Compound Semiconductor Applications

Power Electronics in Electricity Networks:

Applications, Opportunities and Challenges

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Power Electronics in Electricity Networks: Applications, Opportunities and Challenges

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Introduction

Compound Semiconductor Applications (CSA) Catapult, PowerelectronicsUK and SP Energy Networks (SPEN) are in collaboration to stimulate the supply chain and manufacturing of power electronic technologies within electricity networks by raising awareness on existing and emerging opportunities. We believe there is a promising and attractive market for UK manufacturing capabilities and SMEs to grow in the electricity network sector with historic annual investment of around £6.0bn which is set to grow significantly.

This document aims to outline these opportunities and some representative applications of power electronics, and introduce the challenges and lessons learned from recent innovative power electronic technology deployments in the UK.

The opportunities for working in the electricity network sector is set to grow considerably with further incentives from government to meet its Zero Carbon targets. This document is only part of a longer journey planned to ensure the UK power electronics industry does not miss the opportunities to grow stronger in delivering electricity network solutions. It is very timely that the UK power electronics industry uses its ultimate potential to be a major player in providing solutions for grid applications. It should be mentioned, although this document covers the UK project examples and opportunities, the grid application power electronic technologies are growingly recognised by all countries providing a much larger worldwide market opportunity.

In addition, the existing innovation funding mechanisms to support innovation in electricity networks are summarised in this paper. These funds can be used as matching funds to expedite developments of new technologies or change in applications by transferring the solutions from other industries e.g. Aerospace or Automotive.

Existing electricity networks

Electricity networks, part of the energy sector business, provide the essential infrastructure to allow the energy transmission from central and distributed energy resources to electricity customers in all types and sizes. Depending on the voltage level, the assets of the electricity networks may be part of transmission networks (400kV and 275kV) or distribution networks (132kV, 66kV, 33kV, 11kV and 0.4kV). Figure 1 shows the boundary of the UK electricity network which is owned and managed by eight network operators depending on the regional operation, see Figure 2.

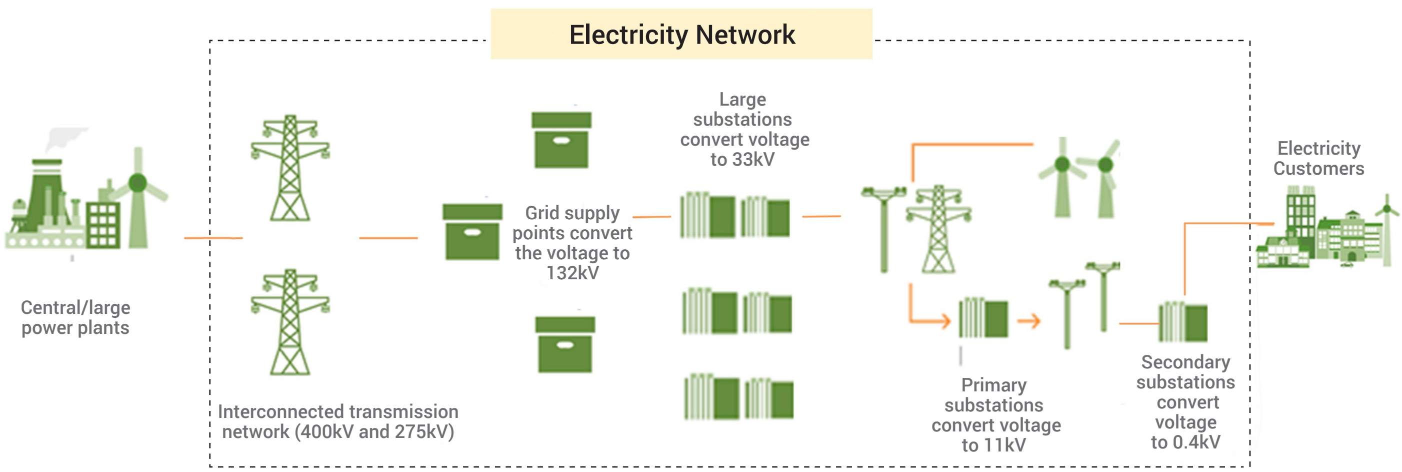
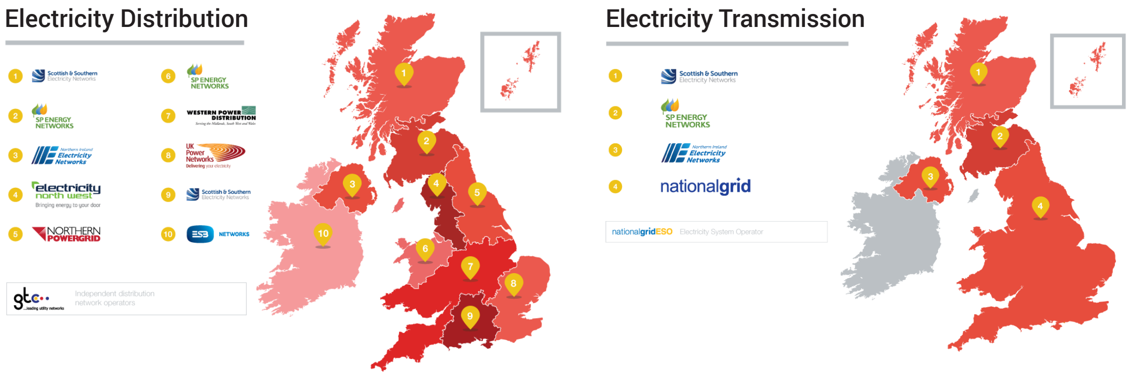


