NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

SPECS Smart Grid + Power Electronics Consortium Singapore

Advanced Power Electronics: Enabler for Energy Transition & Efficiency

CONTENTS

BACKGROUND

Climate change is the existential threat of today. With improving living standards, growth in the global energy demand along with increasing emissions is inevitable. These seemingly contradictory priorities, of increasing economic growth vs reducing environmental impact, compel a paradigm shift in electricity generation, transmission / distribution, and efficiency in end-use. Decoupling economic growth from emissions will necessitate a transition towards a carbon free economy; which involves a holistic approach towards addressing the energy trilemma of energy security, environmental sustainability, and economic development. A large proportion of the global strategy for reduction in emissions intensity will rely on deployment of renewable energy and on energy efficiency. The world's primary energy supply continues to rely on fossil fuels (e.g. natural gas, petroleum derivatives), with renewables (e.g. hydropower and solar photovoltaics) contributing less than 25% to the energy mix. Encouraged by reducing costs of wind and solar (viz. 88% reduction in costs from 2001 to 2019), investments in renewables continues to outstrip investments in new capacity of fossil fuel based power generation plants. A significant reduction in the costs of batteries (viz. 86% from 2010 to 2019) has also enabled optimism that the intermittency of renewables (viz. solar cells do not generate electricity under cloudy conditions or at night) can be buffered by batteries.

Energy efficiency – the kilowatt-hours we avoid by eliminating waste – is by far the world's lowest-cost resource. Energy efficiency measures comprise of employing the most efficient means of electricity generation and reducing losses in electrical power systems. Final energy demand delivered by electricity (e.g. transportation, cooking, cooling) will double from 19% in 2017 to 40% in 2050; making electricity the fastest growing form of end-use energy. Functions of control, conversion (e.g. high voltage to low voltage), transmission and distribution can be fulfilled by analog devices (e.g. conventional transformers) or through use of electronic components, viz. power electronics. Power electronics include semiconductor devices that function as switches in electrical systems, and are responsible for controlling the flow of electrical energy from the source to load. Power electronics enable extremely efficient conversion of electrical power and also can provide optimal conditions for integrating distributed generation. Because of their potential to enable digitalization, and their highly efficient operations, it is estimated that the amount of electricity processed by power electronic components will double over the next decade, reaching up to 80% by 2030. Power electronics components used today are based on silicon (Si) and include metal oxide field effect transistors (MOSFET), Insulated Gate Bipolar Transistor (IGBTs), and thyristors. There are few limitations of Si based devices, which include - high losses, low switching frequencies, low thermal conductivity, and poor performance at temperatures >125oC. Materials such as silicon carbide (SiC) and gallium nitride (GaN) have a great potential to overcome the limitations of Si, and as they transit from research and development to commercially viable products, they are driving energy efficiency and performance gains in power electronic systems.

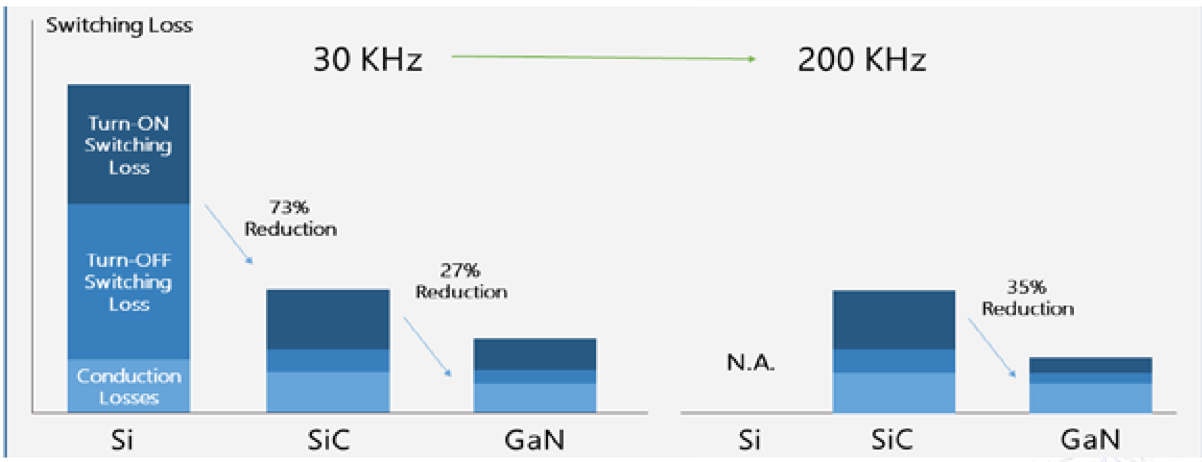

Figure 1: Potential energy savings

The reduced losses as shown in Figure 1 are attributable to material properties of SiC such as high breakdown strength coupled with reasonably high electrical and thermal conductivity. These material properties deliver improved efficiency, savings on cooling requirements, improved signal / noise ratios, and miniaturization due to increased switching frequencies. Advanced power electronics viz. SiC and GaN are thus key enablers for efficient generation, distribution, and use of electrical energy. It is estimated that these advanced power electronics could reduce energy losses in electronic equipment by more than 50%. Domains where power electronics are envisaged to make major impact include electric motor drives, electric mobility, home appliances, industrial applications, data centres, lighting, intelligent buildings, and smart grids.

APPLICATIONS OF ADVANCED POWER ELECTRONICS

Applications of advanced power electronics can be broadly grouped under the four categories of: Smart & Sustainable Buildings, Industrial Energy Efficiency, Transportation (Land, Air, Sea), and Smart Grids. Advanced power electronics is the technology behind the key implementer of low-energy consumption ideas. Power electronics enables this by various means where the most notable among them are to enable operation of the systems at close to unity power factor of operation, and operation at the load's customised voltage level as well as frequency thus ensuring that the system operates at optimal energy equilibrium. With intelligent and smart electronic monitoring and control, the system responds to loads much faster and closer to optimum operations than systems that do not employ power electronics.

Smart and Sustainable Buildings

The building sector accounts for approximately one-third of Singapore's electricity consumption. The Building Construction Authority (BCA) Singapore defines Zero Energy Buildings (ZEB) as those who generate all of their energy needs (including plug loads) from renewable sources and Super Low Energy Buildings (SLEB) need to demonstrate at least 60% energy savings (compared to 2005 levels). Before any gains from renewables are considered, the buildings need to consider energy efficiency measures that include sunlight shading, dynamic facades, air conditioning and mechanical ventilation (ACMV), lighting, building automation, plug load management, building to grid integration, and other options in passive design (e.g. natural ventilation). Power electronics are key enablers of all energy efficiency areas listed here, excluding those of passive design based measures. Other advanced strategies include smart devices that not only meter the energy consumed but also provide real-time information, incentive pricing, deviations from standard consumption etc., to help people living in or managing these environments save energy while maintaining the desired comfort levels. Decentralised monitoring and control systems for power quality management, communication protocols, e-trading platforms for dynamic pricing, virtual power plant and service architectures constitute developments that will also see widespread implementation in the near future. Beside renewables, on-site energy storage (e.g. batteries, or storage of ice/cold water for chiller systems in buildings) and energy storage in electric vehicles (EV) can facilitate stabilisation of power supply and also provide a mechanism to manage peak demand.

The critical technologies for smart and sustainable buildings include solid state lighting, heating, ventilation, and air-conditioning (HVAC), and intelligent control systems for building management. In the buildings area, power electronics plays a critical role for actuation, and control. HVAC systems get their controls through electric motor drives controlled by power electronics. Lighting systems cannot have adaptive controls without power electronics. Any automated management of safety systems, elevators, water management, and building use runs on modern advanced power electronics. Approximately 25% of total electrical energy is consumed by lighting. Savings of 70% - 90% can be achieved through the use of solid state lighting with electronic ballasts, dynamic dimming controlled by adaptive sensors that measure occupancy / natural lighting, and higher efficiency power supplies that control the individual LEDs. Heating, ventilation and air conditioning (HVAC) accounts for about 56% in tropical areas and about 40% of the total energy consumption in buildings, including electrical and non-electrical heating / cooling in regions like US and Australia. Using advanced control together with energy-efficient appliances based on advanced power electronics, it is possible to save around 20% of total energy consumption both in electrical and non-electrical systems. In Singapore, buildings account for 31% of the total energy consumption Households and building loads together form the largest users of energy.

Heating, ventilation and air conditioning (HVAC) accounts for 70% of the total energy consumption in buildings, including electrical and non-electrical heating / cooling. Lighting loads have improved specially for the new buildings but are still responsible for 15% of the total energy consumed. Most residential and commercial buildings deploy lifts and escalators that are designed using conventional technology in which energy savings was not the main guiding factor. They suffer from gradually falling efficiencies and account for more than 10% of the energy consumed in buildings. Singapore’s tropical climate challenges the classical methods of achieving high energy efficiencies, and new approaches are needed to create a sustainable impact. Various approaches have been recommended in the “super low energy” technology roadmap by the buildings and construction authority (BCA) which aims to achieve Net zero energy consumption in buildings. The approaches consider passive strategies, (Figure 2) in which building design forms the key focus. New buildings have started adopting methods in which both building thermal management and lighting will be designed in more creative ways so that natural light and ventilation can reduce the need to use electrical energy for the purpose. While such passive approaches of building and campus designs will work for the new installations, the existing ones (which form the majority of the buildings load) can benefit from actively managing and controlling the air-conditioning, ventilation and lighting loads.

Smart and modular building energy management systems that are either custom built or will be made to specific standards are proposed as an important approach to reduce energy consumption in existing and new buildings. Using advanced control together with energy-efficient appliances based on advanced power electronics, it is possible to save more than 30% of total energy consumption both in electrical and non-electrical HVAC. Replacing all the motors and pumps in the HVAC electric systems by higher-efficiency ones, including external continuous control, variable speed drives based on power electronics and using intelligent control for HVAC and the environmental data gathered by wireless sensors, the energy efficiency of a complete system can be improved by 30–40%. Approximately 25% of total electrical energy is consumed by lighting; and significant savings can be achieved through the use of solid state lighting, coupled with electronic and smart controls. By replacing hydraulic lifts with electric traction lifts using advance power electronics-based speed control, feedback and low consumption stand-by mode (~80% of a lift’s annual energy consumption), one can achieve savings of over 50%. These energy efficient measures reduce energy consumption by between 50 and 75%. Escalators form an essential load in commercial buildings. With advanced power electronic conversion, highly efficient electric motors can be used in a variable voltage variable frequency (VVVF) control mode.

