DC Is the Future

By NESIMI ERTUGRUL, *Member IEEE*
School of Electrical and Electronic Engineering, The University of Adelaide, Adelaide, SA 5005, Australia
DEREK ABBOTT, *Fellow IEEE*
School of Electrical and Electronic Engineering, The University of Adelaide, Adelaide, SA 5005, Australia

For ac electricity grids, the aim has always been at low-cost and disruption-proof solutions. The power grid is inherently vulnerable to environmental disturbances. However, the introduction of power electronics (PEs) and changes in load and generator characteristics have introduced a game changer at an unprecedented pace over the last decade.

During this change, load specifications, load characteristics, and control and monitoring requirements for power system security have also dramatically evolved. Efficiency and reliability of system components have progressed in parallel with this evolution. However, high penetration of renewable energy sources has reduced the percentage contribution of conventional electricity based on synchronous generation, which affects grid stability and hence reliability. Furthermore, numerous camouflaged dc generators and dc loads are being embedded in ac and dc microgrids at ever increasing rates.

While embedded generation rapidly increases its share in the hybrid power grid (where ac and dc coexist), the current developments in PE switches—based on wide bandgap (WBG) technology—indicate that within the next two decades Max Planck's well-known sentiment that science advances one funeral at a time will repeat itself on the ac grid.

This article aims to summarize the technical developments and problems facing the utilization of ac during widescale electrification of the world using numerous distributed energy resources (DERs). Then, it will map out evolutionary changes toward a future dc grid.

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I. HISTORY OF AC POWER NETWORKS—OPERATIONAL PROBLEMS AND CHALLENGES

Just over 100 years ago, the ac electricity industry started to develop and reached wider communities in a short duration (see Fig. 1). Large-scale utilization of various major ac system components—such as transformers, transmission lines and towers, switching gear and circuit breakers, light bulbs, motors—underpinned exponential growth based on a centralized power grid approach. For many decades, a centralized ac grid offered, stable and reliable energy at relatively low cost. Electricity generation sources on the conventional ac grid were usually far away from load centers, requiring long-distance transmission and multiple step changes of voltage to reduce losses before reaching load centers.

The existing energy market has also evolved out of this centralized structure, which has been based on limited controllable generation and roughly predictable demand characteristics of conventional ac-only loads. However, as the utilization of ac increased and the load characteristics changed—mainly due to the introduction of PE devices—a very high imbalance now occurs between controllable generation (although slow, as in

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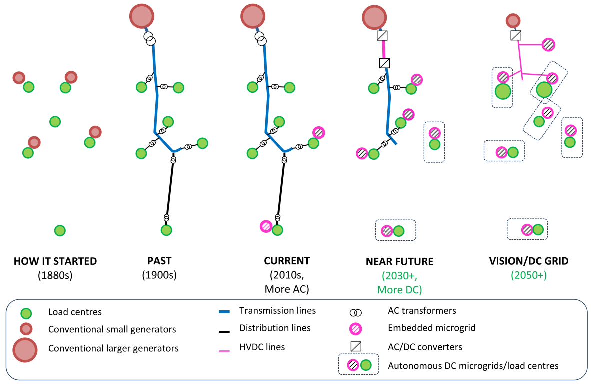


Fig. 1. ***Overview of the grid transformation timeline and the future.***

Table 1 Summary of Observed Undesirable Features and Negative Impacts of AC and the Factors Favoring DC Supply

UNDESIRABLE FEATURES OF AC
Regulation issues (voltage, frequency, and phase)
Synchronization and time delay
Impedance and reactive power
Four quadrant control
Power quality issues including harmonics
Large initial currents in motors, lines and transformers
Imbalance issues and sequence impedances (positive, negative, and zero)
Skin effect and losses
Inductive and capacitive coupling, and induced voltage
Limited stepped regulation via conventional transformers, unidirectional power flow
Multiple T/D lines and exposure to environmental factors
Conversion required to integrate DC sources, such as PV and wind
FACTORS THAT FAVOR DC
Drastic increase in number of DC sources and load types
Wide utilization of power electronics
Demand for high efficiency
Demand for accurate control
Demand for multiple DC voltage levels

minutes and hours) and unpredictable demand. This gives rise to the emergence of numerous problems and complexities on the ac-based grid, which continue to increase over time.

A. Limitations of the AC Grid

Table 1 summarizes the issues associated with ac supply. The major complication of ac supply is related to difficulty in regulation since the three parameters: 1) magnitude; 2) frequency; and 3) phase are simultaneously affected. The same three parameters are also the direct causes of the other limitations such as impedance, reactive power, power quality, and harmonics.

