NEXTSTEP – Developing future smart secondary substations

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Keywords: BATTERY ENERGY STORAGE, DYNAMIC VOLTAGE REGULATION, SMART GRID, SMART SECONDARY SUBSTATION, SELF-HEALING

Abstract

Future Secondary Substation (SS) design requires a more integrated approach, from the building envelope design, electromechanically equipments to the advanced monitoring and control, taking into account new technical, environmental and economic requirements. The main objective of the project is to develop an integrated solution for the SSS, considering innovative solutions for the building envelope and thermal behavior, power transformer and switching equipment as well as monitoring, protection and control system. This paper presents the specification of future SS developed in Portuguese project NEXTSTEP - Next Distribution SubsTation ImprovEd Platform and describes its mains innovative solution and advanced control functionalities.

1 Introduction

Secondary Substations (SS) are playing an increasingly important and Smart (S) role on distribution network, foster the concept of smart grids , namely in the management of smart metering infrastructure and smart integration of Distributed Energy Resources (DER).
This paper presents the SS developed in pioneer Portuguese project NEXTSTEP. The project combines innovative smart grid technologies with Eco design and housing solutions, proposing a complete design solution for future Smart Secondary Substation (SSS). The main objective is to design cost-effective solutions for improved monitoring of SS assets and LV networks, implementation of asset management, improve of thermal performance while minimizing visual impact in the urban environment.

2 NEXTSTEP conceptual architecture

Figure 1 shows the general architecture of the SSS developed in the context of the project. The system has been divided in four main functional blocks based on previous specifications described in [1]:

- MV functional block –includes the functionalities such as remote monitoring and control, fault detection and self-healing. Regarding power equipment a circuit-breaker are being considered to be installed in the Ring Main Unit (RMU).
- Power transformer functional block – includes the conditioning monitoring, measurement and voltage regulation functionalities.
- LV functional block – monitoring and control of the LV switchboard and distribution cabinets, smart metering infrastructure management, advanced control and self-healing of LV networks.
- Building functional block – security systems, flood detection and smart ventilation systems.

The solutions developed for the different domains of the SSS design are summarized in Table 1.

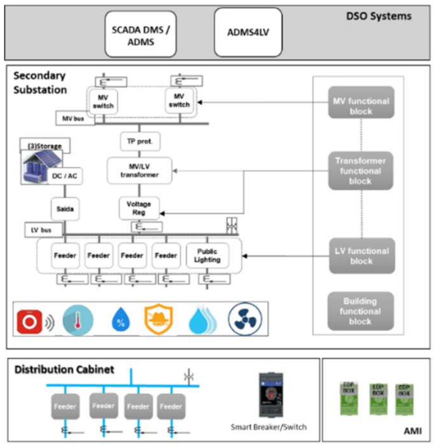

Figure 1. NEXTSTEP conceptual architecture.

Table 1 NEXTSTEP use cases and proposed solutions.

Use cases	Solutions proposed
Eco-housing	Landscape integration and the use of sustainable materials;
Power equipment	- Free SF6 Medium Voltage (MV) Switchgear with IoT sensors - Eco-design Tier-2 Distribution Power Transformer; - Dynamic Voltage Regulator (DVR) - Battery energy storage system (BESS)
Monitoring and control	New-Generation IoT sensors for: LV feeder monitoring, earth resistance measurement, environmental conditions, flood, security and safety.
Smart Grid functionalities	- LV active voltage control and self-healing - Coordination with central SCADA/ LV ADMS and asset management systems

3 Smart Substation Eco-housing and environment control

The use of natural materials with insulating capabilities contributes to the sustainability and the improvement of the SS operating conditions. Thermal insulation ensures a mitigation of the risk of internal condensation during winter and reduction of thermal loads associated with solar heat gains. The choice of solutions based on 100% renewable and recyclable material such as cork – Insulation Cork Board (ICB) meets the criteria outlined above, promoting: good thermal insulation contributing to the reduction of thermal bridges and condensation risks, and the increase of thermal delay. Good water vapour permeability ([2]) an increase in wall or roof protection against aggressive environments (solar radiation, rain, wind, salty atmospheres, among others); good thermal behavior, drainage and water retention layer for green roofs ([3],[4]); high dimensional stability and durability; compatible with different support materials (wood, concrete, metal, among others); great aesthetic potential. Table 2 below presents solutions and describes their main technical characteristics.

