Control Architecture for Smart Digital Node providing Hybrid AC/DC Supply

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Abstract—**STRATA project develops a fully new digitally enabled concept for increasing the intelligence of distribution transformers and for enabling them to serve as local service nodes for different stakeholders. The project is building multiple prototypes for the new unit as well as the control system around it. This paper focuses on the architecture work taken for the concept to allow proper information exchange and controllability across different use cases and stakeholders under different conditions. The paper discusses the high-level architecture as well as the functional dimensions of defined use cases. Practical examples from different setups are presented, complemented with first experiences and ideas for future work to be undertaken.**

Keywords—smart grids, energy communities, grid architectures, resilience, renewable energy, digitalization

I. INTRODUCTION

Within the fast-progressing energy transition and trend of societal electrification, the typical distribution transformer is in a key position to provide customer-oriented energy services. These services can support, for instance, the integration of local renewables, fast EV charging or establishment of local energy communities. At the same, services can be offered for energy markets or as ancillary services for the local grid. In order to provide such services, and bring more features to LV grid management, a conventional MV/LV transformer is upgraded to a Smart Digital Node (SDN). In this concept, the distribution transformer will act as a service centre for local energy communities and create value in terms of new services and resilience for distribution grid and flexibility markets [1].

The implementation concept of SDN or more generally Smart Transformer (STx) to materialise successfully requires an active integration of all stakeholders' needs, translated into physical and logical actions by systems, technologies, and devices that must jointly and effectively coordinate and communicate their state and actions. Therefore, devices and systems from different domains, disciplines, and vendors must be interoperable which means to exchange information easily without any technical constraints.

To address the increase in complexity of reflecting the large number and diversity of system solutions and interoperability needs, the Smart Grid Architecture Model (SGAM) framework has been employed [2]. The SGAM framework is useful in describing STx functional solutions holistically, on a case-by-case basis, in a consistent and unambiguous manner. The benefit of using the SGAM framework can be considered twofold. From the system operator perspective, SGAM provides a useful representation of a smart grid solution placed into the context of the network assets, supporting utilities to identify interoperability requirements to be accomplished and technical functions and components to be added to the system to fulfil their business objective [3], [4]. From the point of view of testing and validation of the smart grid solutions prior to commercialisation and deployment, SGAM framework can support research institutes to analyse interoperability requirements at an early stage and facilitate the design of a testing environment for integration of new functions, components, equipment, or complete control solutions [5], [6]. For the above reasons, the SGAM approach has been employed to develop and present the use cases supported by the smart transformer functionalities. Use of such reference framework also allows more integrated approach for evaluating the performance of complex systemic solution, providing easier progress to test case definitions, prototype validation, piloting and eventually to rollout of the verified solution [5], [6].

This paper presents the further findings of ERA-NET project STRATA -*Smart Transformation for Resilience And community services Through digitAl grid layer* – with a focus on the control architecture for the smart digital node to provide LV AC and DC supply. The paper is organized as follows. Firstly, the SDN concept is explained briefly. Secondly, the functional architecture is discussed with reference to the SGAM model.

Thirdly, the data and communication architecture are defined. Finally, application examples are listed for the planned architecture in Scottish, Finnish and German application cases.

II. CONTROL ARCHITECTURE FOR SMART DIGITAL NODE CONCEPT

The Smart Digital Node (SDN) concept proposes an alternative to a conventional MV/LV distribution transformer. SDN is connected to the MV grid on the infeed side and provides both LVAC and LVDC as an output. The LVDC supply can be extended to a DC microgrid or kept in close vicinity to SDN as a DC bus for better DER integration or EV charging. The SDN concept also integrates on-site batteries for energy storage and local EV fast charging.

Other alternatives to support the smart operation and management of distribution networks, and to increase network flexibility and release additional capacity within the LV network infrastructure have been proposed utilizing smart transformer (STx) [7], and Solid State Transformers (SST) [8], [9].

