Overview of Intelligent Substation Automation in Distribution Systems

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***Abstract*— New trends in electricity production, that involve generating power locally at the distribution voltage level by using renewable energy sources, are changing the paradigm of the distribution network, giving it an active role with the integration of Distributed Generators (DG), which leads to the concept of active distribution networks. A key element that connects the distribution system to the rest of the power system is the medium to low voltage transformer substation, which requires further research and development in order to develop active distribution networks. This document presents an overview about the components and functions that an intelligent substation automation system may have.**

Keywords—intelligent substation; renewable energy resources; self-healing; IEC 61850, Smart Grid.

I. Introduction

The electrical grid is one of the largest infrastructures ever built. Its design has been based on a generation model where large centrals provide the electricity to supply all the customers. In this grid paradigm, the power produced by these power plants is transmitted through high voltage transmission lines to substations, where power is transformed to medium voltage (MV) for its distribution and finally to low voltage (LV) for its consumption. However, due to environmental concern and the variable price of fossil fuels, renewable energy sources are getting more importance for power generation.

The increase in worldwide energy demand is part of the evolution of power systems, and the form energy is generated, distributed and consumed energy will also have to evolve to cover this demand. The solution should integrate an intelligent electrical grid, including: Flexible Distribution (FD) systems, Distributed Energy Resources (DERs), intelligent buildings, Electrical Vehicles (EV) and anything else that can be useful to manage the distribution side, in order to improve both the high and low voltage grids. It is in this context where smart grids are of interest.

The Smart Grid (SG) aims to raise operational efficiencies of operators by increasing the flow of information and automation in order to enable better and faster decisions, hence reducing operational cost [1]. Gradually, automation has reached subtransmission to some extent and even medium voltage levels in some cases. Furthermore, as larger volumes of distributed resources are connected, distribution networks will have to become smarter, so that Distribution Automation (DA) is an issue of the utmost importance [2]. Due to the increasing penetration of Distributed Generation in the LV distribution network, the control of these grids becomes more complicated and an Intelligent Substation Automation System (ISAS) is necessary. Taking this into account, the medium to low voltage transformer substation becomes a key element in the distribution system.

Conventionally, substations have been understood as passive elements with unidirectional power flow. But the new trend of generating power locally at the distribution voltage level by non-conventional/renewable energy sources is forcing a shift in their design.

This paper presents an overview of definitions and concepts about the Intelligent Substation Automation System from the perspective of the services this kind of systems can offer, reviewing the work of several authors. In the future, those services will enable the full integration of renewable energy resources with active participation in a market. This paper is divided in five sections. Section II introduces the main technological characteristics of intelligent substation automation, section III introduces the key ancillary services that the intelligent substation should have, section IV brings in suggestions for data and communication, and section V presents the conclusions of this work.

II. Intelligent Substation technologies

Until recently, substations were understood as passive elements with unidirectional power flow. Those substations fundamentally change voltage from one level to another and regulate voltage to compensate for system voltage changes. But this has changed, upgrading the distribution network to make it active, and allowing bidirectional power flow.

A substation that can manage the new and complex environment of a smart grid must itself possess an environment and functions that can control smart grid characteristics. Therefore, the realization of an intelligent substation automation system, as shown in the scheme of Fig. 1, is quite important for the application of smart grids within a power system.

Reliability is critical in the implementation of an intelligent substation automation system. The design can achieve this reliability through a three-step procedure. The first step is to create a functional model of the ISAS. In the second step, the

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hardware of the ISAS is considered. And finally the third step links each function to its hardware implementation. The method developed in [3] quantitatively provides a basis for comparison in order to select the appropriate type of automation system for a specific substation.

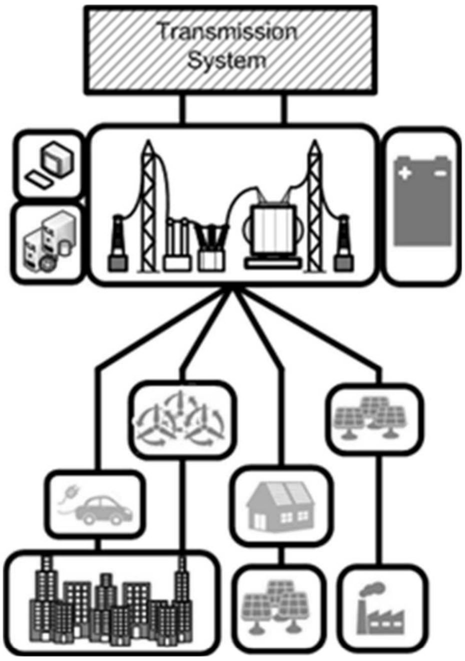

Fig. 1. Generic scheme of an Intelligent Substation Automation System (ISAS).