Table 2. Cork based solutions

Uncoated cork boards

Materials: Medium density Insulation Cork Board (ICB)
Dimensions: 1000x500 mm (standard)
Thickness: from 40 to 120 mm
Density: from 130 to 170 kg/m^3
Thermal conductivity: 0.045 W/(m.K)
Vapour resistance factor (μ): 54
Maintenance level: low

Cork-based green roof

Materials: Insulation Cork Board (ICB), technical substrate, and vegetation.
Type: extensive
Thickness: ICB > 50 mm, substrate >100 mm
Weight*: > 97 kg/m^2
Water retention*: >15 l/m^2
Vertical water drainage*: 75 l/(min.m^2)
Maintenance level: regular
* values for 100 mm of ICB and 100 m of substrate

4 Power transformer, voltage regulation and grid support battery storage devices

New solutions for the substation power equipment were considered to respond to future environmental and network operation challenges. A new design for power transformer was developed complying with EU Eco-design directive 584/2014 and EN 50588-1. The transformer is connected in series with a Dynamic voltage regulator enabling effective voltage regulation in future LV networks. A battery energy storage system (BESS) connected to the LV bus will also provide grid support.

4.1 Eco-design for power transformer

In order to improve efficiency, a more compact geometry of the magnetic plate was adopted (e.g. Super High Grade type) was adopted. This also reduces plates cutting time and facilitates the magnetic circuit assembly, improving the overall production capacity. The changes performed also required the adaptation of the windings and tubs. The solution allowed to reduce the interior dimensions of the tank, cooling panels, area, and density of stuns. These changes, accompanied by the reduction of the plate thickness of the panels, allowed a significant gain of natural ester masses and welded construction.

The various innovations have been tested individually with the production of test specimens on a full scale. In the case of the tank, the construction solution was tested to the limit by successfully passing through the "Special test for corrugated tank" test of EN 50588-1, exceeding 25 000 cycles (requirement of standard 2 000 cycles).

It should also be noted that the use of a natural ester as a dielectric fluid allows to obtain an "environmentally friendly" solution, with characteristics of biodegradability and fire resistance due to its flash point of 330 ºC (the mineral oil usually used has an inflammation point of the order of 160º).

4.2 Active Voltage regulator and distributed storage

The DVR is connected in series with the secondary winding of the power transformer (Figure 2), allowing for dynamic and onload regulation of voltage at the LV bus of the SS. The technical characteristics of the DVR are described in Table 3. The main regulating capabilities are the following: compensate voltage disturbances up to ±0.1 p.u., in presence of unbalance and/or non-linear loads. DVR controls the direct, inverse and zero sequence symmetrical voltage components to meet standard voltage unbalance limits ($VUF_{neg}<2\%$); dynamic and continuous voltage compensation, per phase, according to an external reference setpoint control within ±0.1 p.u.; voltage sag compensation up to a 20% limit, representative of most voltage sags in the distribution network.

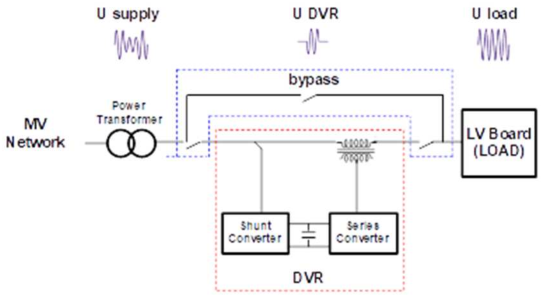

Figure 2. DVR topology diagram.

Considering the topology adopted, the DVR will be subjected to high fault currents, in the event of faults occurring at the LV network side. Also, in case of DVR fault, an overvoltage will appear in the injection transformer. In order to ensure continuous load supply, through the coordinated and controlled application of breakers and thyristors its provided an alternative/protective path to avoid service interruption. Also, a dedicated power bypass board was implemented allowing for online commissioning and decommissioning of the DVR without any load service outages.

4.3 Distributed storage

The integration of the BESS at SSS level is foreseen for the following use cases: respond to the power profile defined by the DSO, provide reactive power compensation a pre-defined P-Q profile control. A 3-level BESS control topology has been adopted, divided into the following main 3 layers: low-level control: internal and dedicated BESS closed-loop control algorithms, allowing for safe and dynamic response of the system according to an external operational mode and setpoint, always within the components allowed operational ranges; High-level control interface: bi-directional communication interface layer for integration with a higher hierarchy level control system; Safety and component monitoring: allowing for battery modules, AVAC, fire suppression system and converter data gathering and control. The technical characteristics of the BESS system are described in Table 4.