Figure 1: UK Electricity Network



(a) Distribution Network Operators (b) Transmission Network Operators

Figure 2: UK Network Operators [1]

The resilience and reliability of electricity networks contribute directly to security and continuity of energy supply which is crucial to our nation. The recent lockdown condition imposed by government due to the Covid-19 pandemic demonstrated that the energy industry is an essential and business critical sector, which needs to remain fully operational while other sectors may have to reduce their activities.

The majority of the existing electricity networks were built in the 1950s and 1960s, therefore a significant investment is required to renovate these networks while at the same time expanding them to meet the growth in electricity demand. GB distribution network operators have collectively been set to spend over £26bn between 2015 and 2023 with Ofgem's approval to ensure the GB grid can provide adequate available capacity to allow secure energy transfer to customers. Additional investments of around £2bn per annuum have been also seen within transmission networks.

This level of investment is expected to be significantly higher beyond 2023 with strong emphasis on deploying innovative solutions as considerable changes are happening in the energy sector, in line with the government's energy transition strategy with the goal to achieve net zero emissions by 2050. The electricity demand is expected to rise significantly due to the upcoming electrification of heat and transport. When it comes to electric vehicles (EVs), it is predicted that 50% of cars in the UK will be electric by 2040. Similarly, the government has already announced that gas boilers will be banned from new houses by 2025.

[1] https://www.energynetworks.org/

Changes in energy sector and impact on electricity networks

The electricity networks in the UK are experiencing significant changes in the way energy is generated and consumed due to the growing integration of low carbon technologies (LCTs). The UK government's intention to electrify the transport and heating sectors will result in a significant increase in network demand despite improvements in energy efficiency. The growing connections of distributed renewable generations is also causing an additional strain on our electricity networks. The level and time horizon of these changes in demand and generation are also difficult to predict as they highly depend on customers' behaviours, technology maturity, costs of LCTs and government policies.

The conventional planning and operation philosophy of electricity networks is no longer the most cost-effective approach to accommodate the uncertainties in demand and generation, while maintaining the quality and continuity of electricity supply. Electricity networks need to be more flexible and controllable at all voltage levels to allow better use of existing assets, defer network reinforcements and ultimately offer the best value to electricity customers.

