Mission Possible – Easy Upgradable and Cost-Efficient Distribution Substation

Janne Starck
janne.starck@fi.abb.com
ABB Finland Oy

Bruno de Oliveira e Sousa
ABB Finland Oy

Goran Leci
Koncar-KET

Peter Kreutzer
ABB Switzerland Ltd.

Introduction

Customer expectations pose challenges to automating distribution grid and substantiate the expected change in protection and control strategies for such networks in the next few years. As the passive network with unidirectional power flow evolves into an active network with a varying power flow direction and with variety of different distributed generation resources, the requirements for the distribution substations will also change, requiring the utilities to adaptive action.

Distribution utilities are reluctant to undertake continuous and costly upgrades of the whole substation protection, control and automation system infrastructure. However, there is still a clear need to increase the level of automation in the distribution system and this has been clearly noticed both on the vendor side and on the utility side.

Periodic upgrades are expensive, not only because of new installations and because of new equipment, but also, because of the necessary engineering and commissioning work. Modern protection and control devices are complex devices with extensive functionality requiring configuration work by skilled personnel before deployment. Additionally, older substations need to be refurbished in a future-proof manner so that new requirements can be met without substantial added costs or interruptions in electricity distribution.

The challenge is to find an appropriate solution to aspects that would be opposite to each other based on contemporary solutions. Recent technologies enable gathering and processing much more measurement data than before, and the standard IEC 61850 Edition 2 can be fully utilized using merging unit and its functionality. These developed technologies result in a concept that enables running bay and substation functions in a flexible manner, *i.e.*, distributed between bay and station levels [1]. This concept is named hybrid protection and control (HPC) system. This concept addresses these challenges concurrently combining both centralized and decentralized bay and substation functionality into a central protection and control (CPC) unit. The measures to update the central unit allow smooth utilization of new functions if used in decentralized way as a combination of centralized and merging units. Furthermore, to facilitate ‘free’ distribution of bay and substation functions across automation system hierarchies.

In this hybrid approach, only a part of the bay level functionality is moved to a substation level centralized computer. The functionality is divided so that the most critical and important functionality would remain in the bay level devices assuring network safety in all situations and protection system with a long life cycle.

The functionality defined for the substation level would consist of value added applications and other "nice-to-have" features, for which a faster upgrade cycle is necessary and has a natural inbuilt backup scheme, where bay level and substation level devices provide a redundant protection system. Redundant centralized computers and process devices could be also alternate solution with merging unit function and circuit breaker handling (command and failure protection).

The architecture of the secondary system must be selected so that the lifecycle of the equipment is not forced to follow the lifecycle of the functionality and that possible updates can be done cost-efficiently. This new concept facilitates easy upgradeability of substations, while still keeping the installation costs low and ensuring high reliability of the system [2]. New value added functionality will also increase the cost-efficiency thereby making the refurbishment of substation profitable even before the end of the lifetime of the secondary technology.

Hybrid protection and control system (HPC)

The hybrid protection and control secondary substation systems consists of the employment of state-of-the-art technologies and equipment facilitated by the standardization of communication networks through the IEC 61850 standard. The HPC system is the superposition on the centralized and decentralized architectures [1]. It, further, consists of the partial or integral shift of protection, control, metering and monitoring functions from bay level to station level where the centralized protection and control units are located. These functions are distributed according to their mission-critical importance and complexity: the most critical functions are maintained at the bay level and duplicated to the substation level while the most complex and measurement-comprehensive functions are allocated to station level.

Fig. 1 schematizes a simplified HPC architecture where new devices (IMUs, CPC unit and PIOs) are included. In this diagram, the secondary system is connected via the IEC 61850-8-1 substation bus and the IEC 61850-9-2 process bus. This architecture includes a redundant communication network in order to maintain reliability high. The HPC system can assume several possible topologies and variations; however, two possible solutions emerge as main HPC architecture: combination of IMUs and redundant units; and the combination of multifunctional relays and a single CPC unit.