The problems associated with ac supply are amplified by the ever-increasing trend in renewable energy penetration and utilization of PE converters. These have now reached a level that cannot be ignored, as the present momentum in grid transformation leads to a chronic state in terms of ac power management. Note that a dc source does not demonstrate any of the negative factors listed in Table 1, except for a small resistive power loss.

Note that ac grid-connected rectifiers have significant losses—due to device conduction loss and front-end low-frequency transformers—and have very poor power factors and form factors, which are also the main sources of harmonic generation.

B. Changing Load Landscape in the AC Power Network

Load types have changed primarily due to technical developments and have been accelerated by improvements in economic wealth. The key driving factor in this change is not only controllability of the loads but it is also about energy efficiency, which is directly related to the power loss in the PE converter and the electrical load used. Table 2 outlines the changes in load characteristics and profiles primarily driven by the introduction of PE systems and renewable energy to the ac grid, which shift us toward a dc paradigm. This trend will increase exponentially via the introduction of new PE switching devices, which is likely to favor a pure dc network combined with smart dc appliances and devices.

Note that variable speed drives (VSDs), widely used in the industrial world, use rectifiers with large polarized dc-link capacitors, which are critical components as they increase cost, footprint, volume, and reduce the lifetime of the system. An immediate benefit of a dc grid is to eliminate the ac/dc front end, which will offer an increase in energy efficiency and reduce the impact of magnetizing current.

II. OPERATIONAL CHALLENGES IN HYBRID NETWORKS

Due to the undesirable features of ac, power network operation has become highly complex with numerous operational challenges. Specifically, the changes in load characteristics and profiles (variable and time shift), and large intermittent generation, large load variations (e.g., due to heat waves), and increasing use of PE converters give rise to these challenges.

In many countries with high penetration of renewable energy, these issues have now reached a level that cannot be ignored as the present momentum in grid transformation amplifies the highlighted problems, rendering ac power systems vulnerable to instability. The major operational challenges in the hybrid power network are: 1) ac grid stability; 2) reduction in power system inertia; and 3) reverse power flow.

The primary ac network problems associated with system stability are usually divided into five different categories: 1) transient; 2) oscillatory;

Table 2 Classification of the Existing Load Types

AC-only loads	DC loads (camouflaged)	DC loads (genuine)
▸Direct on-line start motors - universal AC, induction, synchronous ▸Cycloconverters	▸All variable speed drives ▸HVDC systems ▸Universal AC motors that run on DC ▸Computers ▸All consumer electronics ▸All modern high efficiency appliances and power tools	▸Batteries ▸12/24/48 V DC devices ▸EV chargers ▸Modern data centers/servers ▸LED lights

3) control systems; 4) voltage; and 5) frequency. These also define the system security, which are entirely associated with ac supply.

Conventional centralized power networks commonly involve multiple large synchronous generators with large moment of inertia—which can vary with the number of generators active at a given time—that also assist frequency stability due to their slower response (smaller rate of change of frequency). However, even known stability solutions become difficult to implement due to the large-scale integration of renewable energy sources with decoupling PE converters and decommissioning of conventional power stations, which reduce power system inertia. Fig. 2(a) shows that due to the changing generation mix, a descending inertia trend indicates that minimum inertia is declining, and low inertia periods are more frequent. Virtual system inertia concepts are found to be ineffective due to the fast pace of grid modernization and transformation, regulatory issues, and as well as political decisions. The low inertia issue has also challenged the control and stability of small-scale ac power systems, including islanding mode operation, in remote areas, and other off-grid applications such as in remote towns and mining sites.

Due to increasing photovoltaic (PV) power penetration, reverse power flow is now a common phenomenon not only observed at the distribution level but also at the transmission level. Fig. 2(c) illustrates the section of load duration curves in a transmission line that is connected to a region with high penetration of solar rooftop PV, which reached a level of about 16% in 2018. The impacts of reverse power vary from overvoltages and voltage imbalances to power quality, protection, and stability issues.

In many cases, reverse power flow results in primary transformer limits being exceeded, reducing their lifetime. Although the thermal limits of transformers are symmetrical, transformers with an on-load tap changing mechanism can manifest an asymmetrical thermal limit due to frequent reverse power flow [see Fig. 2(b)]. Unfortunately, conventional voltage regulation by transformer tap changes and utilization of off-peak water heaters are not found to be sufficiently effective solutions in practice.

Moreover, unlike the early stage of the conventional grid, the curtailment or “wasting generated energy,” has become a common phenomenon in current grid operation practice. Today, specifically in market-based generation dispatch, curtailment has been practiced frequently for various reasons including transmission congestion, excess generation during low demand periods, and voltage, or interconnection issues, which are primarily the result of large scale of penetration of intermittent renewable energy resources.

Semi-conventional solutions, such as static volt-ampere reactive compensator (SVC), static synchronous compensator (STATCOM), synchronous condensers, network augmentation, and redesign, are considered to address some ac network problems. However, these methods are found to be highly expensive and they cannot respond to the fast changes both in demand and renewable energy generation.