These drastic changes in the networks led by the integration of distributed generation and a more difficult-to-predict electricity consumption, are leading the network operators to transition their operating models from Distribution Network Operators (DNOs) to Distribution System Operators (DSOs) that rely on active network management using real-time data for fast and precise network intervention, see Figure 3.

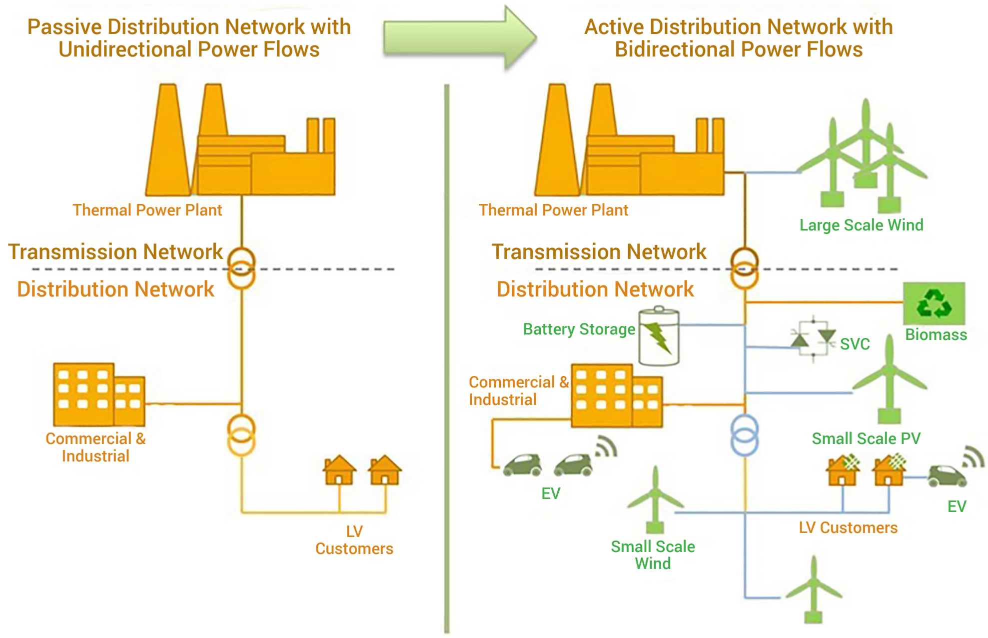


Figure 3: Transition from a passive network operation to active and intelligent operation philosophy

Application of power electronics in electricity networks

In this transition to a low carbon economy, the priority strategy for all network operators is to enhance network controllability and flexibility. One of the main enablers in this strategy is the use of power electronic technologies, which is growingly recognised by network operators. The market demand together with advancement in software and semiconductor technologies have made power electronic devices a very attractive solution for a wide range of applications in all voltage levels i.e. transmission and distribution networks.

Network operators have given special focus to the development and deployment of power electronic devices as part of their innovation and investment strategy. This has led to extensive designs and trials of power electronic applications to firstly ensure a toolbox of fit-for-purpose solutions is developed and commercially available for roll out across the UK electricity networks, and secondly, that the skillsets required to operate and maintain the power electronic devices are fully adopted by network operator staff. Some of the UK power electronic flagship projects are:

- **Angle -DC** [1] – Angle-DC is a smart and flexible method for reinforcing 33kV distribution networks, operated by SP Energy Networks. Angle-DC provides a controllable power electronic based flexible connection that facilitates enhanced bi-directional power flow between two sections of the network, Isle of Anglesey and North Wales. The project aims to convert the existing 33kV Alternating Current (AC) assets to DC operation and will trial the first flexible 27kV DC link in the GB distribution system. The solution controls the power flow between the mainland and Anglesey island to alleviate any thermal stress on electricity network assets and also provide regional voltage control.