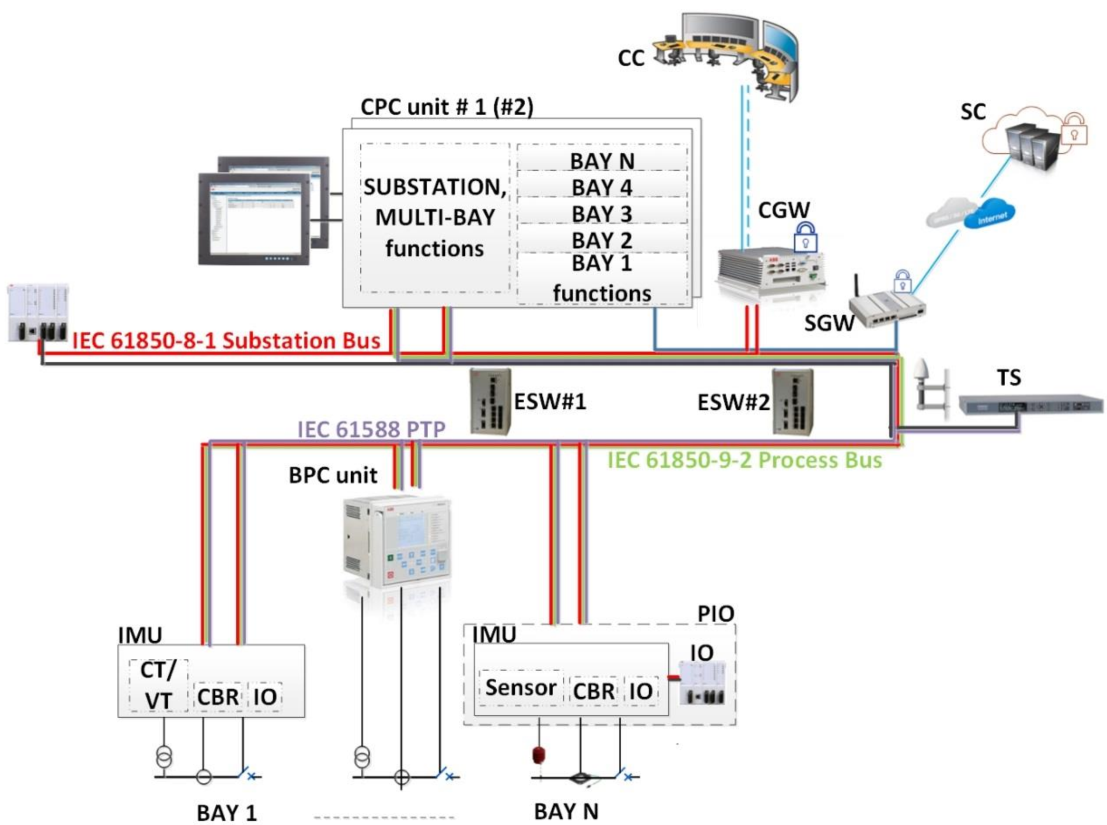

Fig. 1 Hybrid protection and control secondary system architecture. Intelligent merging units and relays (BPC unit) are located at the bay level while the centralized protection and control (CPC) units are located at the station level.

Conversely, the centralized architecture in the secondary system refers to an architecture, where the protection and control functions performed in the relays at the bay level are integrally reallocated to a CPC unit [3]. Under this centralized concept, protection components, relays, are not needed and instead, they are replaced by the intelligent merging units (IMU) and PIO equipment for exchanging the information with the CPC unit. In addition to these, the HPC architecture comprises of control center system with optional cloud service connectivity and time synchronization server gateway. Altogether, the HPC system combines both centralized and decentralized architectures and can include both IMUs and multifunction relays.

IEC 61850 Edition 2

The IEC 61850 Edition 2 comes to complement the earlier version, Edition 1, in order to diagnose a number of shortcomings and enable a broader application of this set of standards to, for instance, as it was first created for substation automation systems [4], [5]. Edition 2 comes to better serve renewable energy systems, combined heat and power (CHP) plants and other recent technologies. Moreover, the IEC 61850 Edition 2 enables link redundancy in the end notes. This redundancy can be radial, parallel redundancy protocol (PRP), or as a ring, high-availability seamless redundancy (HSR) [3]. It, further, improves interoperability, the main target of Edition 1, particularly focused on the process level. At the process level, the conventional current and voltage transformers can be replaced by non-conventional instrument transformers (NCIT) [6]. This replacement reduced required physical space and completes the full digitalization of the secondary substation systems, thus opening way to new possibilities in protection, control, metering and monitoring of primary equipment.