Furthermore, the ac power grid presents further limitations as it is transforming from a traditional centralized to a decentralized structure, which is driven by the embedded and distributed generation concept. This has allowed the development of nano-/microgrids within a macrogrid or standalone, which primarily involves numerous alternative energy generators (see Table 3) such as wind generators, PV systems, fuel cells, flywheels, microturbines, batteries, supercapacitors, and even plug-in electric vehicles (EVs).

Note that all of these alternative energy generators have intermediate dc power converter stages, which are then inverted and synchronized to the ac grid by adding mostly bi-directional PE converters (inverters). Such a topology is necessary to link to the ac grid; but it increases the system cost and reduces system reliability and round-trip efficiency. Moreover, inverter operation is highly complex and requires significant processing power, which limits the instant protection measures and produces delays in the action time. In addition, conventional inverter structures utilize Si-based switching devices that have higher losses—specifically, at higher frequency switching that is desirable for increasing power density and reducing physical size—and have significant cooling requirements.

As can be observed in Table 3, the dc grid versions of the distributed generation sources eliminate the grid connected inverter stages and associated disadvantages.

As is already known, the centralized ac grid usually requires longer T/D lines (costly and higher losses) and is highly exposed to environmental factors with insecure communication. Currently, we are experiencing significant grid transformation, while accommodating both ac and dc systems—generators and loads (primarily dc)—in a hybrid manner. Moreover, there are numerous load types and embedded generation options—with PE converters—including traction systems, all-electric sea and air vessels, EVs (cars, buses, and bikes), charging stations, data

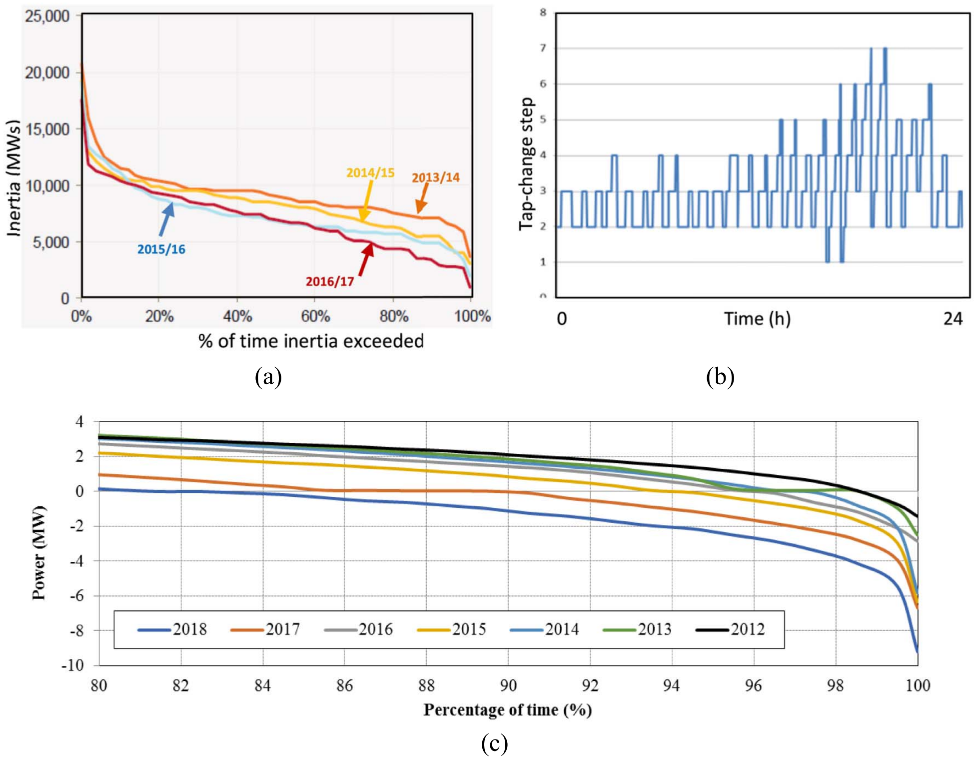


Fig. 2. ***Critical observed results of the transforming ac power grid. (a) Declining power system inertia [1]. (b) Increased activity in on-load transformer cycling due to reverse power. (c) Section of load duration curves over multiple years with increasing reverse power flow in a transmission line.***

centers, DERs, and mining sites (dc trolley trucks, mining lifts, and crashers). However, this volatile and centralized hybrid grid cannot adequately handle bi-directional power flow, and its operation becomes excessively complex and unstable due to the ever-increasing decoupled converter structure and reduced power system inertia.

