TECHNICAL REQUIREMENTS OF SMART TRANSFORMER FOR DEPLOYMENT IN GRID APPLICATION

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ABSTRACT

This paper provides information on the LV Engine project on implementing Smart Transformers into distribution networks as a solution to the network issues. The Smart Transformer, being power electronics-based, allows to increase the network controllability w ad flexibility. Technical requirements are provided on the Smart Transformer including its main components, the Solid-State Transformer and Smart Control System. The recommended power electronic materials and challenges with the manufacturing and control of the Smart Transformer are discussed. A business case is presented highlighting the Smart Transformers advantages over conventional reinforcement solutions with the final section discussing the LV Engine projects' next steps and objectives.

INTRODUCTION

The growing connections of Low Carbon Technologies (LCTs) such as electric vehicles and photovoltaics has caused additional strain on distribution networks, especially LV networks. Voltage limit violations (upper and lower ones) and overload of network assets are the main growing issue in LV networks. The conventional "fit-and-forget" approach which designs a passive network for the worst demand/generation scenarios can be prohibitively expensive, time-consuming and cause disruption to customers.

In addition, LCTs are preliminarily supplied by DC voltage that requires AC/DC conversion for connection to the existing AC networks. Several studies and field trials demonstrated that it can be more efficient if the DC loads/generation can be directly supplied by a LV DC networks [1]. The benefits of using a DC network can be higher power transfer over distance and lower system losses compared to conventional LV AC networks. This will introduce a new opportunity for Distribution Network Operators (DNOs) to provide direct DC connection for the DC customers.

In order to develop an alternative solution to conventional network reinforcement and operation, SP Energy Networks, one the UK DNOs, has started an innovation project, LV Engine[1], aiming to introduce flexible, intelligent and active LV network operation. LV Engine intends to design and trial a power electronics-based Smart Transformer [8] for operation in secondary substations (11kV/0.4kV). LV Engine aims to demonstrate the functionalities and benefits of Smart Transformers over conventional transformers. However, Smart Transformer is not a commercially ready product and technical specification requirements of this device yet need to be fully developed and proved before mass production.

LV Engine is the first project of its kind (to our best knowledge at least in the UK) that aims to design fit for purpose STs, trial them in various network schemes and inform the technical requirements of this device. This paper aims to introduce LV Engine project, the initial technical requirements which have been developed for the ST and challenges need to be addressed during this project.

LV ENGINE INTRODUCTION

LV Engine is a flagship innovation project lead by SPEN which will bring Smart Transformers (ST) to the Distribution network for the first time. The project is funded by Ofgem through the Network Innovation Competition (NIC) funding mechanism. NIC funding mechanism has designed for development of new technology that can significantly bring benefit to UK electricity customer and facilitate the UK government targets for green-house gas emission reduction.

LV Engine aims to enhance LV networks operation by adding intelligent controls and automation functionalities to the Secondary Substations. A general concept of the LV Engine is shown in Figure 1. LV Engine will trial STs in a number of schemes to demonstrate various functionalities including:

- Phase Voltage Regulation – The overall voltage profile of an LV feeder can be optimised by intelligently adjusting the phase voltage in real-time at the Secondary

[1]https://www.spenergynetworks.co.uk/pages/lv_engine.aspx

Substation in response to monitored voltage data points along the length of each LV feeder.

- Power Flow Control – STs have the capability to control power flow due to the inclusion of power electronics. This allows an ST to load share with nearby conventional transformers in real time for the purposes of reducing the thermal strain at peak times and maximising network capacity.
- Reactive Power Control – An ST can offer independent voltage regulations at the LV and HV terminals. Reactive power support and local voltage regulation at the HV terminal can be deployed to improve the voltage profile along the HV network. This function can be complementary to the conventional Automatic Voltage Control (AVC) scheme at the upstream Primary Substations.
- Low Voltage DC Supply – Voltage conversion from HV to LV by use of power electronics provides access to a DC voltage at the Secondary Substation. A DC connection can be made available to satisfy any local DC demand, renewable energy sources (RES), or energy storage without repeated rectification from AC to DC and the resulting network and customer losses. Running the LV network at DC can also increase the transfer capacity of the network allowing more Electric Vehicle (EV) load to connect to the network before costly reinforcement is required.