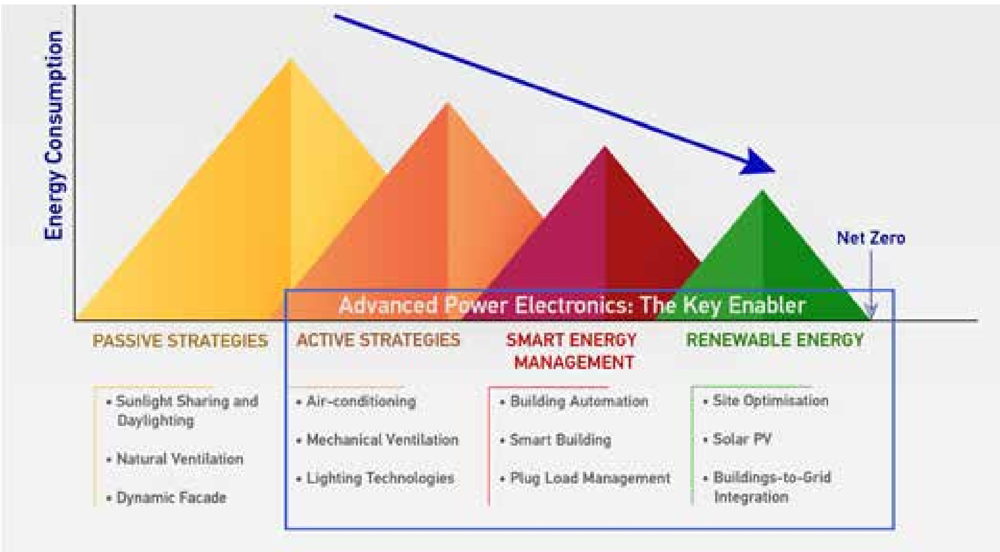

Figure 2: Advanced power electronics will enable buildings to achieve net zero in energy consumption (Source: Building and Construction Authority Singapore)

Escalator speeds can be varied according to the passenger load and seamlessly automatic start/stop control or variable-speed controls can be implemented. In idle conditions of no passenger or low passenger numbers, significant energy savings can be achieved with this approach. Additionally, integration of the roof-top solar in buildings has been a growing practice in tropical mega-cities. For sustainable net zero (per year) in a building, it is possible to estimate the renewable energy contribution based on the location and weather at that place. This data is indicative of the extent of other measures like “active strategies” and “smart energy management” required to achieve a net zero per year. Advanced power electronics enables multi-functional interface devices to maximise energy capture. Together with energy saving measures, this will play a significant role in achieving net zero in building energy consumption.

Globally, there has been a shift towards energy efficient building technologies mentioned above. In the USA for instance, there are efforts towards investigating smart alternating current (AC) nanogrids for today’s technology and direct current (DC) nanogrids for smart, sustainable homes and buildings of tomorrow. The AC nanogrids incorporate smart appliances, lighting and HVAC with on-site power generation and an Energy Control Centre (ECC). The ECC can communicate with the power system operator for energy trading purposes, while also acting as a data acquisition unit. The ECC can collect and record the power flow data not only from and towards the grid, but also from all the converters and smart appliances in the home. Industries have also aligned their products around green and energy efficient buildings with the objectives of improved efficiency, greener footprint from renewables and energy management.

Another important aspect is the reactive power, which is that part of the power that does not participate in active work done, but aids in stabilising voltage, and is an integral requirement for the grid. This is critical in residential and more so industrial units, as the motors, which perform most work, need inductive reactive current for magnetisation. This required reactive current is either supplied by means of passive or power electronics based active means. The potential advanced loads and interconnection in building environment can be represented as given in Figure 3.

DC distribution in buildings is another area that is being researched in Singapore and globally. In high performance buildings, most loads (e.g. laptops, LEDs) have power supplies / converters that convert AC supply to DC currents. Electrical power storage and solar power generation, which are both growing at unprecedented rates, deliver power through DC. Most of our electrical appliances, both at home and at the office, also use DC. Still, because the power grid supplies AC power to households, electricity from battery storages or PV has to be converted to AC and then back to DC before it can be used in households or office buildings.

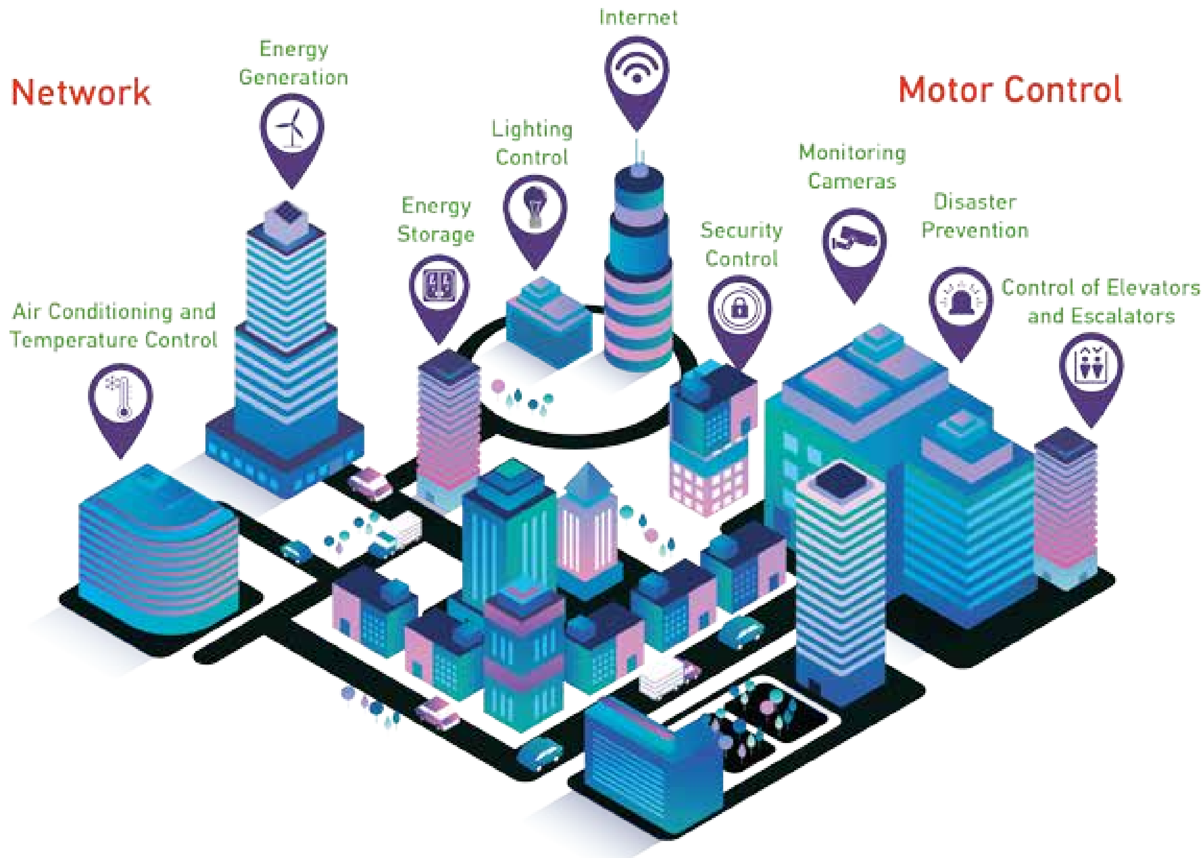

Figure 3: Smart Building and City

While high-end AC/DC converters used for battery storage and PV typically lose 3-6% of the electricity in the conversion, standard consumer electronic converters and LED-drivers have losses of up to 25 %. A "direct-DC" building distribution system with onsite PV and DC appliances could between save 5-15% energy by avoiding power conversion losses from DC to AC and back to DC.

Industrial Energy Efficiency

Efficiency is a powerful driving force in all industries, as inefficiency often translates into unnecessarily high costs. The manner in which industrial systems are powered is changing dramatically as the demand for power increases and, at the same time, as environmental, commercial, and legislative pressure mounts to reduce energy consumption and increase energy efficiencies. The industrial sector across the globe, uses up to 50% of the useful delivered energy. Energy savings in the range of 30% – 50% could be realised with the use of efficient motor systems with variable speed drives using advanced power electronics. The fourth industrial revolution (or Industry 4.0) is expected to be highly efficient with a cyber-physical system to monitor the physical processes of the factory with all programmed and artificial intelligence (AI) based decision making algorithms.

For this to be a reality, smart and connected factories mandate a new and better approach for powering them. Advanced power electronics plays a crucial part here when a high voltage is converted to a lower voltage, with minimal energy loss during the conversion. Advanced power electronics reduces such energy losses by (1) minimising the number of times that a voltage must be converted, and (2) decreasing the inefficiencies during such voltage conversions. Approximately 65% of the electricity use by industry is used to drive electric motor systems. Use of Variable Speed Drives (VSDs), High Efficiency Motors (HEMs), efficient pumps, compressors and fans can each achieve energy savings of up to 40% as per estimations, and could translate into overall energy savings in the range of 30-40%, with payback periods of 2-3 years, and a CO2 reduction potential of ~25%. Such enhanced efficiencies are achieved through the seamless control of compressor functions rather than an ON and OFF switching.

Industrial motors mainly are those that find application in elevators, refrigerators, air conditioners, washing machines and factories. The vast majority of these motors do not have electronic controls. Electric motion (motion excluding transportation) accounts for 80Q Btu (0.02kWh). Simple electric motors (without intelligent control electronics) account for about 70Q Btu. These simple electric motors are either fully on or fully off, which is like driving with the accelerator pushed all the way to the floor then taking it off, over and over again. Besides this being a poor way to drive, it also turns out to be less efficient. By converting all such simple electric motors to variable speed drives (VSD), it is possible to cut power consumption by almost half, as shown in Figure 4. Similar gains are achievable in air-conditioners using VSD by using seamless power electronics control, compared to conventional controllers that leads to oscillations and slow response as shown in Figure 5. There is an additional energy saving of 20% through the recuperation of electrical machines during breaking, which is frequently used in elevators and traction application of trains and heavy vehicles with power electronic converters.