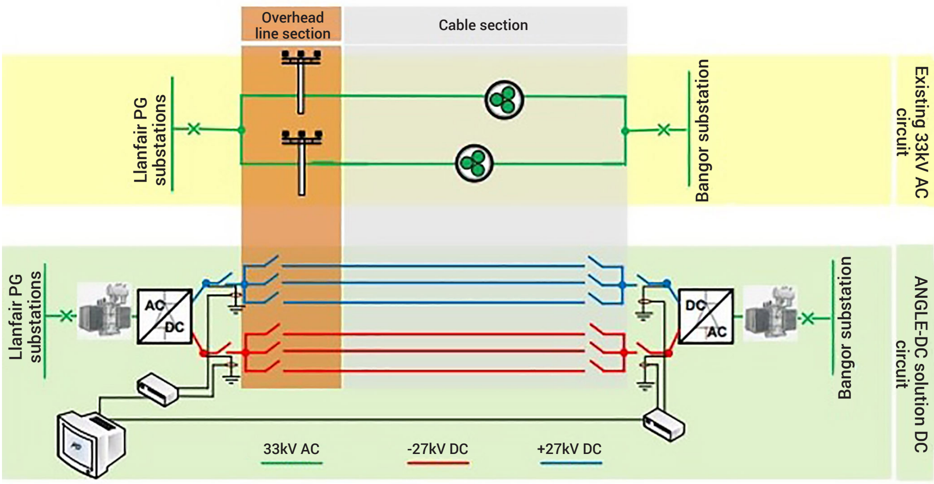


Figure 4:

- **Network Equilibrium** [2] – Network Equilibrium aims to install a back to back power electronic convertor (AC-DC-AC), which will allow power transfers across two different 33kV networks which cannot currently be connected due to a number of issues including circulating currents, protection grading or fault level constraints. This has been called a Flexible Power Link (FPL). The project installed and trialled one 20MVA FPL between two 33kV networks for controlling reactive and active power within interconnection as well as provision of voltage control.

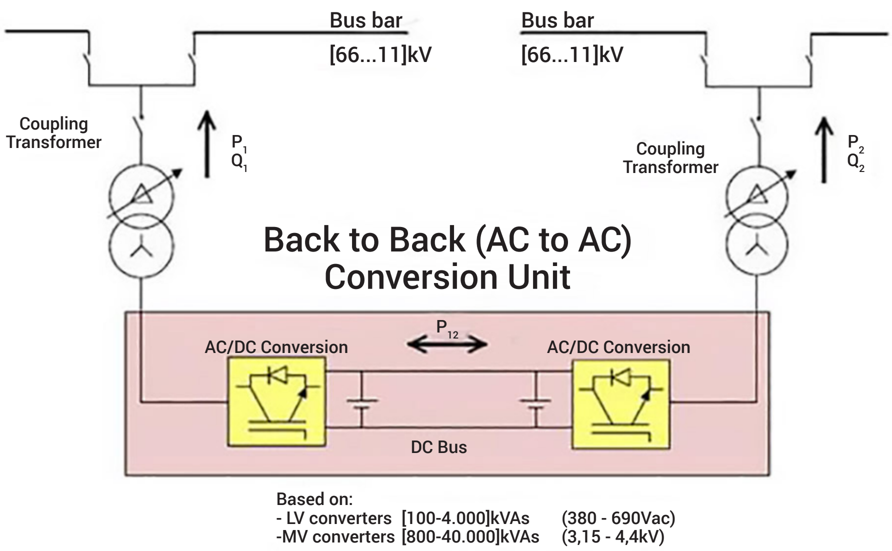


Figure 5:

[1] https://www.spenergynetworks.co.uk/pages/angle_dc.aspx
[2] https://www.westernpower.co.uk/innovation/projects/network-equilibrium

- **LV Engine** [1] – A globally innovative project which aims to design, manufacture and trial Smart Transformer technology for deployment at secondary substations (11kV/0.4kV). The solutions will significantly enhance the controllability at secondary substations. Several functionalities are expected to be delivered by this technology including voltage control, power factor correction, load imbalance cancellation, active/reactive power flow control and provision of LVDC supply. The functionalities offered by an LV Engine solution will allow higher uptake of EVs and PVs.

