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White Paper

Designing the Next-Generation Power Grid for Bidirectional Power and Data Flow with Real-Time Communication

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Designing the Next-Generation Power Grid for Bidirectional Power and Data Flow with Real-Time Communication

1. Executive Summary

The global energy landscape is undergoing a transformative shift driven by the rapid integration of distributed energy resources (DERs), the rise of electric vehicles (EVs), the proliferation of data centers with artificial intelligence (AI), the electrification and digitalization of manufacturing (with robots and AI), the emergence of virtual power plants (VPPs) at the edge of the grid, the rise of dynamically islandable microgrids, and the increasing reliance on utility scale renewable energy sources. Traditional power grids, which were designed for one-way power flow from centralized generation to consumers, are becoming inadequate in the face of these changes. This white paper addresses the challenges, stakeholders, solutions, and societal benefits associated with the need to design a modern power grid that supports two-way power flow and two-way data flow with real-time communication capabilities. Additionally, and equally important, it discusses the role of new advanced power electronics needed, in particularly those using Silicon Carbide (SiC) and Gallium Nitride (GaN), in achieving the higher efficiency, high-temperature tolerance (above 55 degree C), and higher to lower voltage handling required for the grid of the future.

The existing grid system is powered by synchronous rotating machines, generating the alternating current (AC) waveforms at a given frequency (60Hz or 50Hz). The supply and the demand of electricity in a network should match every cycle (50 or 60 cycles per second) in order to maintain the power system at stable voltage and frequency. In a typical power system, the supply or generation is controlled by the power system operator while the demand is controlled by the consumers. Hence, there are instantaneous moments when sudden loss of load or demand leads to higher voltage and frequency or vice versa when load increases suddenly or generation dips. The synchronous rotating generator has an associated system inertia which helps to bring back the system to equilibrium - constant frequency and voltage. This inertia of the rotating machines is the basis of the determination of the rate of change of the frequency of the power grid when the failure scenario is triggered. The grid frequency is electromechanically correlated with the rotation rate of the generators powering the grid. Any imbalance between load and generation is compensated for by the rotational energy of the remaining active generators of the grid system. And the system inertia of the in-active generators allow the timing window for the output elevation of the remaining active generators. The system resilience is determined by the defined threshold frequency (the frequency level below which remaining active generators are also not able to fulfill the requirement level of the output gap created due to in-active generators). However, the distributed energy resources (DER) such as solar and wind generate direct current (DC) which is converted to AC by inverters and fed to the grid. These inverter-based resources (IBR) do not have inertia and synchronized with the AC grid through inverters to deliver stable output.

The DC to AC conversion in the inverters is based on the waveform created by the switching of the power transistors by the software control. The software control relies on the phase locked loop control system following the grid voltage. There is no advantage of system inertia as the case with the electromechanical mechanism (rotating generator) with the resultant stability of the grid system is less resilient in the case of the IBRs connected to the powered grid. Unless these inverters are also able to formulate the voltage and frequency requirements of the grid on the similar lines of the electromechanical generators through the software control mechanism, maintaining grid stability in a power system with increasing share of IBRs will be difficult.

For example, for fixed voltage control system the inverters need to meet the current surge demands which can damage the power transistors of the inverter. The maximum current flow capacity of the power transistors in the inverter design requires significant scale-up than the existing limits to match-up the capacity levels of the electromechanical mechanism.

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2. Challenges Facing the Modern Power Grid

1.1 Infrastructure Strain and Aging Grid

- **Increased Demand**: The rapid growth of EVs, electrification of industrial processes[1], data centers, and cryptocurrency farms is significantly increasing electricity demand, putting a strain on the existing grid infrastructure.
- **Integration of Renewable Energy**: Solar PV panels, wind turbines, and other renewable energy sources introduce variability and intermittency into the grid, complicating the frequency balance (at 60Hz or 50Hz) of supply and demand.
- **Aging Infrastructure**: Much of the current grid infrastructure was designed decades ago and is not equipped to handle modern requirements, leading to increased maintenance costs, reduced reliability, and reduced lifespan.