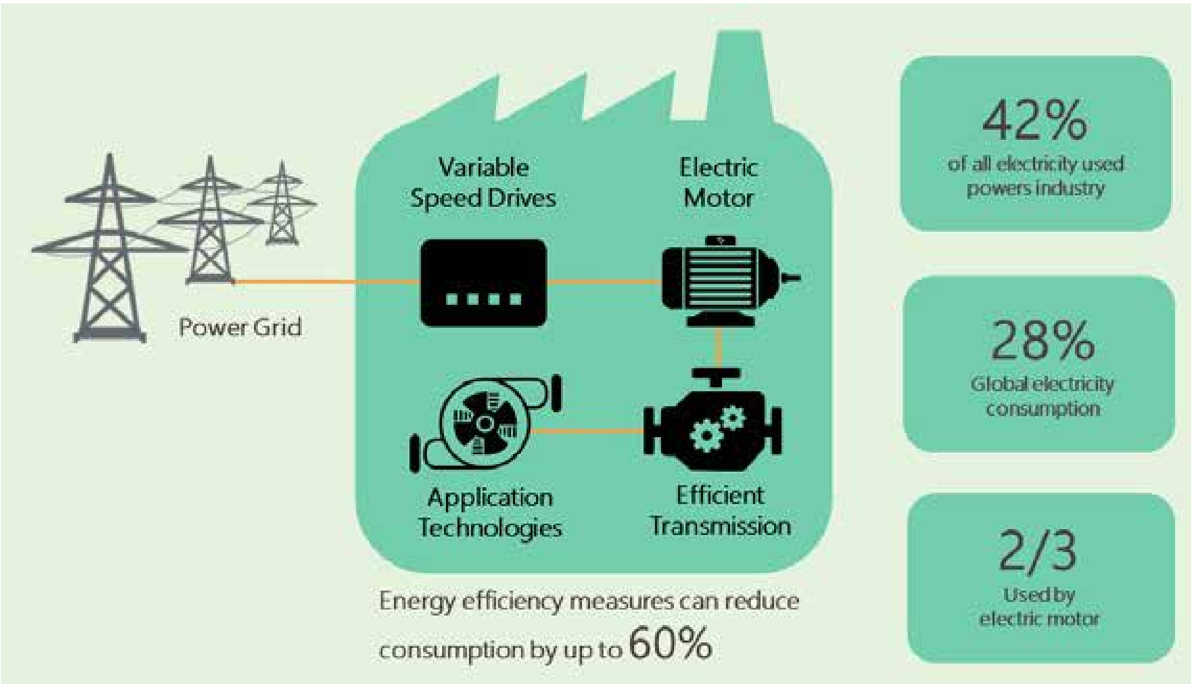

Figure 4: VSDs based improved energy savings

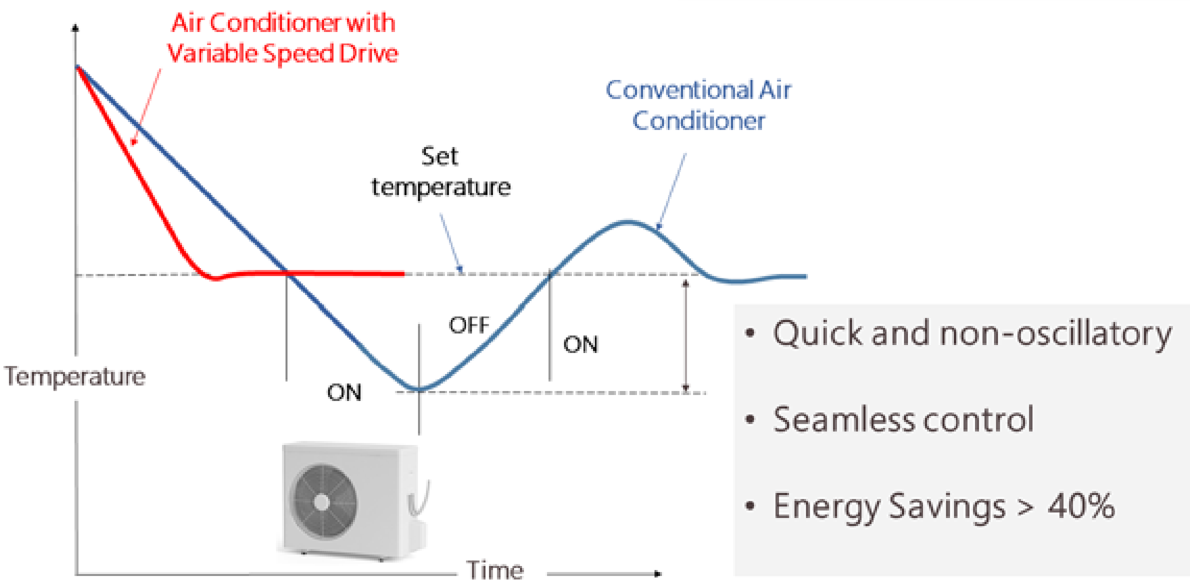

Figure 5: Variable speed drive in air-con

The energy use by data centres grew by a whopping 90% between 2000 and 2005 and 24% between 2005 and 2010. What's more impressive is, that between 2014 and 2020, the data centre energy use increased again by only 4% (8). This massive energy savings accomplishment occurred due to the efforts of giant internet companies (such as Google, Amazon, and Facebook) to stay focused on making their data centres operate more efficiently.

Such massive gains were achieved mainly due to innovative energy management means including energy-efficiency software, automatically switching to a low-power state at low utilisation rates, outdoor air cooling, and advanced power electronics. Power distribution to IT equipment in a data centre is accomplished using AC or DC power. AC power is distributed at the voltage of 120 V, 208 V, or 230 V. DC power is typically distributed at the telecommunications standard voltage of 48 V. Most existing installations use AC distribution; however, the use of DC power is gaining interest since it improves electrical efficiency when some steps of power conversions are eliminated, resulting in reduced losses. Typical data centre power distribution is shown in Figure 6, where many of the components in such AC distribution including double conversion UPS and PDU can be removed if the distribution platform is DC.

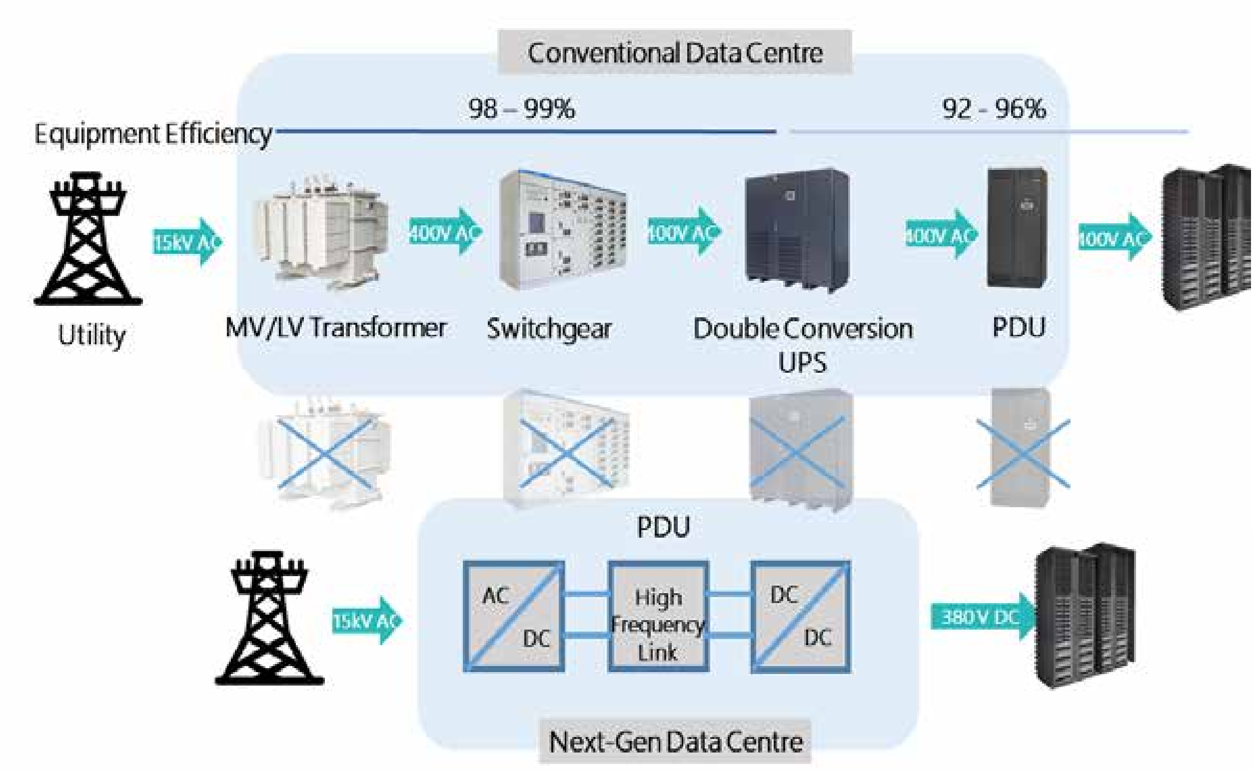

Figure 6: Typical Data Centre power distribution using AC

The various advantages of using advanced power electronics & DC power include fewer power conversion stages, smaller cable sizes, improved redundancy through distributed energy storage, reduced component counts, and reduced space requirements providing more server area space for actual end use.

Transportation (Land, Air, Sea)

Transportation as a whole is estimated to be responsible for over 20% of the world's CO2 discharges, with aviation and shipping contributing 2% & 3% respectively, and road transport contributing to the rest. Electrification of road transport, and more electric aircrafts as well as ships are considered to be very significant opportunities for emissions reduction. Application of power electronics in automotive applications plays a major role in controlling automotive electronics including modern electric power steering, main inverter, central body control, braking system, seat control etc., as shown below (Figure 7).