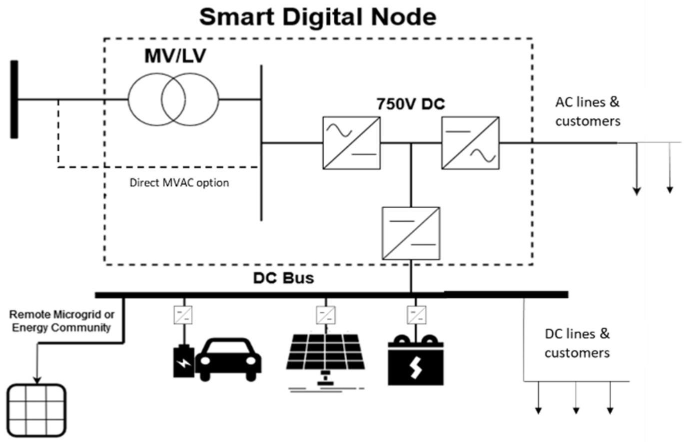


Figure 1: Smart Digital Node primary system overview.

A step-down transformer or direct MVAC infeed can be utilized on the grid input side depending on the power electronics configuration (this selection may change at different stages of concept piloting). For control and monitoring purposes, SDN is equipped with communication and data gateway devices connected remotely to customer terminals. An overview of the technical concept is presented in Figure 1.

For efficient organization within existing grid architectures, the SDN utilizes a layered control hierarchy. As illustrated in Figure 2, SDN controls are coordinated towards medium voltage (MV) and low voltage (LV) grid sides. In addition to power hardware infrastructure, the SDN concept includes capabilities for control and functionalities as well as data and communication. In addition, business models and applications are developed upon the concept.

At the local level, the control architecture utilizes different subsystems. The converter drive is controlled via power line communication (PLC) or a similar controller. A higher-level control and optimization system is also foreseen, integrating the controls for the power electronics, battery storage, EV charging, customer-side demand response as well as other controllable resources. This system is responsible for overall optimization for market prices, self-sufficiency for local energy production, coordination with other SDNs to provide grid services, participation in local peer-to-peer markets or other objectives, depending on the targeted use case. Some of the components have subsystems responsible for specific characteristics: for example, battery storage has a local battery management system (BMS) to manage battery lifetime issues, and an EV charging unit is dependent on the conditions of the EV being charged. The SDN management system will prioritize all the potential (and possibly competing and contradictory) service requests, according to rules established in advance.

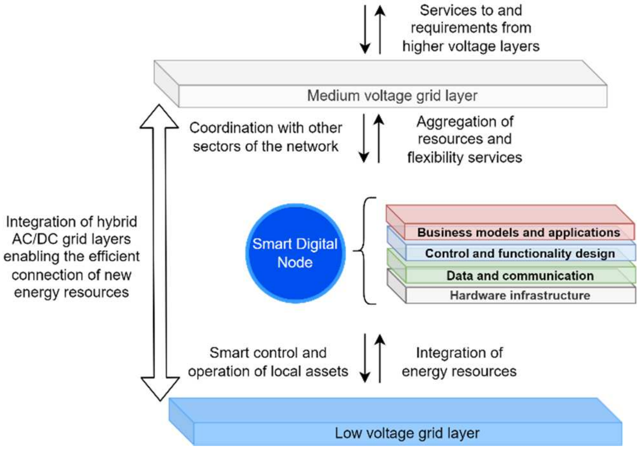


Figure 2: Layered control architecture for SDN and its integration with grid architecture

The SDN control system integrates with the SCADA system on grid control side, which is a common requirement for DNOs. On the customer side, the SDN can utilize several measurements, for instance data from smart meters, dedicated control boxes or PV inverters. Within the SDN concept, the final customer can be AC or DC connected depending on the setup. In case of AC customer, the metering arrangement is

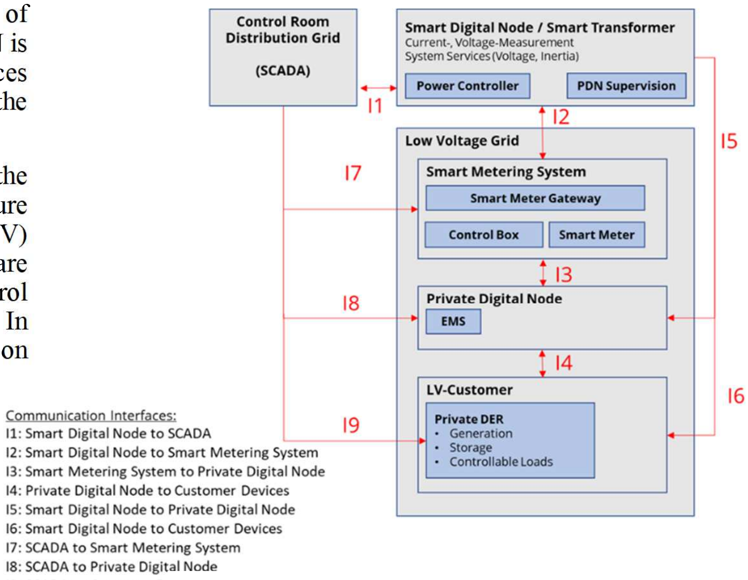


Figure 3: Local communication interface options

standardised at national levels, whereas for full DC customer supply, the interface needs to be designed differently for metering, protection and other features [10]. Figure 3 presents options for communication interfaces between subsystems.