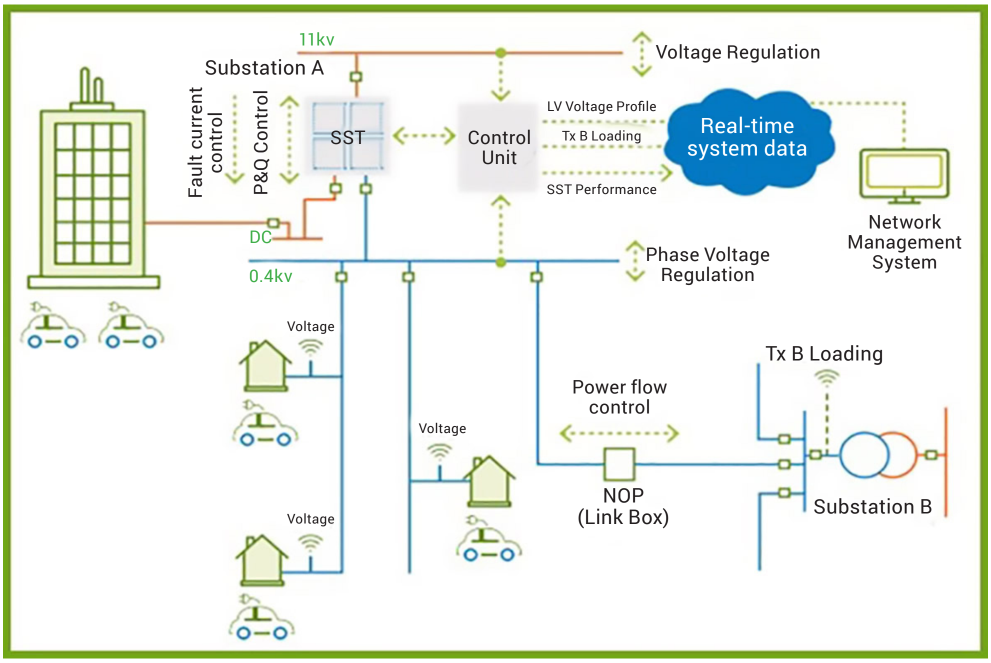


Figure 6:

- **Active Response** [2] – Active Response aims to deploy power electronic devices for power flow control and voltage control at distribution networks to enhance the network utilisation of the network assets. Two power electronic technologies will be trialled in this project i) Soft Open Point (SOP) which controls the power between two secondary substations at 0.4kV network ii) Soft Power Bridge (SPB) which controls the power within 11kV interconnections between two primary substations. Both technologies also provide voltage regulation services at point of connection. The flexibility offered by Active Response mainly facilitates higher uptake of EVs compared to traditional approaches.

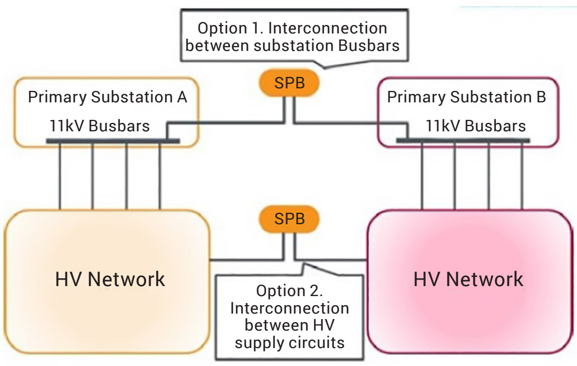


Figure 7:

- **Phoenix** [3] – Phoenix will demonstrate design, deployment and operation of the world's first Hybrid Synchronous Compensator (H-SC) at transmission network. An H-SC is the combination of a static compensator (STATCOM) and a Synchronous Condenser (SC) improving the system inertia and voltage stability. This implementation is expected to increase the UK transmission B6 boundary power transfer capacity from 45 MW to 90 MW. This will allow additional Distributed Energy Resources to be connected and flow through the network.