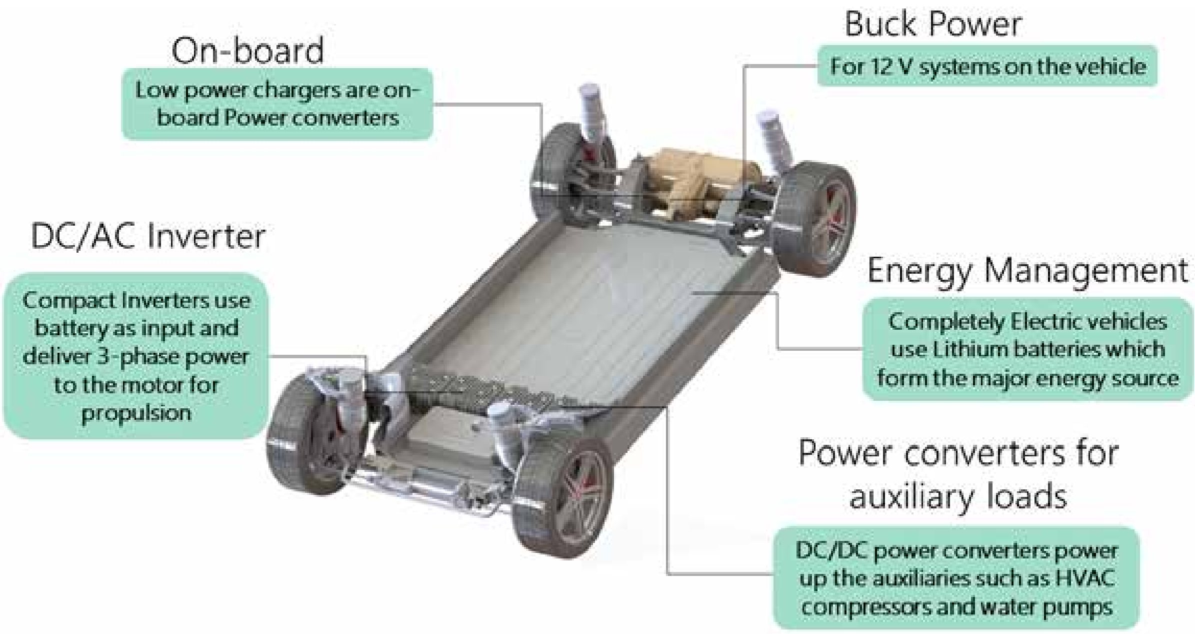

Figure 7: Power electronics in automotive applications

Application of power electronics in the automotive power generation system provides automotive alternators with improved efficiency and high power, along with high temperature withstanding capacity and high-power density. There is a variety of research in designing alternators with switched mode power electronics applications. Power electronics finds applications in four main areas of hybrid power trains: Regenerative braking (AC/DC conversion), On-board charger (AC/DC), Dual battery system and control (DC/DC), and Traction motor (DC/AC). The HV-LV DC-DC converter shown in Figure 7 supplies the 12 V power system from the high voltage battery. The on-board charger helps to charge the battery in EV using a standard power outlet. The main performance factors of these power converters involve efficiency and a high power density for a small form factor. The future design trend is towards an advanced bi-directional charging capability, where the charger feeds power from the battery back to the grid.

Recent years have witnessed increasing progress in the design of high performance controllers for AC motors. Still, the power stored in the battery (HEV/EV) or fueled by petrol must be converted from DC to AC in order to run AC motors. Most commercially available automotive power converters use silicon (Si) based semiconductor devices as switches. The power converter controls turn on/off the Si switches so that the output voltage waveforms meet the desired type (DC or AC), magnitude and frequency (typically for AC it is 50/60Hz). Based on how fast the Si devices can be cycled on and off and the power converter topology, the quality of the output waveform can be very different. Currently Si devices used for high power applications (~100kW - MW) cannot be turned on or off at a fast rate (not beyond few kHz). The switching frequency is limited because of high losses associated with increased switching, and delayed turn off results in high voltages which may damage the semiconductor devices. Thus, most Si based converters are operated at lower frequencies resulting in output voltage waveforms with higher harmonics and noise content.

In order to reduce these harmonic distortions to acceptable levels, large filters with huge inductors and capacitors are used. Since filters are rated for high power, there is significant filter loss, in addition to the Si device conduction and switching losses. This lowers the efficiency and escalates the need for extensive cooling system to manage the operating temperature of the devices. Additionally, in automotive applications, the external environment is very harsh that makes cooling even more complex and bulky. To avoid Si devices from getting damaged, it is necessary to ensure that the converter operating temperature is always below 125°C. Large heat sinks, bulky filters and extensive cooling systems further increase the weight and size. The wideband gap devices, specifically Silicon Carbide (SiC) and Gallium Nitrite (GaN), have been used for several years in Radio Frequency (RF) applications, and low power applications. Recently, several investigations were undertaken to explore their utility in high power applications like electric car chargers, electric drive train power electronics, etc. These new devices could revolutionize the way in which high power converters are designed and built. The many advantages of advanced power electronics based on SIC are captured in Figure 8, including improved efficiency, size reduction and higher power density.

Advanced Power Electronics is the enabling technology that makes this process possible and more efficient. A High Voltage (HV) DC line runs from the battery to the sub-systems and the components of the HEV system. An inverter will convert direct current (DC) from the car's batteries to alternating current (AC) to drive the electric (traction) motor that provides power to the wheels. The inverter also converts AC to DC when it takes power from the generator to recharge the batteries. In the transportation context, they find applications in chargers and drive train applications for hybrid and fully electric cars. In high frequency chargers, it could reduce the charger footprint, lower parasitic & switching losses, and lead to fast charger designs. For drive trains, GaN devices may not scale up to the voltage and power levels needed for drive train converters and SiC may be a better choice. These devices could also find applications in aircrafts, ships and electric train power electronic converters. The future of using GaN and SiC devices in transportation electrification seems to be very promising due to the clear advantages, like lower losses and smaller footprint. However, to realise these advantages in practice, research and development (R&D) is required to specifically address improvement in systems reliability and efficient device packaging.

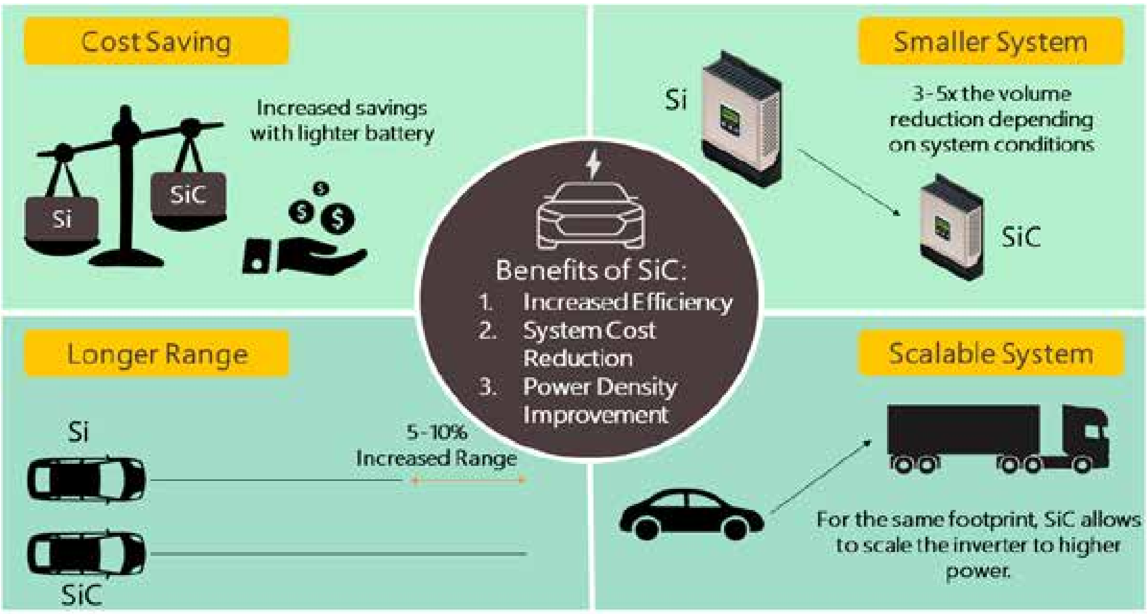

Figure 8: Benefits of advanced power electronics in automotive segment

Power electronics R&D in DC fast charging is helping the EV industry to take the charger out of some vehicles and put it off board for some driving applications. This space constraint of an on-board charger along with the time to charge which ranges from 4-5 hours is the motivation factor for the research and product development in DC fast chargers. Typical charging systems for the AC level 2, DC fast charging and wireless charging, which are recently getting popular for the ease of charging are shown in Figure 9.

DC Fast Charging bypasses all the limitations of the on-board charger and required conversion, and instead provide DC power directly to the battery, which has the potential to significantly increase the charging speed. DC fast chargers can provide up to 400 kW of DC output power (typically from 400 VDC to 1000 VDC), converting three-phase AC power sourced from the electrical grid into DC power using highly efficient power semiconductor devices.

This high output power can charge fully depleted batteries on most vehicles to 80% of their full charge in maximum 30 minutes. The charging time is a direct function of the DC charging voltage and the power output. The relation is almost linear between the tradeoff of higher power to charging time. If a 50 kW charger typically takes about 50 mins charging time, a 350 kW charger roughly takes 1/7th the time. Typical of such DC fast chargers would be buck-boost dc-dc converter with controlled pre-charging of the HV DC link and intelligent power and battery energy management. Along with this, the voltage range of DC bus in the range of 600 V – 1000V enables easy interconnection with the grid through a bi-directional inverter to aid power flow from EV to grid for improving its dynamic stability. The future roadmap for EV Charger systems is to bring down that charging time to the same time as filling a traditional vehicle's gas tank. The larger the size of the electric motor and the energy storage system, the higher the functionality and fuel efficiency (FE) benefit. One process that is common across all the HEV systems is the conversion, storage and later usage of energy. Advanced Power Electronics is the enabling technology that makes this process possible and more efficient.