[1] Per one estimate, the power generation capacity needs to be tripled in the next 4-5 decades as over 2 billion machines that are presently run on heat (fossil fuels) will be electrified to meet the Net Zero targets pledged by 140+ countries.

1.2 Climate Change and Weather Events

- **Rise in Ambient Temperature:** The highest summer temperature has been constantly on the rise in the past 3-4 decades. But the rate of change has increased in recent years. The existing equipment of the grid are designed in the last century based on old standards and specifications that are not able to perform efficiently in the present scenario.
- **Frequency and Intensity of Weather Events:** Both the intensity and frequency of weather events have been increasing in the recent past causing hundreds of billions of dollars of damage to the power systems every year.

1.3 Need for Real-Time Communication and Control

- **Two-Way Power Flow**: As prosumers (consumers who also generate electricity) become more prevalent, the grid must manage power flows in both directions, requiring advanced control systems.
- **Two-Way Data Flow**: Real-time monitoring, data analysis, and communication are essential for managing a dynamic grid with decentralized energy generation and storage.
- **Cybersecurity Risks**: The increased connectivity of grid components exposes the system to potential cyber threats, necessitating robust security measures.

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3. Stakeholders

2.1 Utilities and Grid Operators

- **Role**: Responsible for maintaining grid stability, managing power flows, and ensuring reliable electricity delivery.
- **Challenges**: Need to upgrade infrastructure, integrate DERs, and implement advanced control and communication systems[2].

2.2 Regulators and Policymakers

- **Role**: Develop regulations and policies that encourage grid modernization, protect consumers, and promote sustainability.
- **Challenges**: Creating flexible regulatory frameworks that accommodate new technologies and innovative business models.

2.3 Technology Providers

- **Role**: Supply the hardware and software needed for grid modernization, including power electronics, communication systems, and cybersecurity solutions.

[2] It is estimated that about 80 million kilometers of new transmission and distribution lines need to be built (to evacuate power from new generation facilities) by 2050 at a cost of US$ 21 trillion which is equivalent to doubling the existing global power grid that we built over last 140 years!

- **Challenges**: Innovating to meet the demands of a modern grid, such as higher efficiency, greater reliability, and enhanced security.

2.4 Consumers and Prosumers

- **Role**: Act as both consumers and generators of electricity, contributing to grid stability and efficiency.
- **Challenges**: Understanding and participating in new market structures, managing energy usage, and integrating DERs like solar panels, EVs and energy storage systems.

2.5 Renewable Energy Providers

- **Role**: Generate electricity from renewable sources and contribute to the grid's energy mix.
- **Challenges**: Managing the variability of renewable energy and ensuring reliable power supply in conjunction with traditional generation.

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4. Possible Solutions

3.1 Infrastructure Upgrades

- **Generation**: Transition to more flexible generation sources, including natural gas peaker plants and energy storage systems, to balance the variability of renewable energy.
- **Transmission and Substations**: Build new transmission lines, upgrade transmission lines to high-voltage direct current (HVDC) systems, install static synchronous compensators (STATCOM), grid-forming (GFM) inverters and automate substations with advanced sensors and control systems.
- **Distribution**: Implement smart grid technologies, such as advanced distribution management systems (ADMS) and distributed energy resources management systems (DERMS), to manage and optimize power flows at the local level.
- **Metering**: Deploy advanced metering infrastructure (AMI) to collect real-time data on energy consumption and generation, enabling dynamic pricing and demand response.

3.2 Real-Time Communication and Control

- **Advanced Communication Networks**: Deploy low-latency, high-bandwidth communication networks that support real-time data exchange between grid components.
- **Distributed Intelligence**: Implement edge computing to process data locally and reduce the need for centralized control, improving response times and reducing bandwidth requirements.