III. MAPPING USE CASES ON FUNCTIONAL LAYERS

STRATA project develops 7 use cases utilizing the SDN concept. While they pose different requirements in terms of control functionalities, the common control and communication architecture is defined to enable all these use cases. Table 1 summarizes the key characteristics of each use case. The use cases have been further processed into requirements for the Smart Digital Node unit, including the converters and other technical equipment, control system as well as connectivity towards customer and DSO systems. The use cases are also processed towards test cases and success criteria for first prototypes built during the project.

Following the principles of SGAM framework [2], detailed LVDC grid use cases for a STx have been mapped on a functionality layer, considering dimensions for different domains and zones. The SGAM reference framework has been considered to address the complexity of representing the large number and diversity of system solutions offered by the STx consistently. This is achieved through unique features of the SGAM framework capturing three dimensions – one dimension representing interoperability aspects across different layers, and two more dimensions capturing the domains and zones of smart grid planes [2]. Each individual layer (business, function, information, communication, and component) details the interaction of systems, services, and components from different perspectives. The SGAM layers have been produced using the Unified Modelling Language (UML) tool of Enterprise Architect in conjunction with the SGAM toolbox [11], [12].

The smart transformer can act as a service node to directly power a fast EV charging station. In supporting the EV charging process during peak electricity demand, an energy storage system (local batteries) may be connected to the DC link of the smart transformer.

Table 1: Summary of STRATA high-level use cases (UCs)

Use case	Description	Objective
UC1: Basic grid management functions including voltage control, frequency control, power quality, protection.	The supply for LVAC and LVDC sides must always follow the general requirements in terms of voltage amplitudes, frequency and power quality aspects such as harmonics or EMC. Protection must also be implemented, following national safety requirements, and considering multiple faults occurring simultaneously on AC and DC sides.	Providing the right quality of supply for all customers, under all conditions.
UC2: Resilience Ability to ride-through short voltage dips and interruptions, ensure stability and fast recovery.	The SDN can improve reliability by means of withstanding short voltage dips and interruptions on the input supply side. Also, the SDN provides support during longer events by utilizing energy storage or demand response.	Being able to improve reliability and quality of supply with SDN.
UC3: Local optimization functions Optimizing the operation for chosen criteria (economic, self-sufficiency, emission related, etc.)	SDN can be controlled according to different objectives and targets. The optimization mode can be related to economic optimization (dynamic tariffs), to self-sufficiency (maximizing use of local generation), to minimizing emissions (depending on grid side emission intensity) as well as other criteria defined by user.	SDN power flow optimization against the desired criteria.
UC4: Improving local hosting capacity for distributed generation, HVAC, EV charging, etc.	To increase local generation and consumption capacity, and minimize the impact on grid connection, controllable resources can be adjusted dynamically. This can be achieved by charging/discharging of SDN battery and by shifting loads through demand response mechanism or utilizing a voltage regulation/reactive power control function in power electronics. When combining these functions, hosting capacity for the high demand from EVs and HVAC can be improved significantly.	Integrate more high-power generation or load. resources without reinforcing the grid.
UC5: Services towards local grid: voltage control, power peak avoidance, temporary backup supply, power quality service.	SDN is able to provide system services towards DSO, including voltage control, power peak avoidance, backup support situations or even power quality improvement. These services can be static agreements, or they can be dynamically requested by DSO.	Provide ancillary services towards grid.
UC6: Services towards markets: reserve markets (FCR, FFR, etc.), balance responsible parties, spot markets.	SDN can contribute to markets-led services, especially reserve markets and similar short-term opportunities. This will most likely happen through an aggregator or balancing participant who activates the flexibility potential within SDN based on the market situation.	Utilize SDN flexibility towards markets for economic benefit.
UC7: Services for local energy community: local peer-to-peer market, shared EV charging, common PV and storage, service provision, etc.	SDN is able to act as a service node for the local energy community. This means community services such as peer-to-peer transactions, shared EVs, shared PV panels close to SDN, shared battery, etc. The community can offer services to the grid and to markets (as in previous use cases), thus generating income for the community. Overall, the community can define different control strategies: being as self-sufficient as possible or performing economic optimization.	Offer flexible services to the energy community.