Table 3. DVR technical characteristics.

	Shunt Converter	**Series Converter**
Nominal Power	75 kVA	
Nominal Voltage	3 x 400 V	3 x 420 V
Voltage range	± 0.1 pu	
Output Current	108 A	
Frequency	47 .. 52 Hz	
THD	< 3 %	
D.C. Voltage	700 V	
Efficiency	> 98 %	> 98 %
Topology	2L w/ LCL filter	
Switching freq.	5 kHz	
Series Transformer	420 V / 42 V - Δ/III (3 independent windings)	

Table 4. BESS technical characteristics.

	Battery rack	
Modules in series	23	
Voltage range	690 V ~ 828 V	
Nominal voltage	736 V	
Nominal capacity	148 Ah	
I charge & disch. (perm. / peak)	74 / 148 A	
RTE	96 %	
Op. temperature	0 ºC - 50 ºC	
	Battery converter	
	DC side	*AC side*
Nominal voltage	720 V	3 x 420 V
Voltage range	675 V ~ 820 V	-
Nominal current	97 A	96 A
Peak current	104 A	107 A
Nominal Power		70 kVA
Frequency		47– 52 Hz
Efficiency		> 98 %

5 SS monitoring and control solution

The SS monitoring and control structured (see Figure 1) is composed of three main building blocks: the MV, transformer and LV functional block. The main controller of the MV and transformer functional block is the DCU 220, ensuring monitoring, protection and control of the MV Ring Main Unit (RMU). In addition, DCU includes the following functionalities: MV feeder fault detectors (50/50N, 51/51N and 67/67N), oscillography and event log. The Distributed Transformer Controller (DTC) is the main controller of the LV functional block, responsible for the monitoring and advanced control of the LV network. The DTC integrates the monitoring and advanced control functionalities for the LV networks. In addition to the data concentrator, the DTC collects data from the IoT monitoring and control (see 5.1), ensures the interface with the DVR and BESS and defines the most adequate control actions based on advanced control functionalities integrated locally (see 5.2) (Figure 3).

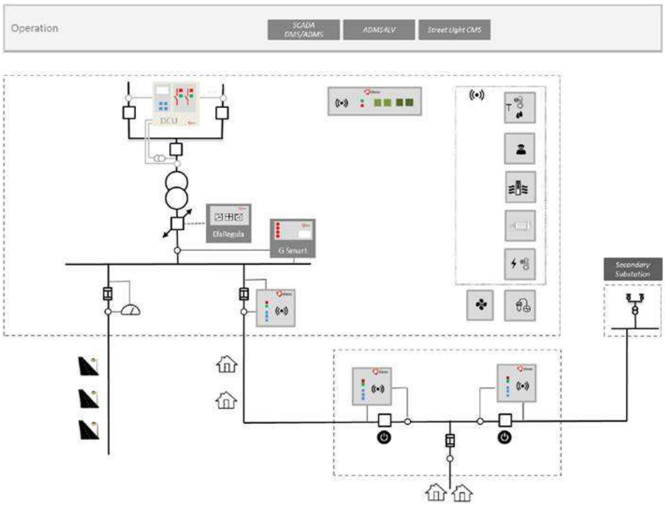

Figure 3 - BESS control and monitoring layer diagram.

5.1 IoT based monitoring and control

The following sensors being capable to trigger alerts and alarms were installed at the SS, namely: the EWS DTVI and the LVS3, both monitor the voltage on the LV busbar and the demand from each outgoing circuit and LV cabinets; the EWS DTE monitors the protective earth resistance; the EWS DTHT monitors the temperature and the humidity both inside and outside the substation; and the EWS DTPD monitors the temperature and the dielectric condition of an active equipment, and it was installed in the transformer and in the MV panel. All these sensors communicate data to the local DTC, directly through IP or via a Bluetooth gateway, developed to interface the wireless sensors with the DTC. On the distribution cabinets, the EWS DTVI and LVS3 sensors include LoRa modules for communication with the DTC via gateway. With these sensors installed along the feeders, DTC can better estimate losses and rank cables condition, as well as support voltage and congestion management.

The aging of a Transformer was also addressed with the - EWS DTPD sensor, designed to evaluate the internal oil temperature and the presence of gases and detect partial discharges. It is a non-invasive technology built wirelessly to easily retrofit existing Transformers [5].