III. STRUCTURAL CHANGES IN THE POWER GRID TOWARD AUTONOMY AND A DC GRID PARADIGM

In some regions around the world, the "instant" renewable energy generation-demand balance [2], if not curtailed, can reach 100% when the environment permits. As the ac grid grows with population increase and increased wealth, predictability of demand reduces. Yet wind and PV solar farms are on the increase. These have already initiated a debate about the reliability of the power network, energy cost, as well as the validity of the conventional centralized power grid and its operational practices that are currently driven by preexisting market rules.

Various short-term measures have been considered to address some of these issues. These measures include building large grid-scale battery storage systems, installing synchronous condensers, developing virtual power plant concepts, distributing gas peak-power plants, as well as defining new regulatory frameworks for both grid operation and for existing/new large-scale renewable energy sources—such as dispatchable wind farms and PV farms with battery storage.

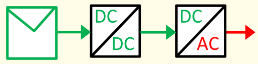
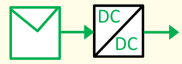
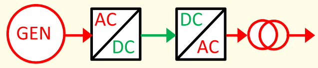
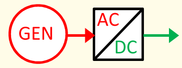
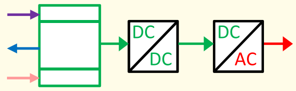
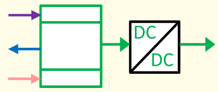
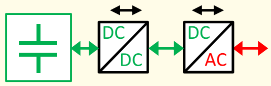
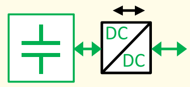
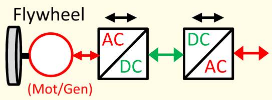
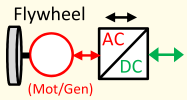
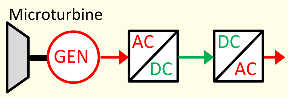
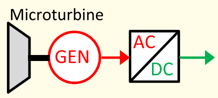
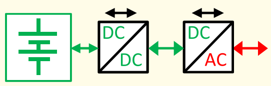
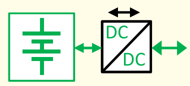
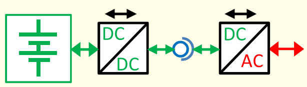
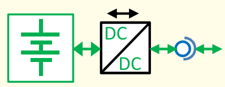
The potential solutions for the future demand increase also include using demand response enable devices, smart appliances, and smart meters. However, as add-on solutions are developed, they lead to technically and economically complex grid systems resulting in a *Verschlimmbesserung* or disimprovement. This contributes to an increase in energy cost, which is then amplified by market rules that were designed for the conventional grid. It is envisioned that the changing paradigm for ac grid transformation is likely to occur in the following three ways.

A. Decentralization

Decentralization will occur first in remote cities/towns and other community-level applications. This will be motivated by improved reliability and low cost of energy. It will also allow sharing reserves—such as solar roof-top PV—and power to be transmitted short distances with low electrical losses. Moreover, it will improve system security due to its autonomy and use a one-way communication feature for system monitoring purposes. Decentralized generation has faster generation ramp up and connection times, hence it can manage both power and energy, and can accommodate local prosumers easily.

Furthermore, it can offer integrated high-power dc charging stations for future EVs [3] and utilize the localized network capacity to its maximum.

Table 3 Embedded Modern Generation Sources and Converter Topologies to Couple the AC Grid, and Topologies for the DC Grid

Embedded Modern Generation Sources	Converter Topologies for AC Grid	Converter Topologies for DC Grid
Solar PV		
Wind Generators		
Fuel Cells		
Supercapacitors		
Flywheel systems		
Microturbine Systems		
Stationary Battery Storage Systems		
EV to Grid		

B. Role of High-Voltage DC (HVDC)

Any long-distance connection and different frequency norms will require HVDC, which can offer bi-directional and four-quadrant power flow at a stable frequency. Large-scale HVDC systems have already been installed in Germany and China, where HVDC transmission corridors expand to increase transmission capacity between regions rich in power sources—such as wind power—and major far-away load centers. The cost of HVDC systems is likely to go down significantly by the utilization of WBG devices, also making shorter HVDC links economical. As the decentralized structure expands and demonstrates its capabilities and reliability to the wider community, public acceptance for big overhead line expansions will diminish. Hence, the technology will even make underground HVDC common for shorter distances. Note also that dc transmission is already the primary choice for sea-crossing and off-shore wind farms.

C. Microgrid Paradigm, DER, and Autonomous Microgrids

With the evolution of the ac power grid, new concepts and definitions have emerged including nano/micro/embedded/distributed grids (ac, dc, or hybrid), smart/future/intelligent grids, smart appliances/meters/inverters, smart cities, grid modernization, and even the concept the electronic grid and the Internet of Energy (IoE). The common specifications of these definitions primarily all center around controllable load/generation aspects, to be able to reduce and quickly respond to the generation and demand imbalance, which aims to improve grid security/reliability, reduce energy cost and mitigate cost escalation due to the way the energy market plays out.