The following technological characteristics must be considered to develop intelligent substation automation:

Intelligent Transformer

The term smart or intelligent transformer refers to transformers that integrate different functionalities in addition to the main objective of voltage transformation. An intelligent transformer is a conventional transformer with a number of sensors for protection, control and management [4]. These features will allow smart transformer substations to enhance operation and maintenance of the system, evolving towards a more active scheme, achieving a more efficient asset management and reducing operation and maintenance costs.

Several authors propose transformers with electronic tap changers to be used in ISAS. On-Load Tap Changers (OLTCs) are used to control the voltage in MV networks, by shifting the phase angle and adjusting the voltage magnitude. This is usually done in conjunction with Automatic Voltage Control (AVC) relays and Line Drop Compensation (LDC) [5]. The OLTCs allow proper coordination between DG and LDC, and ensure voltage regulation without unnecessarily restricting the integration of DG.

In this context, actual network operation and control methods can become insufficient in the future, since the design of these grids was done for a unidirectional power flow. For this reason, the transformer is smart in the sense that its control strategy is able to control the power exchange to a set value by controlling its microgrid-side voltage [6]. The bidirectional flow allows the provision of services for the transmission network from the network distribution.

IED - Intelligent Electronic Devices

The intelligence of the primary equipment is associated to realize digital measurement, networking control, status visualization, function integration, and information interaction of high voltage equipment.

IEDs must be thoroughly transformed to include novel functions and roles along with their existing ones. Recently, many manufacturers have introduced advanced Intelligent Electronic Devices (IED) into their products that can perform functions such as parameter configuration and monitoring. The possibility to connect these distributed IED to a Local Area Network (LAN) would provide highly dynamic systems [7].

Energy Storage System

Recent developments and advances in energy storage and power electronics technologies are making the application of energy storage technologies a potentially viable solution for modern power applications, allowing the system to be operated in a more flexible, controllable manner.

Storage in the distribution system can be used to reduce peaks loads [8]. Large-capacity storage technologies break the limit of power balance between supply and demand in real time. By installing energy storage systems with a certain capacity in the grid, storing the excess electricity at night, and then releasing it during the daytime load peak, which effectively improves the electrical equipment utilization and supply reliability [9].

Simultaneously, the reduction in currents produced by congestion relief and peak reduction may also result in a decrease in line losses, improving the efficiency of the electric transmission and distribution systems. It also increases transmission capacity and can improve system stability. Additionally, it provides the economic benefit of selling a higher percentage of the electricity generated [10].

Furthermore, an intelligent substation can use an energy storage system as a power compensation device. This allows the substation to provide reserves for the transmission system. Taking this into account, the embedded energy storage should be rated to attenuate power gradients, manage energy optimally, and improve power quality at the point of common coupling.

SCADA

The overall control and management of an active distribution grid must be implemented through an intricate network of IED devices interlinked through SCADA and high-speed communication channels.

New-generation distribution SCADA systems need to observe and control distributed power supply in a higher degree than existing SCADA systems. A new-generation

SCADA system built totally on the new high-speed field network would be an ideal solution [11].

The application of SCADA systems across networks with 11–132 kV voltages with a proper active control model would be the best solution for active distribution networks [12]. The integration of synchrophasors in a SCADA systems is done through a Phasor Data Concentrator (PDC), employing redundant systems based on standards, and providing higher interoperability levels [13].

Multi-Agents

Sets of elements can be defined as agents. This definition can consider elements with similar characteristics, or simply sets that are convenient for the operation of the grid. The future smart grid will be more like an artificial nervous system where many tasks are accomplished by the horizontal collaboration of neighboring autonomous control agents, rather than involving the entire system hierarchy [7].

The agents can play a role in power supply, replacing compensating devices, since parameters such as voltage, real power and reactive power of DG can be controlled by the power electronics devices that constitute the distributed generators. Multi-agents exchange information with neighbors and with a centralized controller if necessary, gather data from the environment, and may be able to perform cognitive learning to adapt to changes in the system. Furthermore, a multi-agent system provides a common communication interface for all system components with autonomous control actions in a distributed and decentralized manner.