It is envisaged that the ST consists of two main components:

- Solid-State Transformer (SST) [2]: This unit includes digitally controlled power electronics and hardware which provide various network control functionalities. SST will be installed in the Secondary Substations and provide voltage conversion from (11kV) to Low Voltage (0.4kV). SST can control the power flow passing through itself and voltage at its terminals by adjusting the power electronics switching in response to set points received from the Smart Control System (SCS).

- Smart Control System (SCS): This system includes a number of intelligent units which provide the control set points to SST based on the data monitored at different points in the LV and HV network. SCS has an operational supervisory capability to estimate the latest operation conditions and requirements within a regional control zone to satisfy network optimisation objectives and constraints.

TECHNICAL REQUIREMENTS OF SMART TRANSFORMER

The experience in designing and building of Smart Transformers are limited to mainly laboratory prototypes [3]. Operation of such devices in public networks have not been trialled before. Considering the characteristics of public networks and the grid compliance requirements there are certain technical requirements need to be considered for the design of this device. In addition, in order to achieve the core functionalities specified in LV Engine, there are certain technical specifications need to be fulfilled. The following sections provide an overview on the key technical specifications developed for the Smart Transformer in LV Engine to date.

Solid State Transformer

Topology

Different topologies may be considered for a SST considering the functionality requirements. [2] have extensively discussed the possible topologies and their pros and cons, however, in a summary this may be achieved through 3 possible designs: i) one Stage, ii) two Stage, iii) three Stage as shown in Figure 2. LV Engine is now in a design process to identify a fit for purpose topology which can provide the core functionalities defined in the project.

Rating and Power Capability

SST shall be capable of operating in four quadrant P-Q operation to supply bi-directional operation (Figure 3), including bidirectional active power and reactive power in the full range of loading conditions i.e. from no load to nominal rating. Bi-directional operation is an essential requirement to ensure the reverse power flow from the LV to MV network and flexible voltage control at the LV and MV terminals can be delivered by a SST. LV Engine aims to design and manufacture a 500kVA Solid State Transformer with this capability.

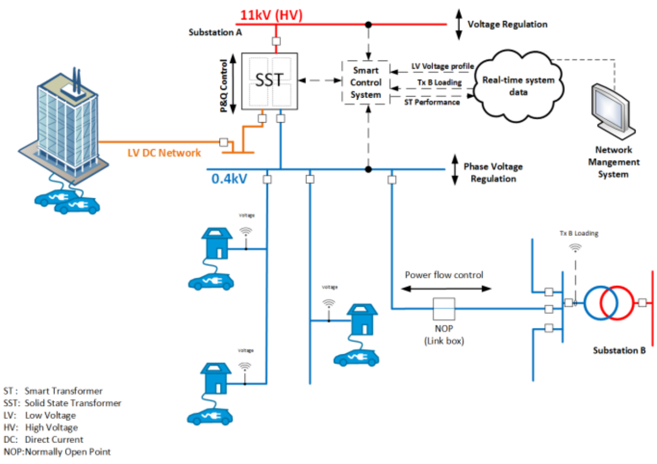

Figure 1 LV Engine concept demonstrating Smart Transformer application

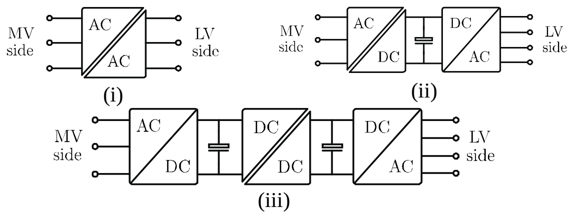

Figure 2 Possible SST topology

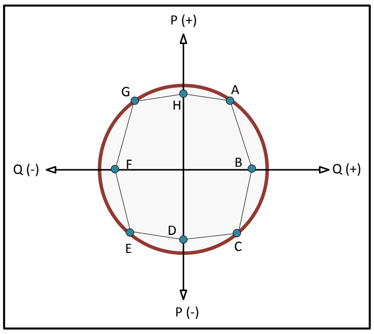

Figure 3 *Four* Quadrant *Operation of SST*

Network Normal Operating Condition

Any design of public networks or network operation scheme in the UK shall comply with Electricity Safety, Quality and Continuity Regulations (ESQCR) which are requirements laid out to ensure there is no interruption to security, quality and continuity of supply to electricity customers.