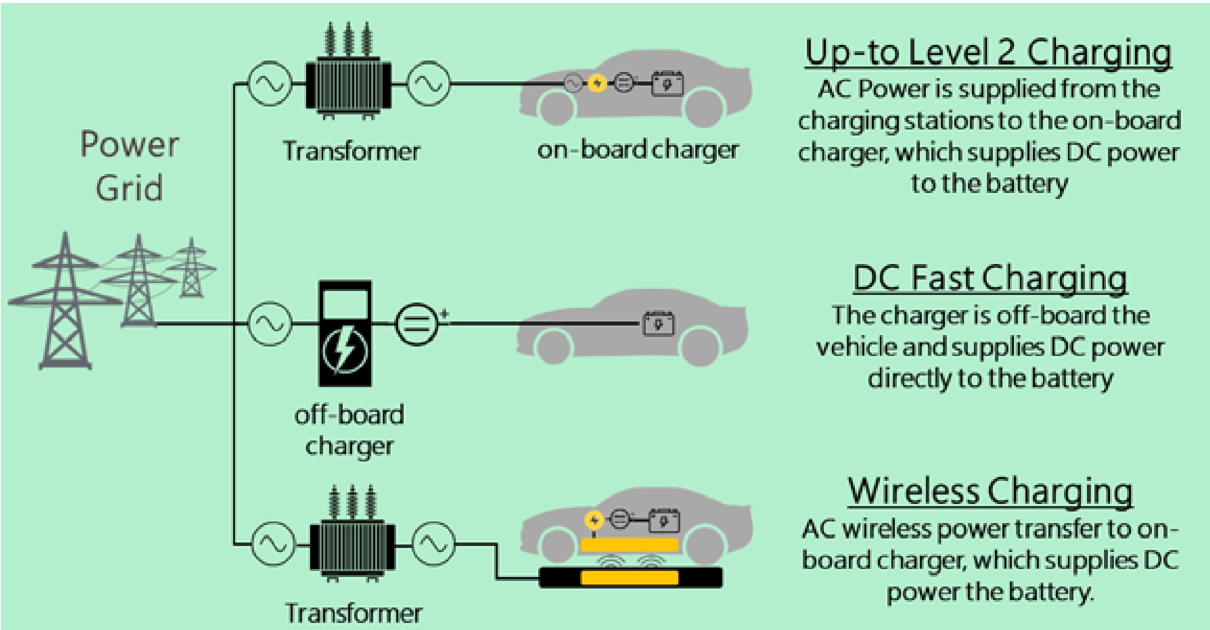

Figure 9: AC level 2 and DC fast charging system structures

High Voltage (HV) DC line runs from the battery to the sub-systems and the components of the HEV system. An inverter will convert direct current (DC) from the car's batteries to alternating current (AC) to drive the electric (traction) motor that provides power to the wheels. The inverter also converts AC to DC when it takes power from the generator to recharge the batteries. Advanced power electronics plays a key role in redesigning aircrafts and developing fully electric planes. Advantages of electric aircraft and more electric aircraft (MEA), include improved manoeuvrability due to the greater torque from electric motors, increased safety due to decreased chance of mechanical failure, less risk of explosion or fire in the event of a collision, and less noise. There would be environmental and cost benefits associated with the elimination of consumption of fossil fuels and resultant emissions. In aerospace systems, power electronic related integration issues are - the level of power and mission dependent high temperature ranges, weight and size, electromagnetic interference and high performance. Resolution of these issues are critical for further progress in MEA. A schematic representation of MEA is shown in Figure 10. The concept to drive aircraft subsystems with electrical power in lieu of mechanical, hydraulic and pneumatic means is the More Electric aircraft. The end objective was to eliminate the need for gearboxes.

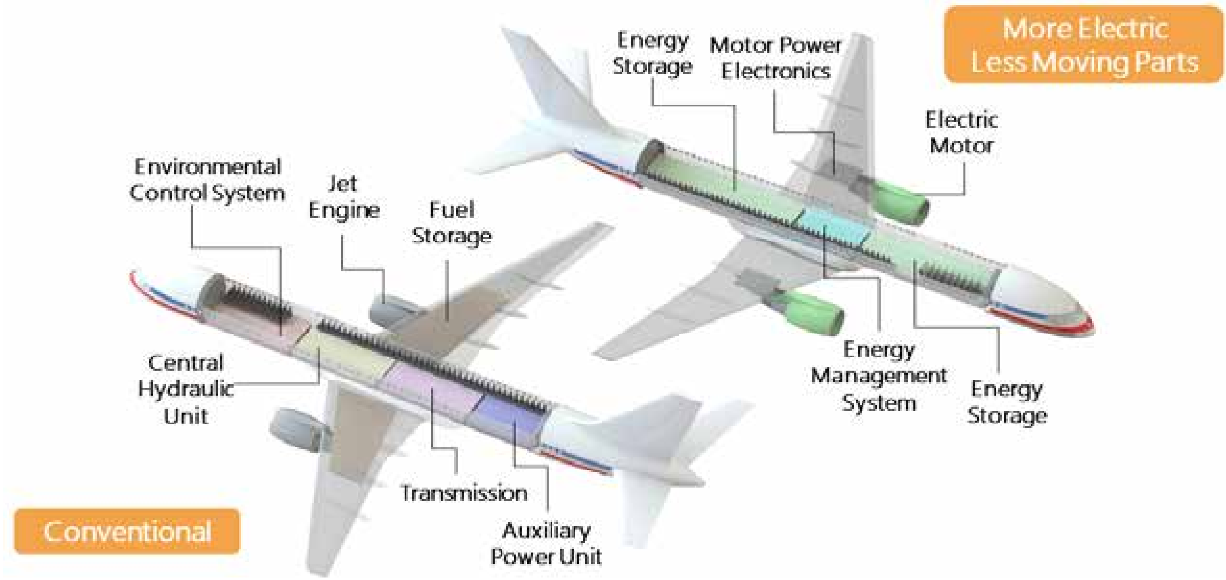

Figure 10: Conventional Vs More electric aircraft

Power electronics provides the means to convert electrical power to drive motor driven actuators, fuel pumps and other subsystems at variable speed. A typical MEA has the components controlled through various power electronic modules used with PV arrays, battery and battery charge and discharge control units (BCCM, BDCM), low voltage converter modules (LVCM) and the main power distribution unit (PDU). Shipping facilitates around 90 percent of the world trade. Facing tight environmental regulations, the shipping operators and port authorities have to look for ways to reduce emission and noise levels. In the majority of ports, ships at berth use their diesel generators to run amenities such as heating, ventilation, cooling as well as galley equipment. Because of that, they produce noxious emissions which have a negative impact not only on the surrounding environment, but also on the global climate.

At the same time noise and vibrations from ships seriously affect the life quality of the local communities. Additionally, most ships' power generation units operate at a frequency of 60 Hz, whereas local grid in most parts of the world is 50 Hz. This means that providing ships with electricity requires a shore-side electricity supply arrangement. Advanced power electronics based Static Frequency Converters (SFCs), provide the means for a safe, economic and highly efficient solution to convert the grid electricity to the appropriate load frequency. The shore-to-ship electric power supply, also known as cold ironing, is the most reasonable and cost-effective choice for greener ports and fleet. The solution enables ships to shut down their diesel generators used to create onboard electric power and plug into an onshore power source while berthed. The leading-edge frequency conversion technology guarantees a seamless automated power transfer of the ship load from the onboard power plant to the onshore source and back.

This contributes to a significant reduction of fuel and lubrication oil consumption, which means less pollution and expenditure. Shore-to-ship power is especially applicable to ships operating on dedicated routes and vessels that consume large amounts of power while in port. This could bring real benefits for terminal operators whose ferries berth daily for a fixed number of hours. Shore power or shore supply is the delivery of shore side electrical power to a ship at berth while its main and auxiliary engines are turned off. The objective is to provide a system including a power converter for converting shore power to shipboard use which is easy to use and cost effective. Such a solution is depicted in Figure 11, where the electricity from shore is used to power auxiliary services of the ship at berth and is more environmentally friendly compared to diesel sets. In such a system, a power electronics converter is used, which can convert shore power to shipboard use and also transfer the ship's main power distribution to the AC shore power without interrupting power to various shipboard electrical components.

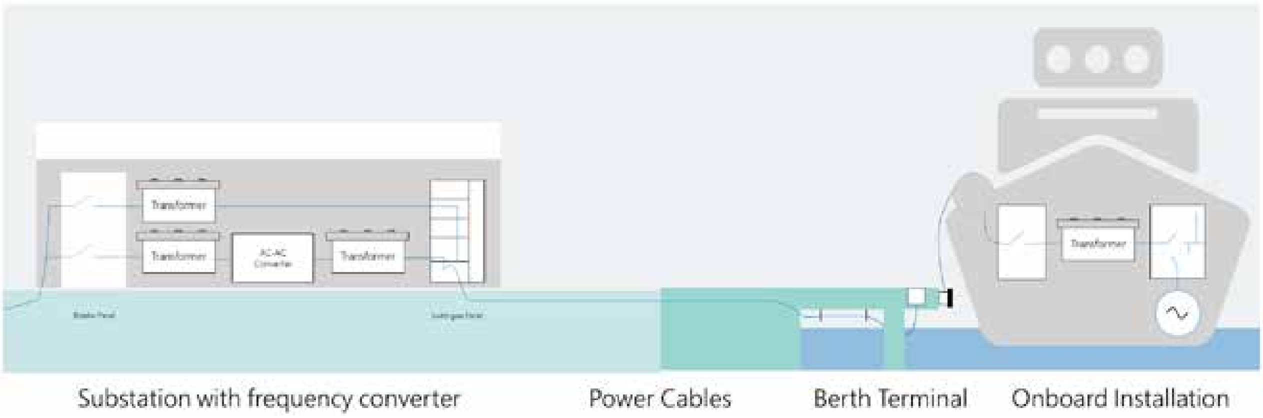

Figure 11: Shore power system based on power electronics

The primary objective of the shore power system is to provide power converter for converting shore power (at shore frequency and voltage) to shipboard use (at ship required frequency and voltage) and to transfer the ship's load from one power path to another without interrupting power to various shipboard electrical components and which can be used in ports around the world.

In terms of on-board ship electric distribution system, DC power distribution in ships is gaining attention. DC based grid power system has following benefits compared to the AC-grid in terms of the power stability and quality aspect.