Fig. 2 exemplifies three stages in secondary substation systems through time yielding to more cost-effective and environmentally friendly solutions. The most recent, the IEC 61850-based systems started in early 2005 [7], enables the elimination of copper wiring, particularly with the use of process bus compliant with the Edition 2 of this standard. This elimination can reduce costs and save hundreds of kilometers of cable [8].

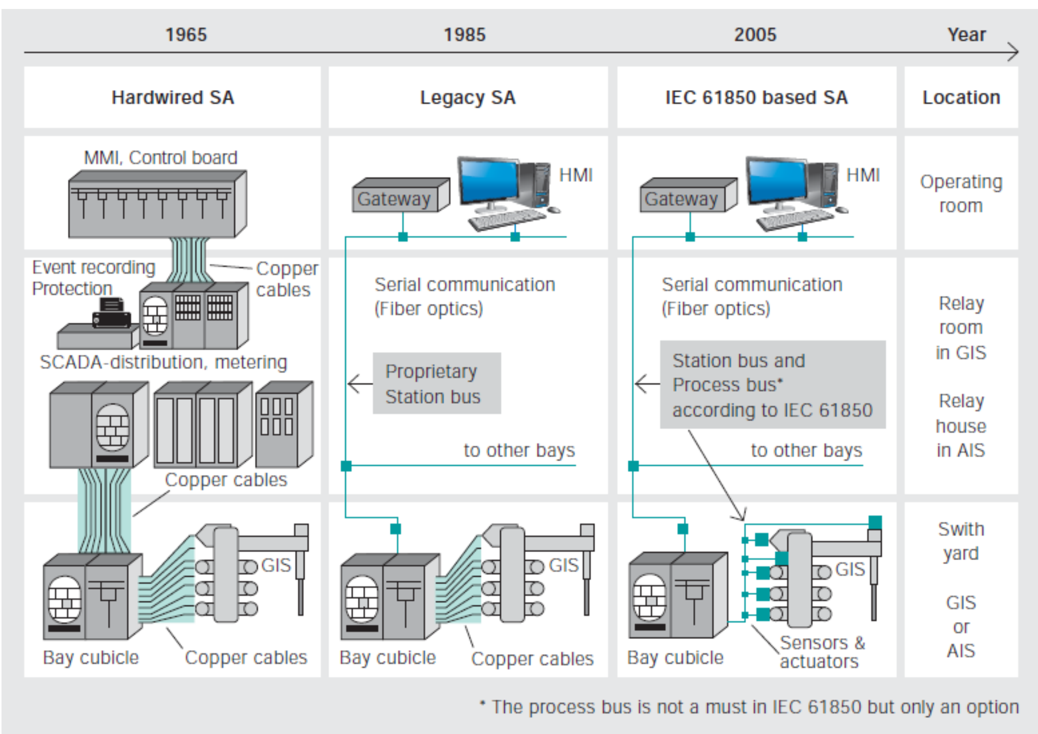

Fig. 2 Secondary substation system in the three levels (process, bay and station levels from bottom to top) in three different stages: hardwired, Legacy and IEC 61850-based systems [7].

The IEC 61850 Edition 2 also includes the parts -8-1 and -9-2 related to communication network protocols at station and process levels, respectively, schematized in Fig. 1. The bay level IEDs, *i.e.*, relays, IMUs and PIOs, repass current and/or voltage samples via the IEC 61850-9-2 process bus to the feeders in the substation; the CPC unit performs the protection, control, metering and monitoring functions for all bays in the substation. Via the IEC 61850-8-1 substation bus, the CPC units can detect faults and initiate trip action using GOOSE messaging to trip the circuit breaker. Additionally, alarms, report status and measurements are also sent upstream to the substation gateway or the human-machine interface using the IEC 61850-8-1 communication network.

Centralized protection and control (CPC) unit

The main idea of centralization is focused on the CPC unit. The CPC unit is a high-performance computing platform that concentrates protection, control, metering and monitoring functionality of distribution power systems and benefits from the optical isolation with the IMUs [1], [3]. This CPC unit processes real-time data for protection and control functionality acquiring information from all bays in the network and operates complex and calculation intensive functions. This computing platform comprehensively stores data collected from the process level and serve as an access point to collect data from the entire substation and forward to upstream levels. This feature facilitates fault analysis and condition monitoring. Also, the existence of such unit creates interface for third-party functions and provides possibility for multivendor software platforms [1]. Moreover, this computing platform opens space for the development of faster, more complex and more comprehensive protection and control functions involving a wide-area coverage.