The smart transformer interfaces outside command signals, from the EV charging user interface, distribution network operator, and electricity market mechanisms. The smart transformer management system ensures dynamic control of the energy flow from the DC link or battery storage system to the EV charger and manages the availability of other services to prioritise this task.

Following the descriptions of the use cases, the functionalities required to realise the use case have been identified and added to the domains and zones of the smart grid plane. Other layers such as the component layer, the information layer, and the communication layer have been produced, but for the sake of brevity, only the functional layer has been presented here.

The functional layer is presented in Figure 4. As can be seen from the SGAM layer, most of the use case focuses on distribution system level domain dimension. In terms of zones, the use cases are distributed widely from market level to process level – this is an indicator of the complex set of inputs and requirements that inform the operation of the Smart Transformer. The SGAM functional layer clearly facilitates the identification of logical interaction required among actors to achieve the functionality of the use case, and accelerate the delivery of new services and new management functionalities through smart transformer technologies. This functional layer drives the identification of interoperability requirements among systems and components (captured by the information and communication layers). Overall, the SGAM framework approach used to represent STx use cases clearly offers a number of advantages. The interoperability aspect supports utilities to recognise technical constraints and requirements for a complete integration of STx functionalities into the distribution network, and testing laboratories to validate these new functionalities in real-time. Additionally, this can support standardisation activities to address uniformity in information and communication technologies for smart transformers.

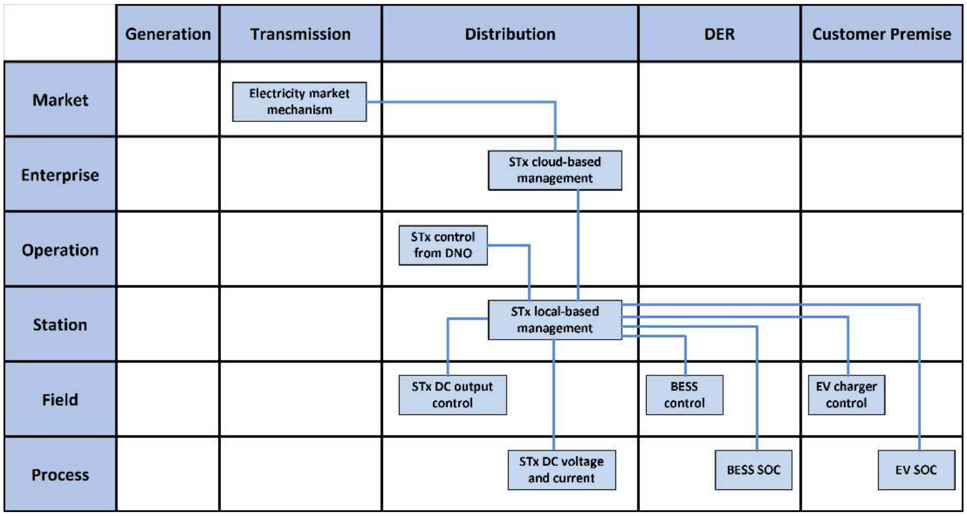


Figure 4. LVDC related use cases mapped on functional layers.

IV. APPLICATION EXAMPLES

The architecture developed has been implemented in different application cases conducted within the project.

A. German application case

In the German case, a central reactive power controller at the SDN has been developed for voltage control and an active power controller for transformer loading control have been developed, based on [13]. The control architecture of the active power controller is shown in Figure 5. Figure 6 shows a simulation of the working controller in a small grid with 5 loads.