III. ANCILLARY SERVICES OF AN INTELLIGENT SUBSTATION

Ancillary services are power and energy products that ensure the continuity in power supply, maintaining appropriate frequency and voltage levels. Those services are traditionally aggregated in an implicit way for its sale, since they do not correspond exactly to the energy supply. An intelligent substation as midpoint between distribution system and transmission system can offer ancillary services to both sides.

Distribution system services

Different ancillary services can be adopted to involve DERs into the functions that allow improving operational reliability from the ISAS. Below are some features the subestation can incorporate to support the distribution system:

a) Demand Response: Demand response is commonly associated with price-based demand response which utilizes the varying rates during the day reflecting actual electricity prices. The key premise of this system is that customers will respond to price signals according to their price elasticity and will use less electricity when prices are high, or they will reshape their consumption [14]. Other authors in references [15] and [16] propose demand response for active voltage control. Demand response is an important ingredient of the smart grid, promoting both market efficiency and operational reliability.

b) Fault location: In case of a fault on a distribution network, substation feeder protections normally shut down power on the entire feeder. FLISR or circuit reconfiguration schemes can greatly enhance the distribution grid reliability by quickly restoring power to as many customers as possible [17], [18]. Technologies implementing self-healing strategies as presented in reference [19] propose other forms to fault location.

c) Self-healing: Control loops are designed to automatically detect a loss of voltage and switch to an alternative source [19]. The healthy portion of the circuitry is restored without any crew dispatch and the restoration time is reduced considerably.

d) Black start: It is the capability of a power system to restart its generation after a total system collapse, without importing any external power. This would be possible with an effective and reliable incorporation and management of DERs.

e) Support to renewables: The structure of the grid itself also presents a huge barrier to the mass integration of DERs [20]. Updating the distribution network is very important to develop tools that allow its interaction with distributed generators. The support renewables will be granted for Distribution Management System (DMS).

Active distribution networks will offer significant opportunities for the integration of DERs. The deployment of DERs provides opportunities to reduce CO2 emissions, save energy, reduce network losses, improve network monitoring and controllability, utilize existing networks more efficiently, and improve visibility of DERs for transmission system operators. Active distribution networks offer also a great potential of reactive power control capabilities. References [21]–[23] show structures and optimization techniques to implement management systems in the distribution system.

Transmission system services

An ISAS can provide support to the transmission network in the form of transmission system services like the following:

a) Frequency regulation: Intelligent substations can provide inertia emulation and participate in frequency regulation as presented in [24]. Additional controllers can be incorporated to an active substation for secondary frequency regulation [25]–[27].

b) Active power and reactive power control: Power electronics, e. g. a STATCOM, and energy storage can support the transmission network from the substation.

c) Regulation and load following: Load following is the capability of on-line generation equipment to track customer load variations. A smart transformer can participate in load following and control the power exchange with the transmission system.

d) Spinning reserves, non-spinning reserves and supplemental/replacement reserve: The ISAS can provide frequency responsive spinning reserve by making their DERs respond at the system operator's request [10]. References [28], [29] show methods to optimize energy capacity by utilizing spinning reserve.

IV. INFO/DATA AND COMMUNICATION

The automation of power distribution systems is designed according to two contradictory design goals. On the one hand, power distribution systems have to be robust to avoid power outages even in the presence of serious external disturbances, such as natural disasters, equipment failures, or demand/supply fluctuations. On the other hand, such systems have to be economically viable and, moreover, provide efficient power consumption in accordance with the latest "green society" trends. A proper development of communications would offer improvements for both distribution and transmission sides. In fact, current communication and computational power allow an intelligent relationship between the DSO and the TSO.

Relevant data

The following data will allow a more active interaction between the Transmission System Operator (TSO) and the Distribution System Operator (DSO):

a) Info/data exchange between TSO and DSO control centers.

b) Info/data exchange among multi-agents.

c) Info/data for market: Renewable energy sources and battery energy storage forecast.

Communication

The new IEC 61850 standard—Communication Networks and Systems in Substation [30]—addresses the interfacing issues and standardizes communication to avoid the use of vendor-specific protocols. Thus, it creates the potential for future automation and control functions and enables power systems to evolve into smart grids. This is a new approach for communication in substation automation and beyond.

TABLE I. Typical networks architecture topologies .