Three common aspects of the new paradigm also include improved utilization of existing T/D capacity to be ready for emerging and growing new load types (such as air conditioning systems and EVs), energy management, control via Internet of Things (IoT), and faster communication tools, but all within the context of an ac grid that was originally designed and operated in a centralized manner.

An embedded microgrid with DERs is characterized in recent years by local generation of sufficient power near demand centers, which can function either in the presence of a larger grid or standalone. The deployment of DERs: 1) offers relatively continuous power; 2) provides power at a higher levels of reliability; 3) offers low variable cost and low maintenance cost; 4) presents higher capacity factor hence reduced overall electricity cost;

5) is resilient since it serves low power demands continuously and sustainable renewable sources of power; 6) reduces the losses due to close proximity to the loads; and 7) has a positive impact on the voltage profile [4].

Note that dc is the critical coupling method in every subsection of an ac microgrid that is currently utilized widely in remote communities, high rise buildings, university campuses and housing communities, and in data centers (as a dc microgrid [5]). One very successful ac microgrid project has also been reported in the Netherlands [6]. It is owned and run by each village or neighborhood and is also operated in islanded mode. Although Navigant Research has reported 4475 microgrid projects (27 GW) around the world [7], Tata Power has recently announced the set up of 10 000 additional renewable microgrids (10.7 GW) in India by 2026 [8].

In an autonomous nano or microgrid, power consumption is managed locally and autonomously. The key benefit is to enhance grid security because the loads interact directly through the local network and not the communications network as in the conventional approach. Since power imbalance is reduced and eliminated, conventional market complexity does not have any impact on the system operation. Therefore, an autonomous microgrid [9] is defined as being able to make its own decisions to regulate electrical quantities and perform energy management. A unique application of an autonomous microgrid has been developed and tested in Australia [10], where solar rooftop PV penetration is high, and the demand profile contains significant reverse power flow. In a microgrid, the ac bus voltage is regulated by four-quadrant power control, the peak active power is limited, and islanded operation is achieved autonomously.

IV. WBG DEVICES IN PE FOR THE POWER GRID

Advancements in PE primarily aim to make a system more efficient resulting in significant energy savings. For example, energy savings from VSDs, in the 500–1000 HP range, can be as high as 3.2% [11]. Therefore, higher efficiency is the primary target in any electrical system as it results in multiple benefits including: 1) reduced energy consumption; 2) reduced cooling requirements—smaller fan and space for heatsinking, in enclosed spaces (as in converters, data centers, and stationary or mobile battery storage systems); 3) less heat hence increased insulation and system life; and 4) higher short-term overloading capacity.

A. Progress in WBG Devices

In PE converters, WBG devices (see 3.26 eV for SiC versus 1.1 eV for Si) offer revolutionary changes that are already finding markets in a wide spectrum of power system applications. For example, SiC devices have ten times lower total power dissipation than Si switches. With higher voltage (400–1700 V) and current ratings (up to 325 A), higher breakdown voltage, and lower ON-resistance, SiC devices are now commercially available. Much higher voltage (10–15 kV) SiC devices—such as insulated gate bipolar transistor (IGBT), MOSFET, and junction barrier Schottky (JBS) diodes—also are designed with modular structures that offer high power density and desirable high-frequency (HF) switching characteristics.