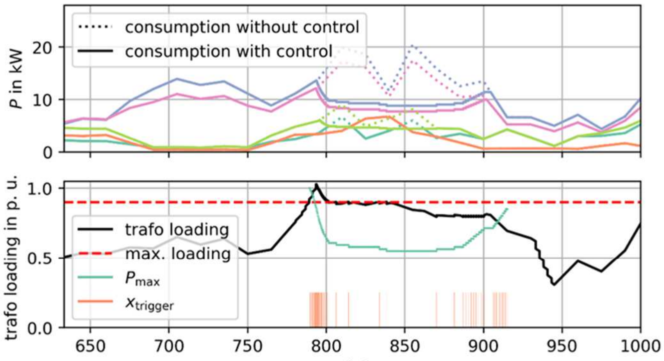


Figure 6: Reference power of the individual households (top) and transformer load and control signal of active power controller (bottom).

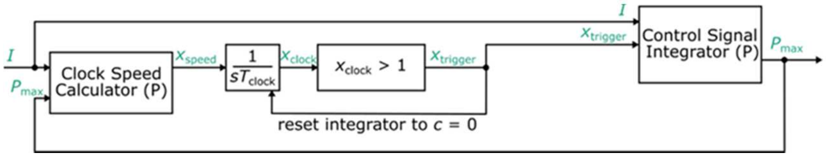


Figure 5: SDN central P controller.

P_max limits the power consumption of distributed loads. The Clock Speed Calculator increases the frequency of triggers if the transformer loading gets closer to its limit. The Control Signal Integrator decreases the power limit with each trigger.

When the transformer loading falls below a first threshold (here: 0.8 p. u.) the power limit is increased again successively. If the loading falls below a second threshold (here: 0.7 p. u.) the power limit is released completely. As can be seen in the figure, the transformer load is successfully brought back below the limit value.

B. Finnish application case

In the Finnish case, the environment to be studied considers a typical suburban or rural area network, where a transformer unit is located above ground, the customers are located within one kilometre from the transformer, and the LV grid is built and operated as a radial network. For initial tests, a community of around 10 customers served by the transformer is considered. These circumstances also match well with foreseen energy community developments within rural villages, remote areas and other limited areas.

The established control architecture relies on 4 Stage Decision Engine (4SDE) by THT Control as high-level control and optimization system. 4SDE is connected with different components, including the PLC-based converter drive control for the actual SDN prototype as well as customer level demand response controls. Communication towards customers will be utilizing Lora WAN wireless communication and simple control signals. 4SDE also receives external signals and performs the optimization as defined in the use case. The overall control hierarchy is presented in Figure 7.

In essence, the 4SDE control system provides a simple and efficient control platform that determines when the time is right to use a particular power supply and when is the right time to use each energy load. For both power supply and load components, the 4SDE applies a four-stage categorization (1. Always active – 2. Can be activated when optimal – 3. Activated as needed – 4. Storage unit: full flexibility). For the dynamic power request for each customer load, similar 4-stage categorization is applied (1. Not needed right now – 2. Can be used if optimal – 3. Should be used now – 4. Must be used now), which is applied for decision making within the demand response process. To perform the optimization, the 4SDE utilizes data for the current situation, as well as history data and forecasts for next 24 hours, and applies different parameters and thresholds defined for component types and customers.

The prototype as well as test setups being built are focusing on control functionality utilizing information like component status, grid measurements and external signals like market prices or weather forecasts. The control loop will cover SDN-level batteries and EV charging as well as customer-level demand response devices through wireless communication.

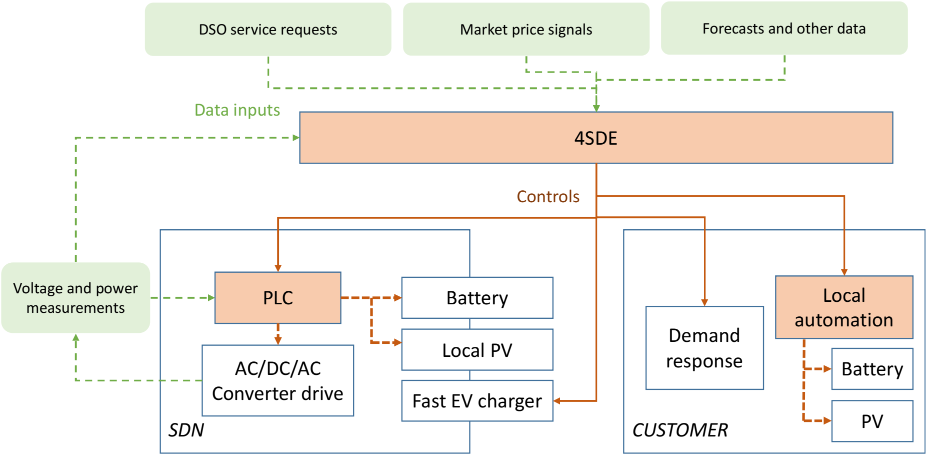


Figure 7: Control hierarchy of Finnish application.