SST needs to be a stable device and perform its core functionalities within an acceptable range of change in system voltage and frequency. ESQCR mainly follows the requirements specified in BS EN 50160 [4] for the acceptable quality of the supply by the public networks. The following ranges of network parameters are considered as Normal Operating Conditions under which SST shall continue its full operation without any interruption.

- *System Frequency between 47.0 Hz and 52.0 Hz* – For the purpose of SST design, this range is considered as the normal frequency variations within the network. It should be noted that the Total System Frequency in public networks is between 49.5 to 50.5 for 95% of the time. However, this range can be temporarily and in rare scenarios extended to 47Hz – 52.0Hz.
- *MV Network Voltage between 85% and 115% of nominal voltage (11 kV)*
- *LV Network Voltage between 85% and 115% of nominal voltage (0.4 kV)*
- *Unbalanced MV Voltage between 0% and 3% of nominal voltage (11 kV)*. Although UK ENA Engineering Recommendation P29 [5] allows 2% unbalanced phase voltage at public MV networks, networks can occasionally see a 3% unbalance conditions.
- *Unbalanced LV Load between 0% and 100%*. This refers to the worst case unbalanced load occurring between any two phases requiring full operation during extreme load imbalances.
- *Total Harmonic Voltage Distortion of up to 8%*. – EN 50160 also defines a limit for individual harmonic orders which need to be considered

Operation During Network Overvoltage and Undervoltage

Voltage dips at the MV network may occur when a fault is present in the network due to the fault or energization of particular devices. Voltage dips due to a fault can be severe and depending on the proximity of the fault location, may temporarily reduce the voltage at the MV terminal of SST to as low as 1.0% for a very short time until the fault is cleared by the protection system. During this time, it is paramount that the SST remains stable, connected to the grid and does not require a restart. However, it would be acceptable that the temporary voltage dip transferring to the AC secondary terminal and that the SST switches to standby mode. The following operation is proposed in LV Engine project:

- The temporary voltage dip at the MV terminal can be transferred to the secondary terminals, the same function as conventional transformer.
- However, the SST switches to standby mode in which it does not supply (no active or reactive power) the LV network when the voltage dip is greater than 20% of nominal MV voltage and lasts for longer than 3.0 second.

Temporary overvoltage may occur in the MV network as a result of network asset switching or phase to ground faults at the MV network. The SST shall remain stable and connected to the network (no need to restart in post-fault) during this temporary overvoltage. However, it is acceptable that SST switches to permissive operation or standby modes during temporary overvoltage. The details of this permissive operation is yet to be finalized in LV Engine.

Reliability and availability

It is very crucial to ensure the minimum impact on continuity and quality of supply to LV customers. SST will be replacing the conventional transformers which are deployed on a “fit and forget” basis. While it is a challenge to reach to the same reliability and availability level of conventional transformers, however, LV Engine is intending to consider the all measures to reach the highest reliability and availability of SST, targeting reliability and availability to be at 99.9% with only 3 forced outages per annum and 2 scheduled outages per annum.

Cooling System

A suitable and fit for purpose cooling system is essential to ensure low maintenance and reliable operation of a SST. LV Engine’s proposed solutions for complete the cooling system will consider air-cooling (natural and forced convention) and liquid-cooling (water exchange or oil-immersed) solutions. The cooling system shall include a design that avoids creating any obstruction within the substations and access to exiting switchgear and equipment.

Smart Control System

The SCS is an important component of a Smart Transformer providing real-time operational set points to the solid state transformer based on the network operation objectives. SCS may consider different objective functions for optimum network operation that include maximizing network capacity release or minimizing network losses while respecting the voltage statutory limits and assets thermal ratings. In LV Engine, these network operation objectives are achieved by the two main controls:

- *Power Flow Control* – The ability to load share between SSTs and/or conventional substations and maintain current loadings within equipment constraints;
- *Voltage Control* – Ensuring that all controlled nodes within the LV AC network are within the defined constraints.