Architecture Type	Advantage	Disadvantage
Bus	Shorter link distance between switches	Without redundancy, higher latency times
Star	Lower latency	Without redundancy, critical head switch
Ring	Support a simple failure between switches, shorter link distances between switches	Higher latency

Highlights in this standard are intended to incorporate the technology available and make a path for further development. The IEC 61850 standard assesses the type topologies architectures networks and presents as a requirement the ring architecture for communication connection. A comparison is illustrated in Table I. Both wired and wireless types of communication networks are considered. If there are sufficient funds for installation, it is optimal to use both wired and wireless networks.

A number of protocols such as MODBUS, DNP 3.0, IEEE C37.118, and IEC 61850 are related to substation operation. [31]. The challenge of the substation of the future involves requiring high speed and reliability digital communications within the demanding environment of high voltage substations. But, several authors and companies propose to use a Common Information Model (CIM) to enable the exchange of information and settings between agents. This is in order to create a route for services in the distribution and transmission networks (Fig. 2).

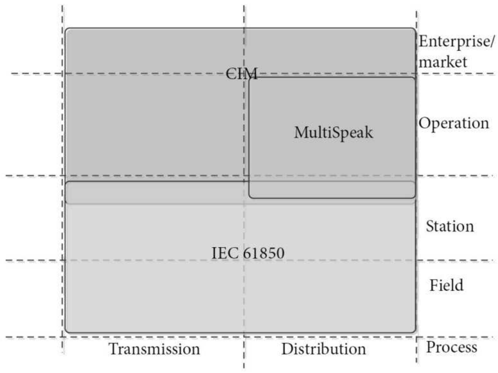

Fig. 2. Information model domains for the interaction between distribution and transmission networks.

Another important aspect to be considered is that substation automation should contemplate for a while the older analogical technologies because usually it is not economically feasible to replace all the instruments that make up a substation immediately. In Fig. 3, the equipment on the right-hand side, including merging units and a process bus, illustrates a modern IEC 61850 substation automation structure. The equipment on the left-hand side, including analog instrumentation channels, relays and PMUs, illustrates a legacy system possibly containing electro-mechanical or digital protection equipment. The remainder of the equipment includes a communication gateway for external communications and local human interface machines (substation control computers, SCC). This heterogeneous mixture is common in substations today and is a major challenge for the progress of substation automation. Several projects about substation automation are being implemented nowadays, such as Smart Substation in Arnhem, Netherland [32], KIC-ASS [33], Intelligent Substation automation for the smart grid [34] and so on. The main focus of this project is to implement new schemes of protection and functions to manage and control the distribution side through new devices in low voltage close to the end-users. The functions of these projects are aimed at low voltage in the distribution grid.

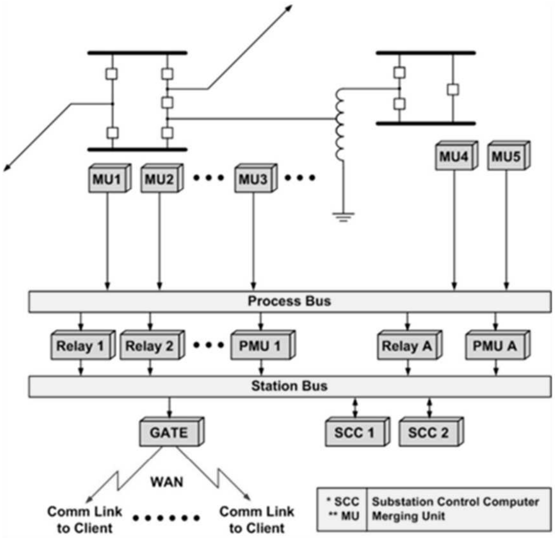

Fig. 3. Combination of technologies typically found in present day ISAS.

V. Conclusions

Conventional distribution schemes are basically designed for unidirectional power flow from sources to loads. Unlike them, active distribution systems would have bidirectional power flows through distribution feeders. The proposed ISAS is based on considerations to include services that increase the capacity of penetration of DERs and make more efficient and reliable the operation of the power grid.

Intelligent substations can provide very high reliability levels, but the optimal degree of automation must be determined in order to ensure the maximum efficiency. With realization and implementation of ISAS, intelligent distribution substations should be seen by the transmission system operator as intelligent aggregators of distributed generators and loads. The proposed ISAS environment should be based on a consideration of the communication network type, the communication network topology and protocol, cyber security, IEDs and automation devices in the substation, and the influence of DG on the substation operation.

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