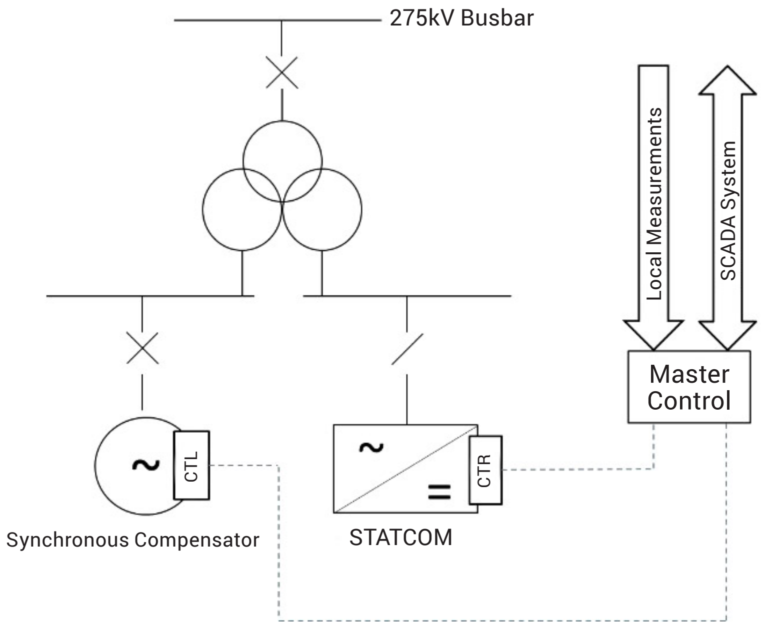


Figure 8:

[1] https://www.spenergynetworks.co.uk/pages/lv_engine.aspx
[2] https://innovation.ukpowernetworks.co.uk/projects/active-response/
[3] https://www.spenergynetworks.co.uk/pages/phoenix.aspx

- **DC Share** [1] – This project will assist with the facilitation of rapid EV charging equipment by providing appropriate network connections where they are needed, whilst making optimal use of the available network capacity. DC share uses power electronic technologies to establish a DC link among multiple secondary substations aiming to equalise the power distribution among them. This solution enhances the utilisation of network assets and allows a quicker uptake of rapid EV chargers.

- **HV DC links:** There are several HV DC links in operation within the UK transmission network delivering bulk controlled power transfer between two long distance locations. HVDC transmission assets comprise either Line Commutated Converters (LCC) using thyristors or Voltage Source Converters (VSC) using IGBTs. Significant investments have been made in the UK over the years to develop these strategic assets. Today, HVDC links connect different regions of the UK (e.g. Caithness-Moray or Western Link), or serve as interconnectors between the UK and other European countries (e.g. IFA-2 link to France, Nemo to Belgium and NSN to Norway). Following the recent Round 3 allocations made under the Contracts for Difference (CfD) scheme in September 2019, new HVDC links will be created to connect the Doggerbank offshore windfarms to the mainland, generating as a result 2 x 1200MW of additional offshore wind power. By 2050, it is predicted that up to 75GW of offshore wind power will be installed and available in the UK.