The system architecture of the Smart Control System depends on different parameters, some of them are:

- Availabilities of the communication solutions between SST and other monitoring devices across the network
- The level of intelligent control and computation required to be carried out locally with SST or regionally in consideration of a decentralized or centralized control system
- The optimum data traffic between control systems and monitoring equipment
- The overall reliability of the SCS against operation under communication failures

Within LV Engine a decentralized control approach has been taken as shown in Figure 4. This allows redundancy of intelligence and share of computational burden that is required between regional and local level.

There is requirements that SCS has artificial intelligence (AI) and machine learning capabilities to address the following issues:

1- accurate LV network electrical parameters including resistance and reactance of LV circuits are usually not available, therefore, SCS cannot rely on a pre-defined network topology for calculating the SST control set points, a AI system that can create (and update) a network model based on monitored data is required.

2- complete set of monitored data might not be available due to failure in communication or monitoring devices, in this case the SCS shall have the capability to continue operation based on the available data and the best network operation conditions previously recorded as successful.

RECOMMENDATIONS ON MATERIALS

Material selection for the power electronics within the ST is important component of the design process. Power electronic semiconductors consisting of Silicon (Si) are well established in the market and the improvement of their performance is continuously ongoing. However, there are technological barriers with respect to their efficiency, which Si-based power semiconductors will not overcome. Other power semiconductor materials are being investigated to further reduce the losses of the power converters. The most prominent examples are Silicon Carbide (SiC) [3] and Gallium Nitride (GaN) [6] which are examples of wide-bandgap devices. Figure 5 compares several important benchmark parameters, which are the electric field strength, the energy gap, the electron velocity, the melting point and the thermal conductivity. Observing Figure 5 shows the wide-bandgap devices outperform in the Si-based power semiconductors in nearly every aspect.

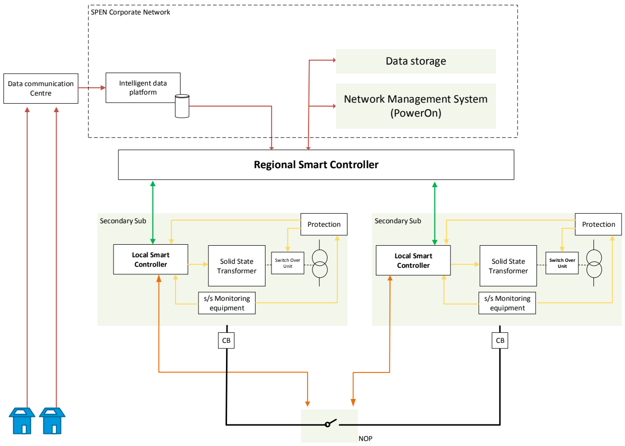

Figure 4 LV Engine Control System Architecture

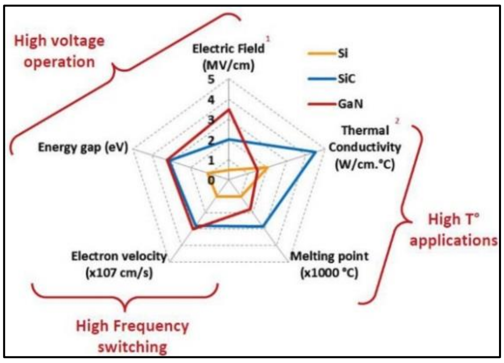

Figure 5 ***Comparison of different power semiconductor technologies [7]***

Compared with Si-based semiconductor devices such as Si-IGBTs and Si-MOSFETS, wide-bandgap devices such as SiC-IGBTS and SiC-MOSFETS have lower switching frequency losses allowing for the converters to operate at a higher switching frequency. Furthermore, combined with the ability to operate at higher temperatures, wide-bandgap devices can achieve a higher power density. The downside to wide-bandgap devices is that they are more expensive and less reliable than their Si counterparts although future trends predict the price of wide-bandgap devices to decrease and become competitive with Si devices.

The ST design could benefit from a combination of semiconductor devices implemented at different stages. At the MV side of the ST, a high blocking voltage is needed; this suggests that the Si-IGBT is best fit for purpose. It also has low conduction losses which is useful for devices with high current ratings. The LV side could also benefit from the Si-IGBT device whereas at the isolation stage, (the connection between the MV and LV side) a SiC-MOSFET would be beneficial due to the stage requiring a high switching frequency. The final choice of semiconductors are yet to be decided.

