilitate fulfillment of multiple monitoring requirements across all layers of the cyber-physical architecture of a DSO. Examples are process-level integrity checking (III-A1), authentication of external information (III-A2) and historical data integrity checking (III-A4). For internal communication network monitoring (III-A3), combining information from the cyber and physical domains is considered a particularly important concept. As stated in Subsection III-A3 the increasing data volume and encryption might require cyber intrusion and anomaly detection to be based only on network flow data, which potentially will make advanced attacks invisible. Especially for detection of attacks which intend to have a physical impact, fusion of network flow information with physical process data might improve performance. A central challenge for integration of multi-domain information will be the fusion of heterogeneous data.

5) **Intrusion and anomaly detection for small flexibility assets:** In threat scenario [II-B2] and [II-C2] respectively, it is demonstrated that edge devices, such as SMs and HEMS, have known security weaknesses (e.g., static encryption key) which can be exploited by cyber attackers. The implementation of FMs will make power system operation partly dependent on such less protected devices. Thus, from the perspective of the DSO, flexibility asset intrusion and anomaly detection are considered important concepts for process level integrity checking (III-A1). However, some challenges exist. As described in Subsection III-A1 advanced attackers can hide manipulation of local devices to central control rooms, making distributed detection on edge devices necessary. As edge devices normally come with computational constraints, detection tools must be lightweight. At the same time, manipulation might be difficult to detect and requires incorporation of information from various domains, increasing the demand for data computation, communication and storage.

### IV. Conclusion

In this work, threat scenarios of the cyber-physical systems of FMs are systematically identified and presented. 17 threat scenarios across all system domains are introduced, revealing several remaining security challenges. Among others, scenarios include simultaneous control of multiple flexibility assets by cyber attackers exploiting weak encryption, and high uncertainty in the determination of flexibility needs and offers due to low meter coverage and high load variability in distribution grids. Based on the threat scenarios and a novel generic monitoring requirements model, monitoring concepts for secure participation of DSOs in FMs are identified and proposed. Proposals include distributed intrusion and anomaly detection for small flexibility assets, quantification of flexibility-induced uncertainty, and integration of multi-domain information for event detection. By proposing possible approaches to tackle the identified challenges, new directions for further investigations are introduced. Future work will be directed towards development of monitoring requirements models for other market participants, such as aggregators and BRPs, to derive required monitoring concepts for all FM actors. Moreover, the introduced monitoring concepts for secure participation of DSOs in FMs will be investigated.

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