- **Cybersecurity**: Develop and implement robust cybersecurity protocols to protect the grid from cyber threats, ensuring the integrity of data and the reliability of power delivery.

3.3 Power Electronics Innovations

- **SiC and GaN Semiconductors**: Utilize SiC and GaN semiconductors in power converters, inverters, switches, feeders, reclosers, fuses, solid-state transformers, energy storage systems, smart meters and other grid components to achieve higher efficiency, operate at higher temperatures, and handle greater voltages.
- **Grid-Forming and Grid-Following Inverters / Converters:** Develop grid-forming and grid-following inverters / converters that use SiC and GaN to offer the fastest management of voltage, harmonics and modulation changes in sub-cycle times (1/60 or 1/50), as well as higher efficiency, and reliability.
- **Smart Solid-State Transformers**: Speed up the development of smart solid-state transformers (SSTs) that use SiC and GaN to offer more efficient, reliable, and compact alternatives to traditional transformers, capable of managing bidirectional power flows, connected and manageable real-time controls, and integrating with renewable energy sources.
- **Wide Band Gap:** The mainstream power devices with silicon based semiconductors are not able to meet the requirements of the evolving grid with the challenges mentioned above. The wideband gap devices having higher electron mobility provides the capability to enhance the switching speeds of the power electronic devices to facilitate instantaneous optimization of the grid to sustain the voltage and frequency fluctuations.
- **Cybersecurity:** The inverters and other power electronic devices on the grid are vulnerable to spoofing attempts resulting from the tampering of the sensing and communication links. For example, false data injection attacks resulting from introduction of false auxiliary signals changing the acquisition gains can alter the correct sensing measurement and misguide the control mechanisms leading to the instability of the grids. Similarly, tampering with the signals can result in the distributed denial-of-service (DDOS) attacks where the grid-forming inverters stop responding to the grid adaptation requirements.

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5. Benefits For Society

4.1 Enhanced Grid Resilience and Reliability

- **Resilient Infrastructure**: A grid designed for bidirectional power and data flow can better withstand disruptions, quickly adapting to changes in supply and demand.
- **Reliable Power Delivery**: Improved monitoring and control systems ensure that power is delivered consistently and efficiently, reducing the likelihood of blackouts or other disruptions.

4.2 Increased Energy Efficiency

- **Optimized Power Flow**: Real-time data and advanced control systems allow for more efficient management of power flows, reducing energy waste and lowering costs for consumers.
- **Reduced Carbon Emissions**: Greater integration of renewable energy sources, combined with efficient power electronics, reduces the reliance on fossil fuels and lowers greenhouse gas emissions.

4.3 Empowerment of Consumers and Prosumers

- **Active Participation**: Consumers can take an active role in the energy market, generating and selling electricity, participating in demand response programs, and benefiting from dynamic pricing.
- **Energy Independence**: With the integration of DERs and energy storage systems, consumers can reduce their reliance on the grid, achieving greater energy independence and resilience.

4.4 Economic Growth and Job Creation

- **Innovation and Investment**: The modernization of the power grid will drive investment in new technologies and infrastructure, creating jobs and fostering economic growth.
- **Sustainable Development**: By enabling the widespread adoption of renewable energy and energy-efficient technologies, a modern grid supports sustainable development and helps meet global climate goals.

6. Conclusion

The evolution of the power grid to support two-way power flow and two-way data flow with real-time communication capabilities is essential for meeting the challenges of the 21st century and achieving the net zero targets pledged by 140+ countries. By investing in infrastructure upgrades, real-time communication and control systems, and advanced power electronics, we can build a resilient, efficient, and sustainable grid that benefits all stakeholders and supports the rapid pace of technological and societal change. The use of SiC and GaN semiconductors will be critical in achieving the higher efficiency, high-temperature tolerance, and voltage handling required for this evolving new grid, ensuring reliable power delivery and empowering consumers to participate actively in the energy market.

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