In addition to the aforementioned examples, there are significant opportunities to introduce more and new power electronic technologies to network operators, so they use these solutions as part of a planning and operation toolbox to support compliance with the continuity and quality of electricity supply standards. Some of the key functions power electronic devices or their control systems can provide are:

- Voltage control capabilities: Reactive power injection, power factor corrections and voltage boost/buck at any voltage level (0.4kV to 400kV), existing technologies are STATCOM and SVC.
- Power flow control: The control of active and reactive power within interconnected networks (at all voltage levels) can allow better use of network assets and losses optimisation.
- Harmonic filtering and damping oscillation: The growing connection of converter connected generators can have impact on overall harmonic voltage distortion in the network and also oscillations. The capability of active harmonic filtering and damping is required to ensure the quality of electricity supply is not compromised.
- Load balancing: Customers connected to different phases may have different consumption behaviour or connection to phases in the network may not be evenly distributed. The imbalance load from an LV network may transfer to higher voltage levels causing multiple issues. The capability to balance the load at any point of network can result in better use of assets and reduce the need for network upgrades.
- Intelligent sensing and condition monitoring: The visibility across networks on asset health conditions (e.g. temperature, noise, partial discharge), without interfering with their normal operation can reduce the costly network maintenance and customers' supply interruption.
- Network automation and switching: Power electronic circuit breakers and fast acting switches which can be remotely controlled and supported with any control intelligent systems.
- Grid forming technology and virtual synchronous machines: Most converter connected generators are grid following technologies as the grid network is considered a "stiff voltage source". However, the ability to control power electronic devices so that they act as virtual synchronous generators, i.e. grid forming operation mode, can contribute to the overall stability of the electricity grid.

Challenges in power electronic technologies

Based on the recent developments and trials of innovation projects conducted by GB network operators, the following key challenges have been identified:

- **Use of new semiconductor technologies (SiC or GaN devices)** – The knowledge and confidence in deploying these technologies are improving. However, there is still a lack of experience in the wider power electronics community in deploying these technologies. In addition, the absence of an established UK supply chain and the long lead time for the provision of these devices have been a challenge.
- **Thermal management** – One of the key aspects of any power electronic technology is the optimum thermal management. Small footprint, low maintenance and high efficiency are mostly required for any electricity network assets
- **Maintenance free and long lifetime products** – Most passive devices in electricity networks have free or little maintenance requirements. Adding any power electronic technology with high maintenance requirements or short lifetime may significantly impact the deployment justification.
- **Temporary overloading (load and fault)** – Electricity network assets usually have temporary overloading capability to withstand any fault current or short-term spikes in demand. This required capability in power electronic devices may cause thermal management issues or affect the footprint and cost of the device significantly

due to the need for oversizing of the equipment.

- **Stability and control** – High control bandwidth capability has to be enabled to ensure that the power electronic equipment is able to maintain stability and control of the network under all operating conditions, including transient and fault conditions.

- **Reliability and availability** – Power electronic equipment offers higher levels of functionalities that are beneficial to electricity networks, but at the same time are characterised by higher levels of complexity. Therefore, to achieve the specified reliability and availability, some redundancy has to be incorporated in the design of these systems. This redundancy must be provided while still achieving a cost-optimised solution.

- **Protection** –The power electronic equipment must be designed to remain operational and provide the required protective functions in support of the network (e.g. grid fault ride through for an HVDC converter), under all expected fault conditions. New equipment must demonstrate full compliance to these requirements through system validation and testing.

- **Efficiency and product cost** – Most electricity network assets are highly efficient e.g. transformers are usually > 99.9% efficient. The efficiency of power electronic devices, however, can be low due to switching losses or other factors. To justify a solution the whole lifetime product cost should be considered against the benefits it can offer. The balance and trade-off between functionalities, efficiency and final product cost is extremely important and has to be right to increase the chance of rollout.

- **Cyber security** – As devices become more intelligent and controllable; the network can be more vulnerable to any security attack. Compliance for full integration into secured network operators' IT systems and secure communication with the power electronic devices are crucial.