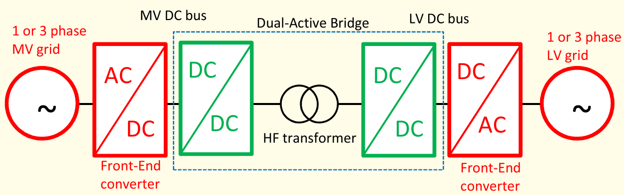
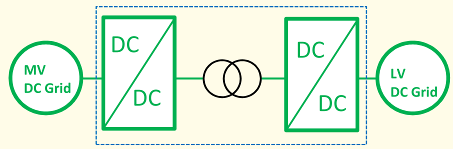
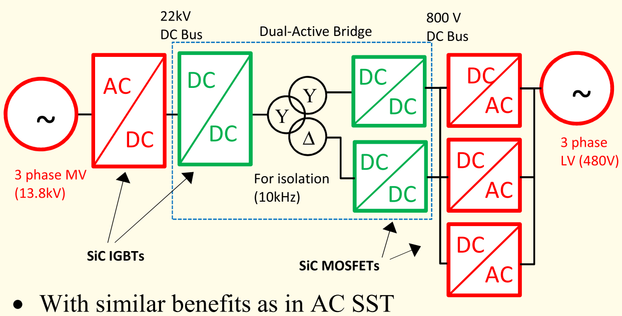
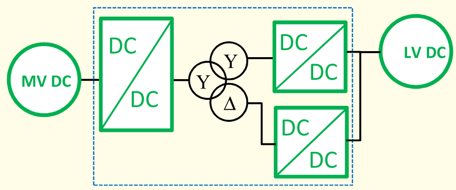
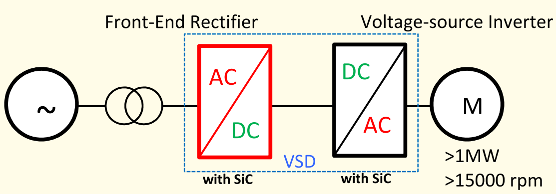
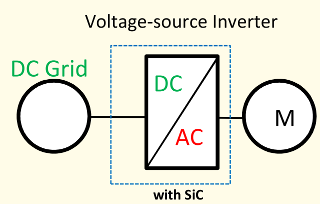
Similarly, GaN HEMT devices have been developed offering excellent short-circuit robustness (600 ns at 350 V) [12]. Moreover, GaN FETs are an emerging technology that can improve the size, cost, and efficiency of various hard switching converters. The current GaN device market is mainly dominated by devices < 200 V, which is predicted to increase to 600 V when GaN begins to replace MOSFETs. Note that GaN is already well-established in high-end computing and telecommunication power supply applications [13]. In addition, GaN devices offer high power density dc/dc converters that are likely to be packaged in solar PV systems at the cell level [14].

Briefly, the desirable characteristics of WBG devices in PE applications are: higher operating temperatures (resulting in smaller heatsinks, smaller die sizes, and lower costs), faster switching speed (reduced size of passive element, but potential for electromagnetic interference (EMI) problems), and higher *dv/dt* and *di/dt* ratios (30–50 kV/μs and 1 kA/μs). However, high *dv/dt* and *di/dt* waveforms contain significant HF components. Therefore, single-ended passive voltage probes and high accuracy current shunts are required for measurements, which reinforce the modularization of WBG devices.

Note that WBG power modules without anti-parallel Schottky-barrier-diodes (SBDs) have been developed to reduce switching time and power module size. Therefore, in WBG inverters without anti-parallel diodes, power loss remains constant for any power factor. Moreover, they are efficient, reliable, and smaller in size. For example, SiC inverters have reduced loss by about 50% and improved inverter efficiency by about 8% compared to Si IGBT-based conventional inverters at the same frequency [15]. Note also that a SiC inverter reduces motor losses with higher switching frequency (as in high speed and high pole number motors) and has reduced heating.

Moreover, WBG devices offer further increase in the system power density at HF since the dc-link capacitor is replaced by ceramic capacitors. For example, three-phase HF inverters for motor control are now developed up to 10 kW and with an efficiency $>99\%$ at a power density of 11 kW/dm^3. Moreover, converters using WBG devices have opened up a new horizon for numerous other applications and have been demonstrated via Google and the IEEE's Little Box Challenge on inverters and solutions for power grids [16], which achieved a power density of 142.9 W/in^3. An impressive power density of 900 W/in^3 has also been achieved in a synchronous buck converter (12 V at 2-MHz switching) using GaN devices [17].

Table 4 Solid-State Benchmark Applications Using WBG Devices in AC and DC Power Networks

Solid State Transformer (SST) for AC Grid (as compared to conventional transformers)	**Solid State Transformer for DC Grid (DC SST)** (as compared to AC SST)
 • Smaller volume and weight • Improved efficiency and reduce cooling requirements • Bi-directional power flow • Improved power quality (unity power factor, harmonic elimination) • Voltage regulation by reactive power control if battery storage capacity is added on the DC bus. • Flexibility in control, also as an AC circuit breaker • Renewable energy integration with AC or DC links • EV chargers can be connected to either MV or LV sides • Complex control and higher processing power required	 • Much simpler hardware and controller, reduced processing power, higher efficiency, greater power density and reduced footprint. • This is the basic building block in SSTs (or DC-DC transformers). Input and output sides can be connected in series for higher voltage levels in HV applications. • Can be used as an DC circuit breaker
Transformerless Intelligent Power Substation (TIPS) for AC Grid (as compared to conventional substations)	**Transformerless Intelligent Power Substation in DC Grid (DC TIPS)** (as compared to AC TIPS)
 • With similar benefits as in AC SST • Isolated DC microgrid can be added (using an isolated output of the transformer with a DC/DC converter)	 • Similar improvements as in DC SST benefits as in AC SST.
Variable Speed Drives for MV Motors in AC Grid	**VSDs for MV Motors in DC Grid**
	

B. Utilization of WBG Devices on the Power Grid

A number of research projects from EV chargers [3] to circuit breakers [18] have been reported using WBG devices. Table 4 illustrates solid-state solutions using WBG devices in utility scale benchmark applications. The research results indicate that in the very near future, the conventional ac transformer will be replaced by the ac solid-state transformers (SSTs), which is an ac grid-tailored smart transformer (ST) with control and communication functions [19], [20]. Other functions of SSTs include: soft load reduction to avoid load shedding (in the case of faults and overload) and ac grid voltage support (with the addition of BSS), active dumping, low voltage (LV) grid fault current limit, providing medium voltage (MV) dc link (e.g., for EV charging), load management, LV grid load identification, phase load balancing, frequency support, and increased reactive power support for an MV grid.