- Freedom of the reactive power (increasing power stability)
- Freedom of the frequency (easy synchronising of power sources)
- DC-based power distribution (reducing harmonic distortions and increasing power quality)

In addition, it is effortless to integrate DC power sources (e.g., fuel cells, lithium–ion batteries, supercapacitors, etc.) into a DC-bus. Especially, the ESS could be used for various purposes: peak shaving, load levelling, absorbing regenerative power, etc. Therefore, the ESS can reduce gensets' running time and improve energy efficiency. Besides, it can also contribute to reducing the maintenance cost of gensets. Similar to MEA, more electric ships (MES), are enabled by the various improvements in power electronics for enabling high voltage and also possible DC distribution. Hybrid electric and fully electric ships are slowly on the rise due to several advantages including reduction of emissions.

In hybrid systems, the electricity is derived from diesel generators and batteries. With higher dense energy storage systems, and advanced PE, the conversion efficiency is moving higher along with the possibility of DC distribution enabled by higher energy efficient architectures. PE driven variable speed drives have also become efficient from both converter and motor perspectives, advanced by SiC devices, PM motors and high frequency electromagnetics. With such DC based systems, the present transformer based AC interface can be removed. With high voltage power conversion, the step down gear can be removed and the generator can be directly integrated with the prime mover to operate at the same speed. With increased voltage using SiC, at the same power level, the MES can be designed for reduced weight, size and cost.

SMART GRIDS

Alternating Current (AC) has been the conduit to transfer electrical energy from power plants to all kinds of industrial and household loads. Conventionally, this mechanism has been well understood and adapted worldwide. The unidirectional power flow architecture that directs electrical energy to flow from generating power stations to load has remained almost unchanged for over a century or more. However, recent global awareness regarding climate change and sharp reduction in costs of renewables (e.g. solar and wind) and energy storage (e.g. lithium ion batteries) have led to increasing renewable energy sources being connected to the network in a distributed manner. Greener technologies for more efficient power generation, distribution and delivery in different sectors are also spreading as a response to the need for mitigation measures for climate change.

Globally, 5.9TWh of renewable energy was produced in the year 2016, representing a 5 to 6-fold increase since 1960s. Renewable energy growth is expected to increase further in the near future to 36% of total energy share by 2030 and to 65% of total energy share by 2050. Electric car sales are projected to bypass internal combustion engine cars by 2030. In addition to these distributed sources of generation and loads, recent years have also seen a very significant advance of digital technologies. These advances include smart meters, communications networks, and data management systems that enable two-way communication between utilities and customers. Better monitoring and control have enhanced both energy efficiency and reliability. The conventional Power Grid is thus migrating to that Smart Grid, which may be viewed as an electricity network that enables integration of renewables and uses smart technologies to better serve consumers.

While the Smart Grid offers a very significant advance over the conventional power grid, its key limitation is that although the flow of communications is bi-directional, the flow of energy remains unidirectional. With the confluence of renewables, energy storage and distributed loads (e.g. electric cars), the grid can no longer operate with the conventional idea of unidirectional power flow and both generation and consumption will be carried out at multiple nodes of the network. It needs a radical change to accommodate such renewable energy sources which can be integrated at any point of the transmission &/or distribution network. The Smart Grid 2.0 (SG2.0) is envisioned to be a technology leap that will usher in the Internet of Energy (Figure 12), with the capability to manage millions of connected devices at all levels of the grid.
Seamless connectivity and on-demand energy routing will replace the conventional unidirectional flow of energy. The modernisation of soft components involves advanced digital information and telecommunication technologies. SG2.0 will be smarter because of its ability to physically route and control various forms of energies and different pockets of generation to the ever-changing nature of connected loads. Such loads have evolved over time and have been embraced globally because of the immense potential of overall energy efficiency in the offer. To be able to rapidly communicate, enabled by evolving power electronics, has been at the heart of this disruptive technological breakthrough that facilitates a paradigm shift in the energy economy. Integration of fast communication and rapid routing of energy through electronic circuits will allow controlled energy management and power regulation. Power electronics will remain one of the most crucial and evolving branches of Smart Grids and SG2.0 power industry over the next century.

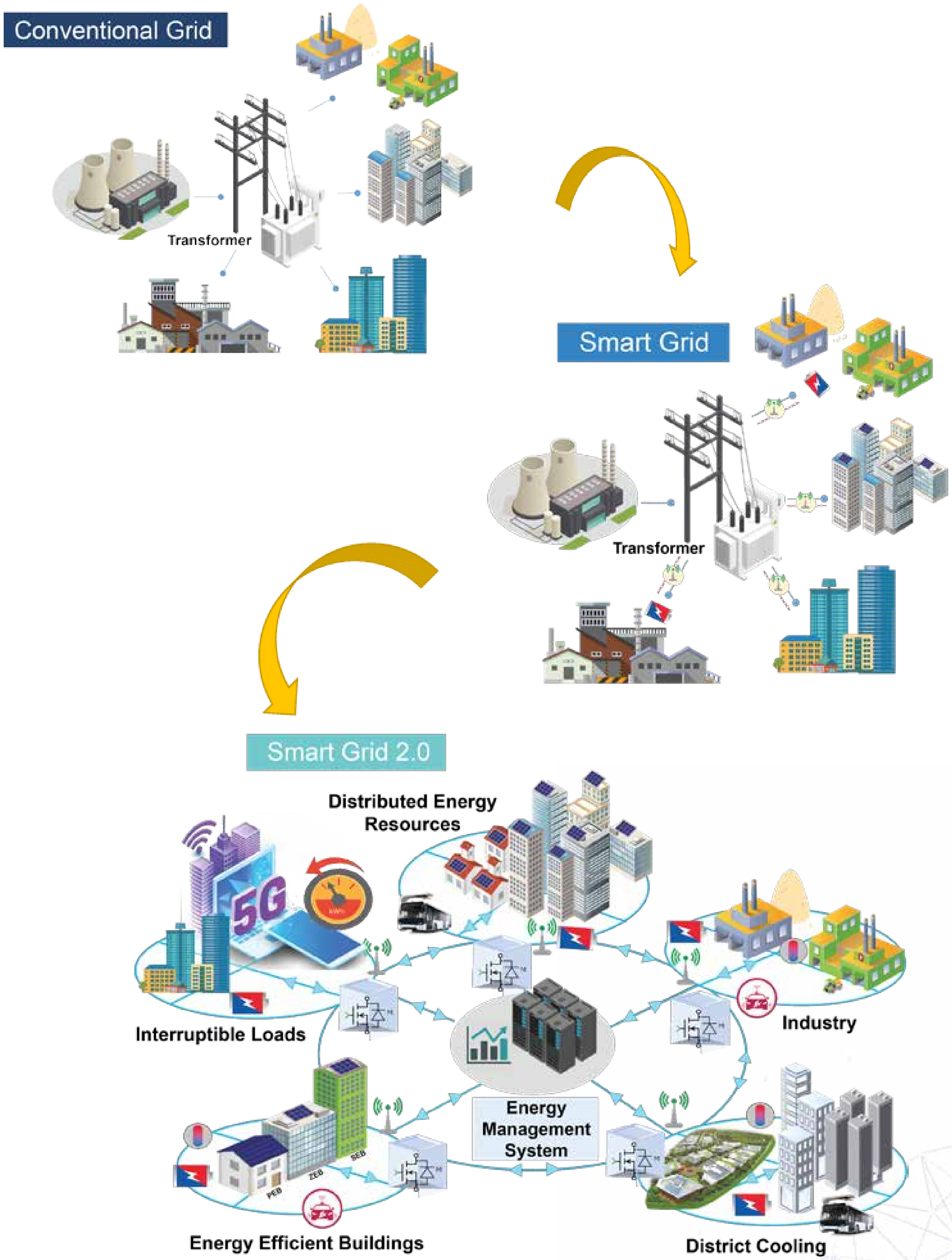

Figure 12: Conventional Grid vs Smart Grid vs Smart Grid 2.0. Smart Grid enables bi-directional information flow (red dotted line), Smart Grid 2.0 enables bi-directional flow of both energy and information (blue arrows)

The latest power electronics market forecasts an increase of 60% for low-voltage technologies (below 900 V) by the year 2020, accompanied by an approximately 100% market increase for medium (1.2–1.7 kV) and high voltage (2 kV and above) technologies (Lacopi, 2015). The power electronics revolution has created a base for a world rigorously working towards greener technologies: improved energy conversion efficiencies, faster switching, more compact, and lighter systems with better thermal management. Smart Grid offers control of power that plays an important role in modern industrial automation and high-efficiency energy network that includes renewable energy systems (viz. photovoltaics, wind energy), bulk energy storage, electric as well as hybrid vehicles, and energy-efficiency improvement of existing electrical equipage.

In modern electric power grid, power electronics is vital in high-voltage DC (HVDC) systems, static VAR (Volt-Ampere Reactive) power compensators (SVCs), flexible AC transmission system (FACTS)-based active and reactive power flow control, and uninterruptible power system (UPS) to name a few. HVDC provides long distance, low-loss transmission (vs AC transmission), and FACTS (Flexible AC Transmission systems), which includes the family of controllable high power devices (viz. SVC, static compensator or STATCOM), and enables improved, more stable & more economical utilisation of power systems.

On the other hand, SVCs are beneficial for increased power transfer capability by maintaining a stable voltage profile under different network and load conditions, thereby improving dynamic stability of the grid. Power electronics for these applications have been mainly based on Thyristors and IGBTs. However, recently advanced power electronics based on SiC are gaining popularity due to various benefits including better power density and system efficiency. All of these components / sub-systems (e.g. FACTs, STATCOMs, voltage / power transfer & power flow converters, and compensators) bring the following benefits to Smart Grids:

- Improved power quality
- Compliance to grid codes of various countries
- Grid voltage stabilisation
- Improved power transfer capability, including those of existing assets
- Steady-state and dynamic reactive power compensation and voltage regulation;
- Steady-state and dynamic stability enhancement;
- Reduced fault current;
- Reduced transmission losses

SG2.0 is about a complete shift from both previous generation of hard and soft components of grid to its modernized digital version for enabling better integration of renewable energy resources. SG2.0 facilitates two-way power and information flow, more active consumer participation, improved quality of service and resilience of grids in a varied and challenging environment (Figure 13). It will also be more penetrating, and will be able to sense the system overloads and reroute the power to prevent or to minimize a potential outage. It will accept energy from virtually any fuel source and offer improved security and resiliency in case of natural disasters or threats. It also will allow real-time communication between the consumer and utility, ushering in a new era of consumer choice.