5.2 Advanced Control and Management of MV and LV networks

This section briefly describes the distributed control algorithms developed considering the improved monitoring capability and the flexibility of DVR and BESS installed at the SSS.

5.2.1 *Smart ventilation control*

The proposed environment control solution consists of using variable natural ventilation, controlled by an automated shutter at the input grills. The ventilation control algorithm takes as input both the inside and outside air temperatures and relative humidity values. Its output is the aperture of the motorized shutter. The algorithm is designed to: i) keep temperatures and humidity values within pre-set optimum intervals; ii) keep temperatures above the dew point to prevent condensation; iii) minimize the number of actuations of the shutter to keep maintenance low. The main objective is to maintain a controlled environment, keeping the internal air temperature and humidity within pre-set interval values.

5.2.2 Voltage and congestion management

The main objective of the voltage regulation in LV networks is to ensure that voltage magnitude remains within acceptable technical limits and to mitigate voltage unbalance, resulting from the uneven connection of single-phase loads to the three phases of the network. The algorithm will determine the most adequate voltage reference to the DVR (in section 2.3), based on conventional line drop compensation strategy, adapted to consider the voltage drop measured in real-time, considering the sensors installed in the LV cabinets. This adaptation provides an effective control without requiring the estimation of the line parameters. The algorithm can also consider the participation of flexible DER connected to the LV nodes, complementing voltage regulation in the LV busbar of the smart substation.

5.2.3. LV Self-healing

Extending self-healing capabilities to LV networks is becoming more relevant as an important share of RES based generation, EV and flexible DER and loads are connected is connected in the network last mile. The self-healing tool developed enables automatic service restoration in LV networks, transferring load between LV feeders or between MV/LV substations, based on the post-fault network topology and on the pre-fault load measured. The restoration procedure can be implemented automatically by the smart substation controller, supervised by the central SCADA, or just recommend the most adequate actions to take. A rule-based algorithm was developed, mapping all the feeder and cabinet switches and open loops, and deciding which are the most adequate actions to take to restore the maximum load possible. It considers the maximum capacity of the feeders.

6 NEXTSTEP test and demonstration

The SSS designed in NEXTSTEP is being implemented and tested in both laboratorial and real distribution networks. The Smart Grids and Electric Vehicle Laboratory at INESC TEC, represents a near-real experimental LV network for testing both hardware and software smart grid solutions in extreme operation conditions, such as over and undervoltages and LV network faults, under a controlled environment. Three main tests are foreseen, namely: overall validation of the monitoring and control hardware and software, validation of the voltage regulation strategy and validation of self-healing.

The SSS will also be installed in an important touristic area of Figueira da Foz City. As shown in Figure 4, is in a noble area of the town, integrated into a yachting marina, where the secondary substation landscape integration is of main importance. Therefore, balance between technical requirements, quality of service and visual impact should be achieved. The SSS will be connected to a MV network ring with 5 low voltage and 3 street lighting feeders. The performance of the SS will be evaluated, namely regarding its improved thermal performance and capability of detecting equipment fault and partial discharges. Evaluating the performance of the DVR in real operating conditions will also be one of the main objectives of the demonstration activities. In order to minimize impacts with operational/maintenance and procurement E-REDES natural process and policies a contingency plan will be implemented to.

7 Conclusion and Future Work

This paper presented the SS developed in Portuguese project NEXTSTEP, which combines innovative smart grid technologies with Eco design and housing solutions. The project followed an integrated approach towards the design of future SS, from the housing to the power and monitoring equipment, including adjustments to the resulting compact layout. Compact IoT sensors deployed where integrated with existing legacy SS equipment, such as with the DTC, for feeders' voltage and current monitoring, fault detection and transformer and switches condition monitoring, through non-invasive solutions. Together with innovative power electronic devices, and more efficient and environmentally friendly power transformer and switches, the integrated demonstration of the SSS in a real environment is expected to improved technical and economic operation efficiency of distribution networks, particularly at the LV network, and enable improved monitoring, fault detection and location and active management strategies at the LV network, required to deal with large scale deployment of DER.

Figure 4 – Implementation of NEXTSTEP SSS (3D simulation).

8 Acknowledgements

This work is co-financed by the ERDF – European Regional Development Fund through the Operational Programme for Competitiveness and Internationalisation - COMPETE 2020 under the PORTUGAL 2020 Partnership Agreement, and through the Portuguese National Innovation Agency (ANI) as a part of project NEXTSTEP: POCI-01-0247-FEDER-018006.

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