Intelligent merging unit (IMU)

The intelligent merging unit is a term coined to define a merging unit with protection and control functionality. It is defined as a device that acquires signal from low power instrument transformers (sensor) or conventional instrument transformers and transmits high sampled digital signals to the upper levels. The IMU combines the standard functionality of a merging unit, working in accordance with the IEC 61850-9-2, with basic protection, such as circuit breaker failure, and supervision functions. The IEC 61850 9-2 LE (Light Edition) and IEC 61869-9 define a sampling rate of 4 kHz (in 50 Hz networks) and 4.8 kHz (in 60 Hz networks) for raw measurement values to be sent to subscribers (CPC unit or relays, in some cases).

The IMU contains all functions needed for digitizing both measurements and other input or output signals. It can also receive trip, open or close signals from an external unit, *e.g.*, CPC unit, and extend the same to operate the circuit breaker. In the context of the centralized systems, the IMU can perform protection and control functionality in case of loss of the communication network at the substation level, and it embodies the combination of a relay and of a merging unit.

Reliability aspects of the HPC system

In addition to physical redundancy, using link redundancy techniques, the HPC architecture offers functional redundancy to improve system reliability. The functional redundancy is the replication of required protection and control functions in the station level, located in the CPC unit, to the bay level, located in the IEDs (i.e., multifunction relays and IMUs). This guarantees that if the Ethernet communication network, for some reason, is out of service, protection and control functionality can still operate, when required. In addition to that, the duplication of CPC units (*i.e.*, two units installed) provides a third place to allocate protection and control functions. In other words, considering both physical and functional redundancies, in a HPC system, only a third-order failure could affect the primary equipment at the process level.

Fig. 3 depicts three examples of redundancy practices to curb protection unavailability to the primary equipment. In order to achieve certain level of reliability, using one relay per bay might not be enough and certain redundancy practices, using back up or certain duplication of protection, are required [9]. It can also be that certain criteria, such as the N-1 criterion, are not cost-effective, particularly for large substations. The HPC architecture does come as an alternative to improve reliability in a cost-effective fashion.

Fig.4 schematizes eight possible failure scenarios in a HPC system with a two CPC-unit and a two Ethernet-switch communication network. In a simple analysis, any first-order failure (single failure in the system) does not cause unavailability to any feeder bay. For a second-order failure (two simultaneous failures), also feeder bays will still be protected. It is important to emphasize that even if the two CPC units are out of service, depending on the HPC protection philosophy, it will not cause any unavailability to the bay feeder. In the case of a third-order failure, depending on which three components are out of service, there will be one feeder bay left unprotected. Nevertheless, in the case of failure of all bay level IEDs (in this example, three, but in practice, it can be tens of IEDs), the CPC unit will still be able to execute protection and control functionality and, consequently, there will not be any unavailability. This situation is highly improbable, as the probability of a third-order failure, unless there is a common-mode factor, is minimal. In the case of protection failure in this substation, it implies that upstream protection must operate, thus leaving a larger area without power supply.