When an ac SST gathers information from generators, consumers, and storage units, it can optimally manage the power grid and can act as a multiple port converter system allowing ac and dc coupling at different

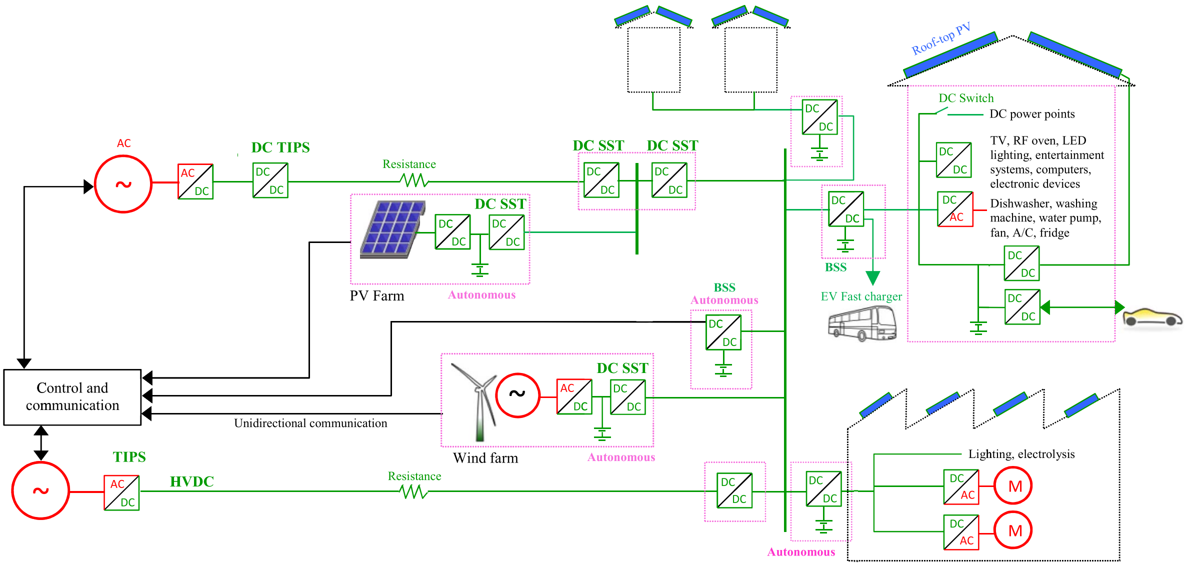


Fig. 3. *Basic components and communication structure of the future dc grid.*

levels. Bi-directional active and reactive power flow can be provided by ac SSTs and will be an alternative to line frequency transformers for connecting MV (13.8 kV) to LV (480 V) distribution lines. Smaller and lightweight HF transformers in such converters can provide electrical isolation.

The future ac power networks will also accommodate Transformerless Intelligent Power Substation (TIPS) units. As shown in Table 4, TIPS (13.8 kV to 480 V) typically involve frontend converters (with SiC IGBTs), dual-active bridges (with SiC IGBTs and HF transformer for isolation) and LV side converters (with SiC MOSFETs). Industry adoption of HV SiC devices in MV power converters (such as SSTs and TIPS) is very close.

V. STRUCTURE OF THE FUTURE DC GRID

Widespread utilization of dc microgrids will depend on the following factors: 1) technological readiness; 2) development of regulatory and legal frameworks; 3) demonstration of power quality and reliability; and 4) economic benefits. Note that dc nanogrids will also be developed as a subset of microgrids mainly around "low or zero net energy" or dc-powered houses with energy management integrated with smart appliances and dc switches.

The ST will be the backbone of the future dc grid. Future dc grids (see Fig. 3) will include highly simplified dc SST and dc TIPS units, which will eliminate the problems related to ac sources. In addition, the SST front end will offer dc integration of commonly used ac synchronous generators as in wind turbines and conventional power stations. Also, MV dc microgrids will be readily developed using the dual-active bridge with HF dc/dc converters. By utilizing multiple converters and connecting their input and output terminals in series, higher voltage dc/dc converters will be achieved.