Furthermore, it will leverage upon advancement of power electronics to make the distribution network more efficient in terms of both energy and space occupied and explore the possibilities for housing some of the components of the power grid at remote underground locations. The modernization of soft components involves advanced digital information and telecommunication technologies. Business intelligence (BI) reporting solutions of the smart grid will migrate to the real-time and predictive analytics. The advanced IT offerings include consumer behaviour analytics, time of use-pricing analytics, cloud-based solutions and most importantly the Internet of Energy. The Internet of Energy intends to link the distributed generation, energy storage and loads to build an energy grid with information flows and power flows simultaneously and bi-directionally. SG2.0 will facilitate integration of renewable energy systems, thus promoting migration towards a fully decarbonized electricity generation.

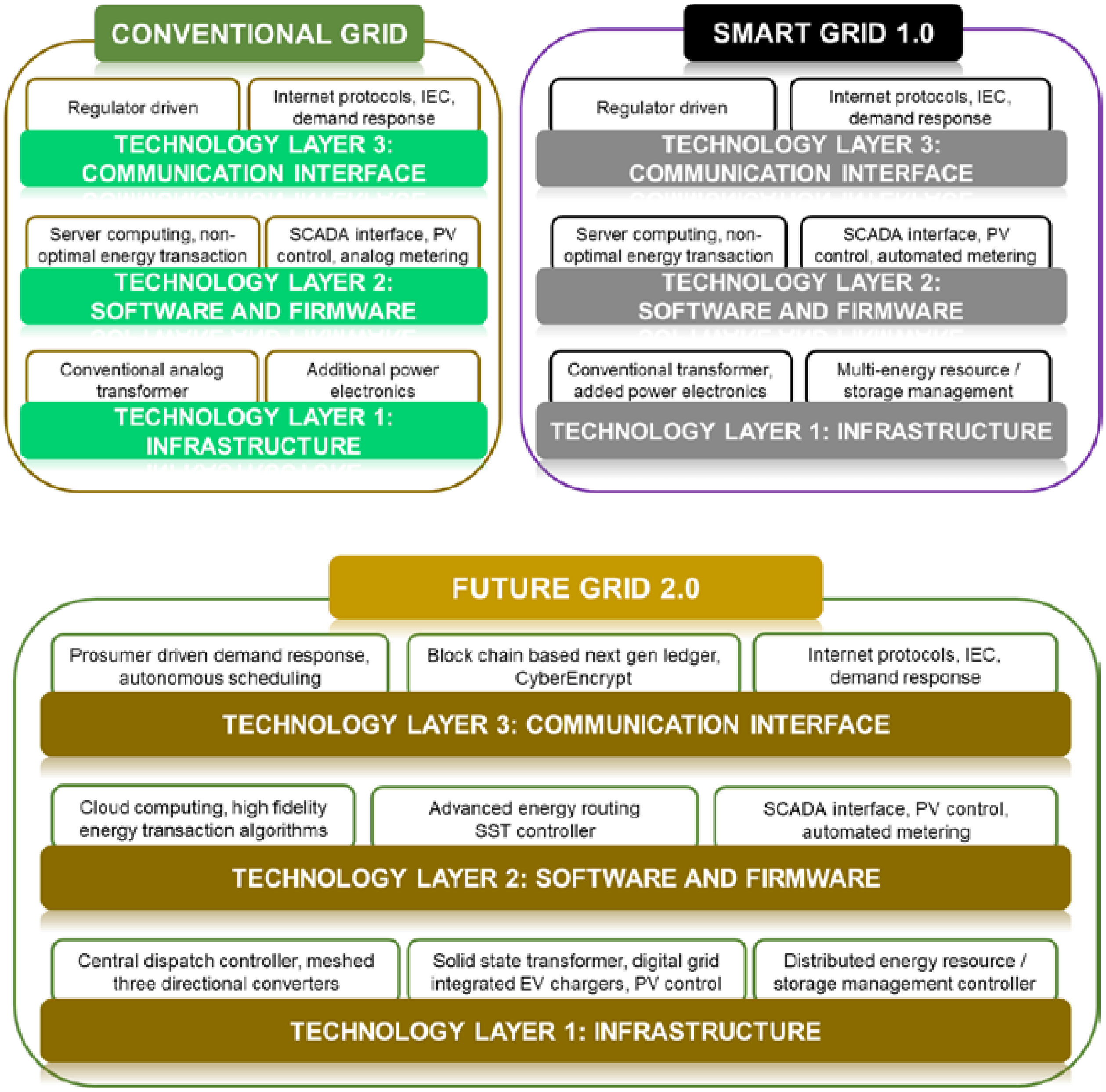

Figure 13: Enablers of SG2.0

Smart use of carefully designed advanced power electronics equipment will form a controlled interface between various sections of a distribution power network. Such equipment will function like conventional transformers but will have a capability to seamlessly route and control the flow of both AC and DC energy sources and loads. This evolving power electronic equipment, solid state transformers (SST), will enable energy efficient integration of distributed energy systems (sustainable power system blocks comprising of renewables, energy storage and DC/AC loads) with the main distribution network. This defines the next generation of power system architecture, as depicted in Figure 14.

An SST is an AC-to-AC and AC-to-DC power conversion equipment combined in one unit. In its modern form, it will use semiconductors such as SiC for its fabrication. A conventional transformer operates at line frequency of 50 Hz/60 Hz and therefore is called line frequency transformer (LFT). Due to its low frequency of operation, an LFT is very large in size and can only handle AC power transfer. For DC integration, many other conventional power electronic equipment are needed. This adversely affects the system efficiency accompanied by a large (spatial) footprint. An SST on the other hand can be much smaller and more efficient than a conventional LFT based AC/DC system. This is because, major power conversion is executed at very high frequencies and additional equipment is not required for DC sources or DC loads. SSTs can be used for regulated power routing from distributed sources to either AC or DC loads.

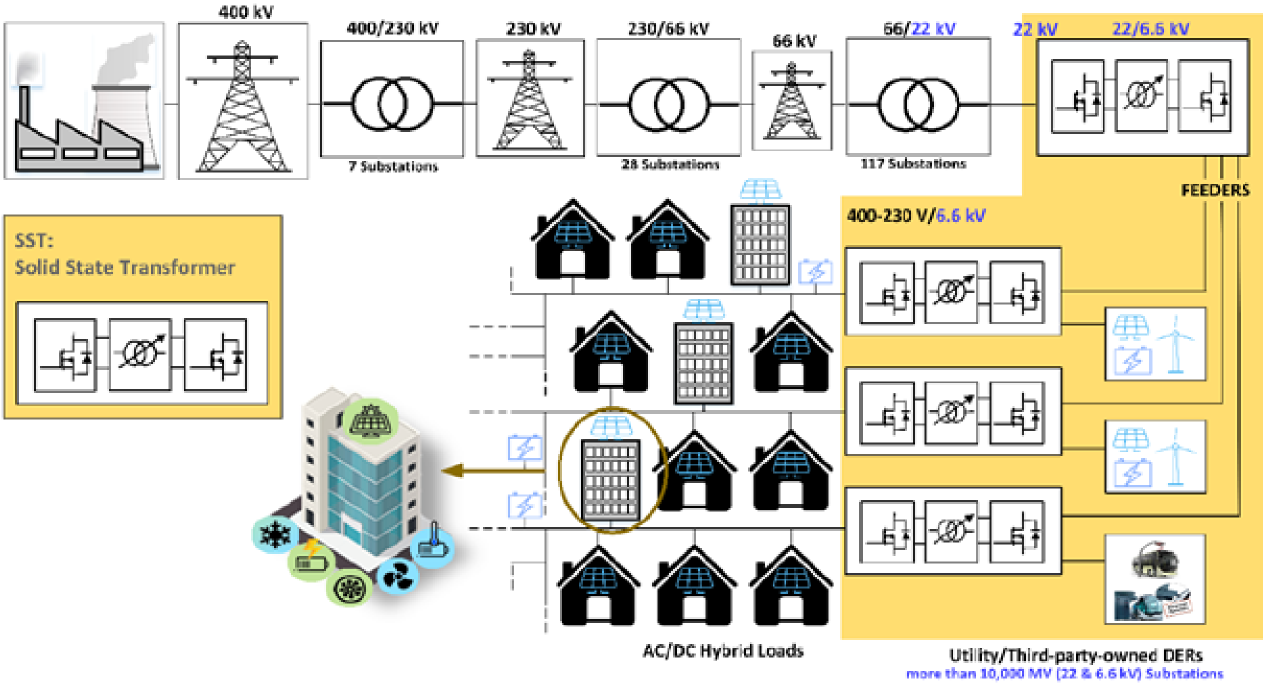

Figure 14: SST based advanced substations integrating a mixed (AC/DC) source-load eco-system

A solid-state transformer usually contains a very high frequency transformer (Figure 16), inside the AC-to-AC converter or DC-to-DC converter, which provides electrical isolation and carries full power. SSTs can actively regulate voltage and current. They can be designed to convert single-phase power to three-phase power and vice-versa and can input or output DC power to reduce the number of conversions, for greater end-to-end efficiency. SST offers several functionalities in smart grid configurations including, protecting loads from power system disturbances, protecting power system from load disturbances, integrating energy storage systems (energy buffers), providing DC ports for interconnections of distributed generation and supporting voltage and power profiles. SST can play an important role in realising the DC/AC zonal power distribution system and can be the link for the micro-grids to the medium voltage transmission system as well as low voltage AC and low voltage DC systems as described in Figure 15.