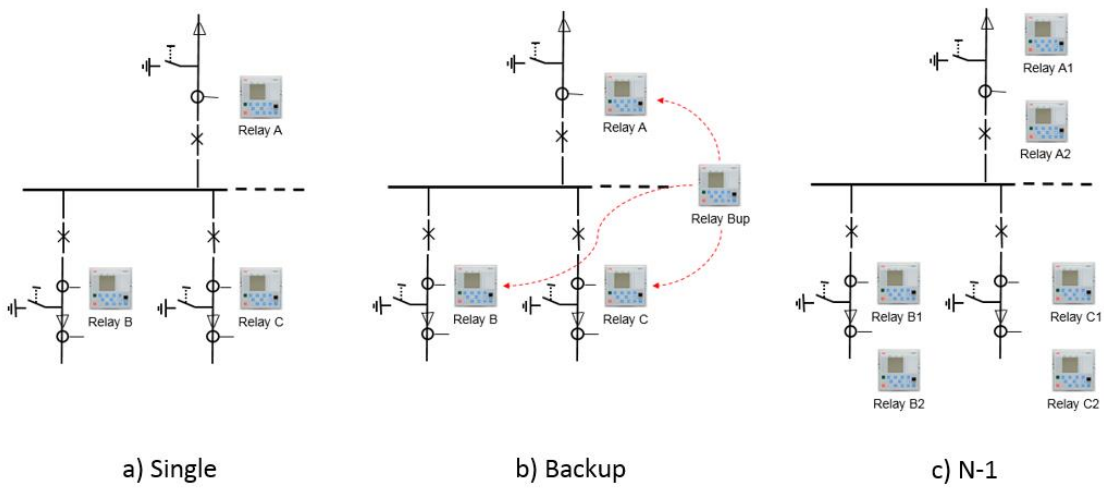

Fig. 3 Three arrangements for multifunction bay protection relays in a decentralized secondary substation system: a) one relay per bay; b) one relay per bay and a “cold” backup relay for the entire substation; and c) redundant protection per bay.

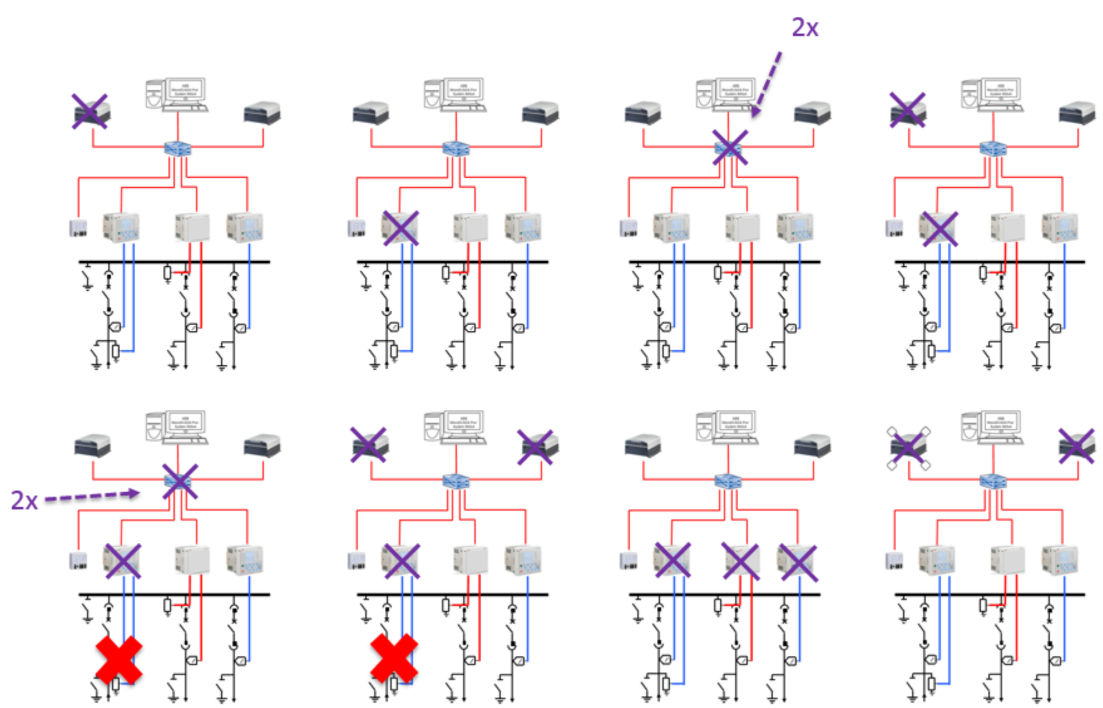

Fig. 4 Eight failure scenarios (clockwise from top-left): one CPC unit out; one bay relay/IMU out; two Ethernet switches out (double failure); one CPC unit and one relay/IMU out; two CPC units out; three relays/IMUs out; two CPC units and one relay/IMU out; and two Ethernet switches and one relay/IMU out. In the latter two scenarios, one feeder (crossed in red) will be left unattended and protection from adjacent bays must be able to protect this feeder.