Autonomous microgrids with advanced WBG device-based converters will be developed around the load centers and critical common coupling points of the dc network. This is very likely to stimulate a ground-up network design as well as new market rules. The transition timeline given in Figs. 1 also illustrates the transmission network level evolution toward the dc grid where reduction in transmission lines and associated losses are significant. Note that the maintenance cost of poles and wires, environmental cost, and retail cost are almost 80% of the energy bill, which can be reduced drastically by transformation to dc decentralized generation.

During the transition stage toward the dc grid, hybrid grid in sea vessels and traction systems for long-range applications are likely to use fuel cell technologies accommodating hydrogen as a fuel, which can be sustainably produced via renewables [21]. The experience gained in stationary dc microgrids will be adapted in the development of the on-board dc grids in sea and air vessels and land vehicles. In addition, all industrial and domestic motor drive applications will utilize VSD techniques primarily to improve drive system efficiency. Note that dc battery storage technology will offer not only community level storage [22], it will also offer reserve power storage, dispatchability for intermittent sources, and will eliminate curtailment (1%–3% in the United States [23]) of large-scale wind and PV energy generation.

The security of the power system is likely to involve two major aspects: cybersecurity with one-way communication and localized autonomous control [24]. One-way communication, as shown in Fig. 3, will reduce the complexity associated with multiple embedded microgrid systems.

Decoupled asynchronous operation of dc microgrids eliminates stability concerns and will not be affected from disturbances in the dc main grid. Solid-state dc converters will also regulate voltage continuously and in bi-directional manner. Short-circuit current protection in autonomous microgrids will utilize WBG devices that can interrupt very large currents in microseconds, leaving nearby microgrids unaffected by the fault. Hence full selectivity among multiple dc microgrids will be achieved.

Due to the specifications of the existing dc loads, the dc grid is highly suitable for both domestic and industrial applications.

Therefore, dc power points will be supported by WBG-based dc switches and high-power density modular dc/dc converters will offer various voltage levels for dc power points.

Note that ac synchronous generators with field windings are the primary choice in large-scale power generation. When they are coupled with ac/dc PE converters based on WBG devices, replacing transformers as in Fig. 3, the speed regulation of their prime mover will not require strict control, as required in the thermal power stations. This will then allow ease of control—as in wind turbine generators—both in steam and hydro turbines, which reduces the system cost and improves system reliability.

VI. CONCLUSION

Reliability of the grid is of highly strategic importance to the wellbeing of modern societies and economies. The centralized electrification approach has been accommodated for over 100 years using a few large ac generation sites and unidirectional ac power flow to remote load centers. The electricity market was also developed around this centralized approach.

However, within the last decade an ever-increasing hybrid structure (with ac and dc sources and almost entirely with dc loads) has reduced the reliability of the power grid significantly and increased the cost of energy while threatening national security. The cost of energy is also related to the losses in the system and interruption due to the unreliability.

Therefore, this article has primarily considered technical challenges and issues that affect the reliability of the ac power grid first. As the hybrid grid is becoming dominated by dc, some of the inherent problems and limitations of ac are becoming apparent.

Moreover, the security aspects of the grid have become critical given that PE converters have become ubiquitous for both domestic and industrial consumers, and a greater number of intermittent renewable power sources are being integrated onto the ac grid. Furthermore, since decentralized operations using many modern DERs and autonomous smart microgrids take hold, new market players and new market trading rules are emerging at an ever-increasing pace.

A number of major unforeseen phenomena have also occurred within the last decade in the traditional unidirectional grid: 1) bi-directional and unpredictable power flows; 2) large voltage sag and swells both in distribution and at transmission levels; and 3) frequent switching of on-load tap changing transformers. The renewable energy uptake, acceptance of DERs, and microgrid concepts are trending toward a reliable and low-cost energy solution manifesting to decentralized dc.

The roadmap to the dc grid is likely to develop around the microgrid concept, which will start with an ac-coupled design first. As WBG devices produce high-power density units and facilitate autonomous structures, the dc microgrid will be the choice in any embedded microgrid applications. The developments in PE and associated technologies from generators to energy storage options will seamlessly facilitate a decentralized topology. The direct outcomes of these changes are the reduction of maintenance and infrastructure cost of T/D lines, increasing capacity utilization and most critically offering reliable supply.

Efficiency improvements and changes in dc load specifications are also two primary driving forces toward the dc grid. For various scales and applications, WBG devices will offer high efficiency and high-power density converters to replace conventional transformers and substations. In addition, WBG devices will replace switching devices in common PE converters heavily used in renewable energy sectors, VSD, and EV charging applications. This is likely to reduce the power demand and energy consumption significantly (10%–30%). Efficiency improvements will also be considered in future systems—such as integrated inverters, motors and loads [25], and PV systems.

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