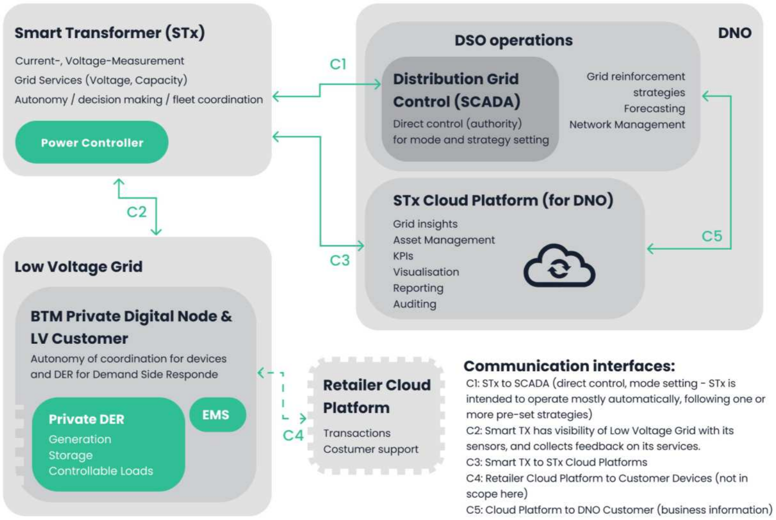
C. Scottish application case

In the Scottish case, a distribution substation transformer for the UK grid is re-designed and augmented with bespoke power electronics and provided as an infrastructure upgrade to the DNO. The resulting Smart Transformer (STx) is currently being trialled on the grid in the UK [14].

Figure 8: Amp X Smart Transformer on the distribution network in the UK.

Dynamic autonomous voltage regulation and power factor optimisation are available to support the LV AC grid. When operating as part of a fleet, the STx can contribute to network stability by providing frequency control at inertial timescales through power flow modulation. With both onboard and AI-enhanced cloud processing of the grid edge sensor data provided by the STx, the DNO can achieve new levels of grid visibility and control. On the DC side, the targeted use cases in the STRATA project centre around the provision of EV charging and harnessing a local BESS asset to supplement all of the above operations.

High-level architecture for the Scottish case is presented in Figure 9.



C1: STx to SCADA (direct control, mode setting - STx is intended to operate mostly automatically, following one or more pre-set strategies)
C2: Smart TX has visibility of Low Voltage Grid with its sensors, and collects feedback on its services.
C3: Smart TX to STx Cloud Platforms
C4: Retailer Cloud Platform to Customer Devices (not in scope here)
C5: Cloud Platform to DNO Customer (business information)

Figure 9: Functional architecture of the Scottish application.

V. CONCLUSIONS AND FURTHER WORK

This paper presents the control architecture definitions made within the project so far. This work integrates with earlier technical specification presented for instance in [1]. The architecture defined is meant to be common, but still allowing different implementations and control logics within different cases as presented. Mapping of functionalities of use cases on SGAM reference framework supports a more uniform presentation of use cases to facilitate the technical and interoperability requirements for smart transformer technologies. This uniformity can facilitate a comprehensive quantitative analysis of different use cases leading to the identification of commonalities and differences, thereby supporting network operators in identifying feasible solutions, and policymakers in recognising gaps in regulatory frameworks. Additionally, it will allow stakeholders from different disciplines and domains to identify business cases of interest, centric on the smart transformer leading to the promotion of inclusiveness and collaboration. And lastly, the interoperability captured by information and communication layers may promote standardisation of data formats and communication protocols for smart transformers allowing different vendors to produce compatible devices with new features to advance the functionalities and benefits of smart transformer technologies.

The control architecture is taken to each development case and further to prototypes and test setups. While different cases presented have their own characteristics, common architecture allows for development of compatible services and business models. In addition to prototyping the SDN concept and validating it in lab and test setups, STRATA will continue to develop new services based on the concept, leading to new business models and possibilities for new actors finding roles.

STRATA has already defined target KPIs for the final products, in terms of technical performance but also regarding societal impact and benefits when applied more widely. Success criteria and KPIs will be an important part of assessment of validation tests to follow.

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