HPC system benefits

The HPC architecture can be a cost-effective solution. The investments aggregated to an HPC system can be reduced as the calculation-intensive functions can be performed in a single unit, *i.e.*, the CPC unit, while the IEDs at bay level can be simplified and cost-optimized. This is better understood in the context of a large substation with several bays. The main functions and benefits to the HPC technology can be (not limited to) the following:

- The HPC system enhances the deployment, commissioning, maintenance and update of the secondary system, for it is focused on a single device, the CPC. It consists of a lower number of devices, thus simplifying maintenance and retrofit and, consequently, the reduction of OPEX costs.
- Improvement of substation protection and control functions and applications over time with increased system availability;
- High-performance computing platform (CPC unit) increases operation times and performance of protection thus opening space for new breakthroughs in relaying engineering.
- The CPC unit is employed as a node to the HPC architecture.
- Hardware and software updates required in protection and control systems can be greatly simplified [10], as protection can be centralized.
- Both centralized and decentralized protection philosophies for each feeder, depending on project specification.
- Decrease of complexity during system extension, for instance, during the inclusion of new feeders into the substation in comparison to substation based on dedicated bay level infrastructure. When a merging unit with fixed configuration is installed at the process level, the additional bay functionality can be easily performed at the substation level in the CPC unit. This decreases wiring, engineering and maintenance efforts and costs;
- Physical redundancy: as HPC system can consist of one or more CPC units;
- Functional redundancy, as protection, control, metering and monitoring functions can be duplicated both at bay and station levels;
- Flexibility: functionality can be distributed between bay and station levels enabled by the principle of location transparency.
- Interoperability between the CPC units and components at bay and process levels from other manufacturers.
- Redundancy in the HPC system can achieve good levels of reliability, thus fulfilling the N-1 criterion, at reduced costs than compared to duplicated decentralized systems at a considerably smaller number of components and decreased wiring.
- Both primary and secondary system reliability is improved by employing CPC units.
- Complete digitalization of the secondary substation system, thus opening for a better understanding of substation;
- The consequent elimination of the hardwiring being replaced for optical fibers and sensor technology [8].
- Advanced functions from the improvement of the higher calculation performance in the CPC unit enhance the protection and control efficiency through a more selective and accurate protection logic;
- New protection and control functions developed for high-end applications are easier and faster to update in the CPC unit. For instance, high-impedance earth fault function can be reliably implemented by collecting data from all the bays in the substation [11];
- Possibility for more sensitive protection, such as high-impedance earth fault protection.
- Direct benefit to interlocking function and busbar differential protection from centralization and data availability from multiple parts of the system.

This list concentrates on the current benefits related to features from centralized and decentralized systems; nevertheless, the HPC architecture is a concept and other unlisted benefits can be achieved. However, the existing instantaneous overcurrent protection might not benefit from system centralization as it requires local bay measurements and simple logics for the algorithm that does not need to be updated often.

Possible applications

The hybrid protection and control system can be applied as any substation secondary system as it is today and can be installed to system expansion. However, the difference is the required approach in which is demanded and the added flexibility. The centralized part of the HPC system can be interpreted as a backup to the existing system. Similarly, the existing secondary substation system can be easily upgradeable to HPC in case it already complies with the IEC 61850 standards.

In small substations, the HPC system can consist of only one CPC unit, as reliability will be secured with bay level protection, and depending on the complexity of the protection philosophy the bay level relay or IMU can provide required protection and control functionality in case of fail in the communication network or in the CPC unit. Nevertheless, a redundant CPC unit set is ideal to secure availability at virtually the entire substation life cycle. For medium-sized and large substations, a two CPC-unit set brings even higher reliability levels. More complex protection and interlocking schemes can be allocated and performed at station level while basic overcurrent protection can be located at bay level and also station level as back up. More comprehensive protection and control philosophy can be applied in these cases and lower or higher priority feeder bay approach can be also employed. In addition, the communication with upper levels can facilitate a wider scale protection also involving adjacent distribution power systems.

Conclusion

This paper described the concept of hybrid protection and control architecture that utilizes features from both centralized and decentralized secondary substation systems. This concept can provide physical and functional redundancies, thus ensuring strong system reliability and high availability to the primary equipment. The HPC concept is enabled by the achievements of the IEC 61850 standard, particularly by the release of its 2nd edition. In this, the possibility of a fully digitalized secondary substation system creates several new functionalities and possibilities for remote upgrades, system configuration management and operation.

Due to its flexibility, the HPC system embodies a cost-effective compromise between reliability, availability and functionality. However, it is important to emphasize that the allocation of protection and control functions depend on a number of factors, including, for instance, project requirements, substation size, number of bays involved and type of redundancy. Currently, certain components are not yet available; nevertheless, the technological feasibility is possible with the existing status-of-the-art protection and control apparatus.

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