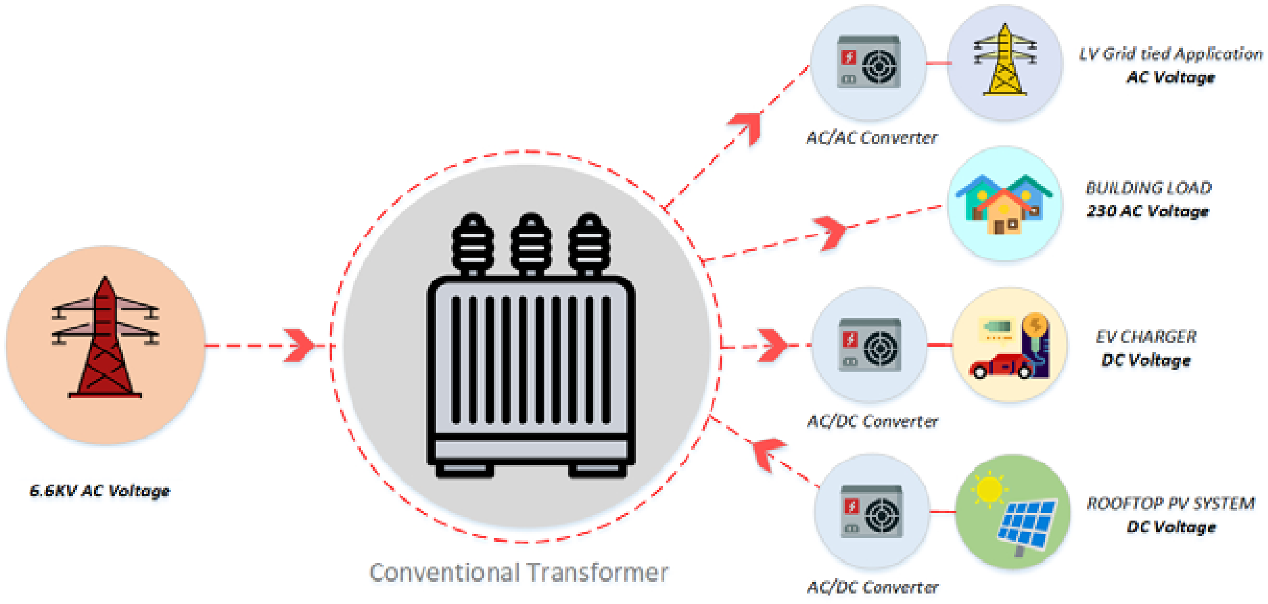

Figure 15: Conventional smart grid 1.0 (communication devices external to the transformer)

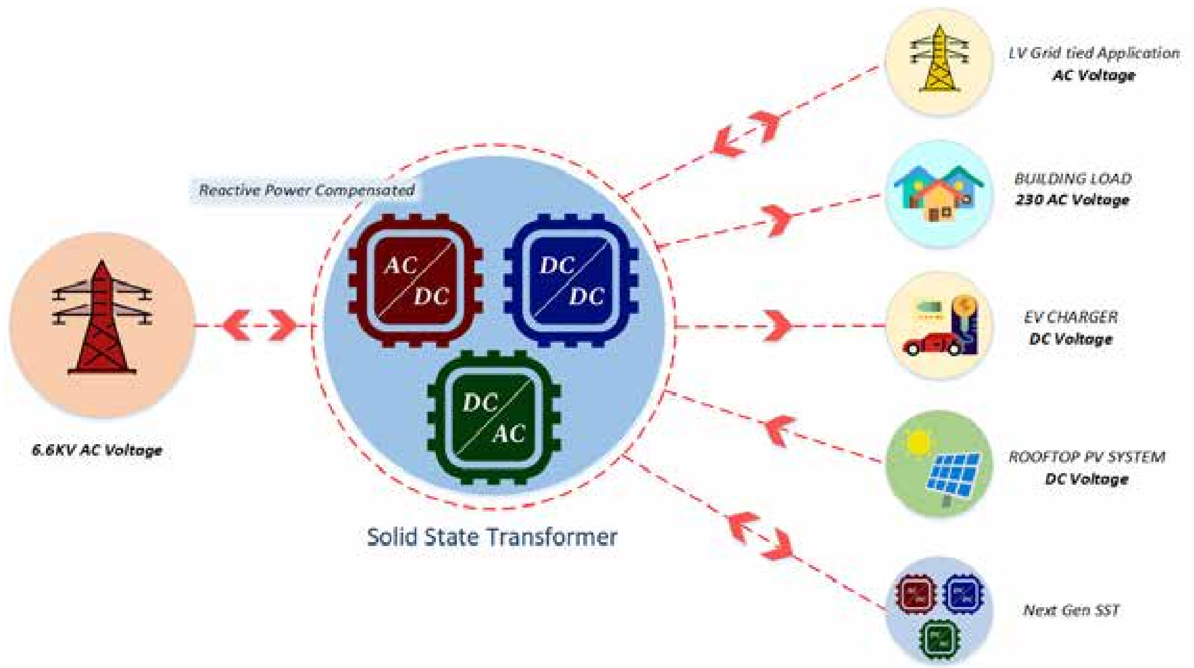

Figure 16: Grid 2.0 using solid state transformer

Because of their design, SSTs do not have large current losses and thus generate less heat than the conventional transformers with a similar power load. SST can enable power transfer from medium voltage to low voltage or DC/AC loads at a substantially reduced weight and size for the same power rating. With advanced power electronic components (e.g. SiC MOSFETs), seamless voltage regulation, and active & reactive power control is possible without the need of additional auxiliary devices. Voltage, frequency and other transients can be remotely controlled leading to a more resilient distribution power network.

The architecture of the conventional grid including smart grid 1.0 is shown in simplified manner in Figure 15. Here the MV is stepped down to LV of about 415 V, and then is used directly to AC loads or is interfaced with multiple converters depending upon the end use to the concerned application. Similar architecture platform using solid state transformer for distribution is envisaged as in Figure 16.

	Conventional	Smart Grid	Grid 2.0
Bi-directional Energy Routing	✗	✗	✓
Seamless integration of solar with additional components	✗	✗	✓
Efficient and controlled power factor operation	✗	✗	✓
Zero blackouts with ESS integration	✗	✗	✓
Underground distribution substation installations	✗	✓	✓
High voltage DC transmission enabler	✗	✗	✓

Table 1: Grid 2.0 benefits for Singapore

The Grid 2.0 architecture shows considerable advantages and flexibility in a relatively more compact footprint. Some key advantages are elimination of conventional 50 Hz transformer, several power conversion stages and complexity of control. Various functional benefits of Grid 2.0 based distribution network for Singapore are summarised in Table 1.

The advanced functionality is being developed and tested in the Energy Research Institute @ NTU (ERI@N) in a state-of-the-art test facility, (Figure 17.) SSTs will be deployed in applications such as renewable integration, seamless integration of PV in Singapore and also aid in possible underground substation development which will free up premium land space.

Figure 17: ERI@N's SST R&D lab at CleanTech One

CONCLUDING REMARKS

Climate change has emerged as the preeminent threat that could destabilise global systems with the onset of sea level rise, extreme weather events, and extreme temperatures affecting every aspect of our civilisation. A global consensus is growing towards a carbon free economy encompassing a holistic approach of sustainable growth and security of energy supply. Clean energy and energy efficiency form the key elements of this strategy. Power electronics is seen to be the disruptive technological breakthrough that facilitates a paradigm shift towards an energy transition to clean energy as well as a major enabler for electrification and energy efficiency. Power electronics enable extremely efficient conversion of electrical power, provide optimal conditions for transmission and distribution, and enable system level digitalisation. Thus, the amount of electricity processed by power electronic components, viz. SiC and GaN, will double over the next decade, reaching up to 80% by 2030.

Domains where power electronics is envisaged to make major impact include - Smart & Sustainable Buildings, Industrial Energy Efficiency, Transportation, and Smart Grids. In the buildings sector, power electronics can provide between 15% - 90% savings in areas including lighting, air-conditioning, escalators, plug load management, and integration of renewables. In the industrial sector, up to 60% energy savings is possible in drive systems for electric motors as well as data centres. Power electronics is considered to be indispensable in applications ranging from hybrid / electric vehicles, more electric aircrafts, and ships. The internet of energy with bi-directional energy flow between all components and systems will be made possible with solid state transformers that rely on advanced power electronics.

The global market for power electronics has approximately grown at a compound annual growth rate (CAGR) of 6.9% between 2014 and 2019 reaching ~$16 billion in 2019. As the devices available reach higher power ratings, viz. 1.7 kV in 2015 to >12 kV by 2024, the application domains in electric vehicles, renewables, industrial & rail systems, and eventually the power grid will reach technological maturity and will achieve economies of scale. With widespread adoption, costs of power electronics will drop over 40% by 2022 and system level cost parity will be achieved over the next 3-7 years, thus accelerating deployments and advancing the renewable energy and energy efficiency deployment strategies. As a signatory to the Paris agreement, Singapore has committed to curtail emission intensity by 36% from 2005 levels by 2030. Besides power generation, emissions contributions of ~17% emanate from the buildings and transportation sectors and ~60% emissions are attributed to the industry sector.

As the 2050 emissions targets are being considered, the key strategies include deployment of solar photovoltaics on rooftops along with floating solar on reservoirs / ocean waters, electrification of transport, energy efficiency, and long-term deployment of hydrogen for generation & transport. Power electronics will be a very significant contributor in these deployments. Significant research and development efforts are ongoing in the Institutes of Higher Learning in Singapore, which include exploring the use of advanced power electronics in applications ranging from solar PV optimisers / inverters, AC / DC grids, power supplies for electric vehicles, building automation, and solid state transformers for Smart Grid 2.0. Deployments of power electronics will promote energy efficiency, power quality, grid resilience, and will also optimise the use of real estate. Singapore's energy policy is based on three core dimensions: Energy Security, Energy Equity, and Environmental Sustainability. It aims to achieve on all these three dimensions as they cannot be thought of, in isolation.

The global energy landscape is changing, and it's changing fast. By 2050, 40% of the end-use of energy would be in the form of electricity. Power electronics will thus form the foundation of this change. Power electronics components, viz. SiC and GaN, are making rapid strides in market penetration and applications ranging from drives for industrial equipment to applications for smart grids are being actively pursued. As the world invests in new technologies for mitigation of climate change, power electronics will usher in a new paradigm as a cornerstone for both energy transition and energy efficiency.

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