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Q3.01: What are the benefits of digital solutions like IoT-sensors, machine learning, artificial intelligence, drones, robots etc. for substation life cycle from planning to maintenance? Which measures are necessary to increase the acceptance of intelligent IoT-based power equipment in substations?

The recent advances in high performance embedded microprocessors, optimized signal processing algorithms and reliable communication protocols, have fostered the development of Internet-of-Things (IoT) architectures, artificial intelligence (AI) and autonomous robotics, as strategic technologies for the next generation of substation O&M activities. Today, research efforts are mainly focused on specific applications at the nexus between emerging technologies and substation asset management needs; nevertheless, a future flourishing research area consists in the definition of sustainable end-to-end architectures, involving cost-effective sensors deployment and maintenance strategies, efficient and secure data management pipelines, and robust resource allocation guidelines.

Pervasive sensing infrastructures allow data extraction from remote and inaccessible locations; for this reason, they have become fundamental to enable continuous, autonomous, and secure asset monitoring. Recently, sensor-equipped robots are becoming fundamental for HV equipment monitoring. Within the IoT community, robots are regarded as mobile sensor platforms, whose perception capabilities are extended once integrated into existing pervasive sensing schemes: as a matter of fact, a robot surrounded by communication-enabled sensing devices has access to a richer amount of information, compared to the localized data collected by its on-board sensors. Moreover, in unmanned robotics, the aggregation of multiple spatially distributed sources allows the robot to learn faster, and to plan more robust and more adaptive strategies under dynamic and uncertain conditions.

The data-transmission capabilities of IoT-devices allow to centralize all the collected data on remote servers, where human analysis tasks take place (**manual centralized monitoring**). The main drawback of this scheme is the cumbersome and time-consuming labour required when large amount of data is collected, or when complex cyber-physical phenomena are involved.

The impressive data ingestion, pattern recognition and data interpretation capabilities of machine learning algorithms allow to transform raw and unstructured data into structured formats (e.g., human-readable reports); hence, artificial intelligence (coupled with data visualization techniques) can be used to automatize data analytics, thus reducing the human effort associated to monitoring and decision-making processes.
According to the **AI-based centralized monitoring** scheme, on-site field data is aggregated on remote servers, where machine learning models are optimized (i.e., trained) to solve specific tasks, like:

- fault recognition and classification, from current and voltage data samples;
- condition-based and predictive maintenance on HV power equipment (e.g., isolators);
- grid state estimation and disturbance identification, from PMU-based synchrophasors;
- security threats detection over network traffic data;
- automatic physical security (e.g., through video surveillance systems);
- diagnosis of IT and OT hardware status through automatic logs parsing techniques.

AI models attain accurate results only through extensive data collection and model training campaigns, which pose severe feasibility issues regarding data accumulation and traffic congestions on central servers. Moreover, privacy and security concerns may arise when local servers (i.e., station computers) share their data to remote servers.
To prevent the aforementioned issues, it is possible to reside on **AI-based distributed monitoring** architectures, such as on-site learning, federated learning, and collaborative learning. In the context of electrical substations, each station computer (i.e., the edge) is endowed with local intelligence

capabilities to provide several services such as real-time data processing, local storage, and embedded data mining, once fed by field data (HV power equipment sensors and bay IEDs diagnostic protocols). In this way, only a small amount of refined, structured, filtered, and encrypted information is sent to the remote central servers. Thus, distributed architectures represent a privacy-preserving, fault-tolerant and scalable monitoring solution (in terms of resource utilization), despite being more difficult to maintain.

In conclusion, IoT and AI solutions offer attractive opportunities for substation O&M, but to increase their acceptance, we envisage a set of technical challenges to be addressed.

- “Pervasive O&M”: ubiquitous sensing increases the substation digital assets; hence, it comes at the cost of a higher system complexity, leading to additional pre- and post-installation efforts, in terms of design, installation, and configuration (especially under the strict performance and EMC requirements of electrical substations).
- Persistent monitoring: IoT-technologies provide continuous data flows, which pose critical technical challenges to be addressed. At first, machine learning algorithms require structured (e.g., labelled) and balanced datasets; hence, to avoid extensive manual data preparation tasks, it is necessary to design automatic data ingestion modules to cope with unbalanced and unreliable datasets, as well as spurious, conflicting, and non-synchronized samples. Secondly, data management schemes should always be coupled with resource scheduling programs since the critical bottleneck of learning tasks lies in the communication bandwidth and in the computational demands. In this regard, distributed architectures and optimal task allocation algorithms could represent a possible solution to release intensive computation from resource constrained devices. Furthermore, self-configuration and self-adaptation strategies are needed to cope with dynamic conditions (e.g., outdoor environments) and changing operation requirements.
- Multi-modality: the integration and correlation of different information sources opens up new perspectives in substation monitoring, since sensor fusion techniques mitigate the uncertainty of measured data, allow inferences that are not possible with single-sensor measurements, and pave the way for robust fault mitigation mechanisms over sensor networks. At the same time, though, there are several issues arising from source diversity, such as data alignment and synchronization.
- Privacy and security: Environmental sensors pose severe questions on possible privacy violations, while complex data flows are exposed to data breach and poisoning attacks. Accordingly, new research lines are born around privacy-aware IoT-solutions and security-by-design signal processing techniques. However, some challenges are still ahead since some of these techniques impose significant communication distress or accuracy loss. As a result, a call for designing robust privacy-preserved and secure systems is urged, where formal guarantee of privacy and security is needed with tight accuracy loss.