ST BUSINESS CASE

As previously mentioned, network reinforcement is undertaken by DNO's as a way to alleviate any non-compliance conditions in the network due to an increase in loading connections and distributed generation.

A traditional reinforcement scenario includes the replacement of current substation transformers to transformers with a larger capacity and the replacement of LV cables to larger sized cables. Whilst these solutions facilitate the load growth, they are prohibitively expensive, time consuming and may cause disruptions due to extensive and costly excavation of public roads and pavements.

An alternative approach is implementing the LV Engine project by installing STs within 11 kV/0.4 kV substations. STs, providing higher controllability and more services in the distribution grid, introduce several advantages:

- *Reduction in network charging cost* – The ST will reduce the network charging costs imposed on customers by avoiding and deferring the costly network reinforcement required in both the LV and MV grids.
- *Facilitate access to low cost energy* – The ST acts as an enabler of PV connection, due to its voltage regulation feature and availability of DC grid connection.
- *Providing scalability to secondary substations* – The modular nature of the ST allows it to increase the substation capacity with limited cost and disruption to customers, by adding additional hardware blocks to meet the demand increase.
- *Enabling the transition to DSO* – The ST increases the flexibility and adaptability of the LV network. This provides DSO with the tools required to intelligently and efficiently operate the distribution grid and also delays the point at which the DSO is required to interact with customers to remove local constraints.

The initial estimation by SP Energy Networks showed that there can be a considerable deployment opportunity for STs within the UK distribution network, conservatively reaching to deployment within 16% of existing ground mounted secondary substations by 2050. This estimation has considered other potential smart solutions that may deliver part or full functionalities of ST. The initial cost benefit analysis showed that by deploying smart transformers, there can be a total saving of £62m by 2030 and £528m by 2050 at national level [?].

FUTURE PROJECT WORK

The LV Engine project has now completed the first year by producing the technical requirements for SST and SCS. In the coming year the project delivery team are planning to design and manufacture number of SSTs for live trial in the network and under different schemes.

CONCLUSION

Smart Transformers have not been deployed for grid application yet and the exact technical requirements of them need to be developed. This paper provided an overview of technical requirements considered in LV Engine project aiming to trial number of SSTs. There are number of manufacturing challenges such as optimum topology, cooling systems, protection requirements and high manufacturing costs. However, if this product become commercially available, it can offer a significant saving in network reinforcement and provide a flexible solution for accommodating the fast growing LCTs.

REFERENCES

[1] A. Emrani and S. Spadoni, 2017, "Improving multi-voltage electrical system performance with smart step-down converters," SAE Technical Paper, Tech. Rep, 1668.

[2] J. E. Huber and J. W. Kolar, "Solid-State Transformers: On the Origins and Evolution of Key Concepts," in IEEE Industrial Electronics Magazine, vol. 10, no. 3, pp. 19-28, Sept. 2016.

[3] L. F. Costa, G. Buticchi and M. Liserre, "Highly Efficient and Reliable SiC-Based DC–DC Converter for Smart Transformer," in IEEE Transactions on Industrial Electronics, vol. 64, no. 10, pp. 8383-8392, Oct. 2017.

[4] BS EN 50160:2015, VOLTAGE characteristics of electricity supplied by public electricity networks

[5] ENA ER P9, 1990, Planning limits for voltage unbalance in the United Kingdom for 132kV and below

[6] P. Kumar Prasobhu, V. Raveendran, G. Buticchi and M. Liserre, "Active Thermal Control of GaN-Based DC/DC Converter," in IEEE Transactions on Industry Applications, vol. 54, no. 4, pp. 3529-3540, July-Aug. 2018.

[7] D.Antoniou, A. Tzimas, S. M. Rowland. "DC utilization of existing LVAC distribution cables" in *IEEE EIC*, Ottawa, Canada, 2013, pp. 518-522.

[8] M. Liserre, G. Buticchi, M. Andresen, G. De Carne, L. F. Costa and Z. Zou, "The Smart Transformer: Impact on the Electric Grid and Technology Challenges," in IEEE Industrial Electronics Magazine, vol. 10, no. 2, pp. 46-58, June 2016.