Supply chain challenges and funding opportunities

It should be emphasised that network operators usually follow a 'traditional' OEM-Tier 1 supply chain model that requires complete solution delivering operation services, rather than a power electronic module which is only small part of a device. In other words, it is much preferable to see the power electronic device as a black box delivering specific functionalities. It is not a normal practice for a network operator to buy different components (semiconductors, magnetics, filters etc.), and assemble them to build a device.

Such a supply chain model presents a significant challenge for the adoption of next generation power electronics where co-design of integrated solutions is often carried out across an extended and disaggregated supply chain.

To be able to adopt and deploy next generation solutions, we envisage groups of companies from across the power electronics supply chain with different technical capabilities, working together to form consortia to deliver grid application solutions. If carried out effectively, this approach has the potential to deliver supply chain flexibility and innovation in a timely manner with quality and reliability assured.

UK government have recognised that some of the new solutions including power electronic technologies need to go through design, prototyping and trialling stages before they can be commercially available for wider deployment. In order to facilitate these developments, some funding mechanisms have been introduced to provide matching funds for developing innovative solutions. It is expected that companies entering the market provide in kind contribution towards these developments funded under governments schemes. We believe that electricity networks, and the energy sector as a whole, have been becoming a strong market for the power electronics industry which should be utilised to its full potential by UK companies and manufacturers. Some of the funding mechanisms are as follows:

Network Innovation allowance:
https://www.ofgem.gov.uk/network-regulation-riio-model/current-network-price-controls-riio-1/network-innovation/electricity-network-innovation-competition

Network innovation competition:
https://www.ofgem.gov.uk/network-regulation-riio-model/network-innovation/electricity-network-innovation-allowance

Innovate UK:
https://www.gov.uk/apply-funding-innovation

Next steps

The UK has a very strong and deep power electronics supply chain capability from semiconductors through packaging, design, modelling, software, test and reliability to system integration. To a considerable extent, particularly in the automotive and aerospace sectors, the industry has shown it has the capability to work together as a cohesive supply chain to provide innovative solutions. For example, the £20m Advanced Propulsion Centre (APC) ESCAPE project involves 12 partners across the supply chain from semiconductor companies through to Tier 1s working to develop innovative all-UK integrated SiC power inverter, converter and charger solutions.

The challenge here is to bring together UK electricity network needs and UK power electronics capabilities to develop a new, vibrant and world-leading supply chain.

We propose a coherent, multi-facetted programme of activity to facilitate supply chain and solution development. CSA Catapult as a leading industrial power electronics research hub and PowerelectronicsUK as the voice of the UK power electronics industry, will work closely with SP Energy Networks and the UK DNO/DSO base to help drive the programme.

Crucially, this must actively involve key stakeholders and institutions such as the market-focused sister Catapults of CSA; the Energy Systems Catapult and the Offshore Renewables Catapult liaising with the extended and excellent UK industrial and academic base. In addition, CSA Catapult is also the Driving the Electric Revolution (DER) industrialisation centre lead for materials and components, and links into the DER community and collaborative research programmes will be essential.

Principal elements of the grid power electronics deployment programme will include:

1. The development of a broad industrial community that ties network primes with the underpinning supply chain. A first gathering of this community would be through a dissemination event around this document followed by a series of webinars and/or physical meetings addressing key technology and business challenges.

2. The development of specific supply chain cohorts and collaborations aimed at addressing and solving some of the key challenges presented above. The aim is to develop a broad programme of projects that build on the current Ofgem project portfolio. Examples of initial projects or cohorts could include focus on technology platforms, general system challenges or enabling technologies such as:

- MVDC solution development
- Wide bandgap power electronics reliability proving for grid application
- Novel and resilient sensing and control solutions for grid applications

If you consider that the products developed by your organisation and your expertise are relevant to those described in this document and you would like to participate in the programme, please contact **collaboration@csa.catapult.org.uk**.

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