Cyber-Controlled Smart Microgrid Systems of the Future: The High Penetration of Renewable and Green Energy Sources

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The mission of the North American Electric Reliability Corporation (NERC**)** is to ensure the reliability of the bulk power system in North America. NERC develops and enforces reliability standards for control centers to monitor the bulk power system and to assure the stability of the US interconnected grid system**,** consisting of a number of regional reliability centers, as shown in Figure 1.

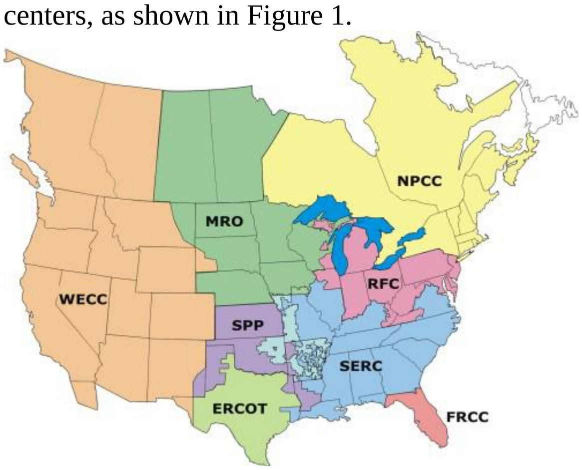

Figure 1. North American Electric Reliability Centers.

Similarly, it is natural to expect that future Cyber-Controlled Smart Microgrid Systems will be developed for the NERC mandated reliability centers of the U.S. grid. A future cyber controlled system is depicted in Figure 1.

The cyber-fusion point (CFP) represents a node of the smart grid system where the renewable and green energy system is connected to large scale interconnected systems, such as Reliability First Corporation (RFC) transmission systems. The CFP is the node in the system that receives data from upstream, that is, from the interconnected network, and downstream, that is, from the microgrid renewable and green energy (MRG) system and its associated smart metering systems. The CFP node is the smart node of the system where the status of the network is evaluated and controlled, and where economic decisions are made as to how to operate the local MRG. A CFP also evaluates whether its MRG should be operated as an independent grid system or as a grid system separate from the large interconnected system. Cyber system is the backbone of the communication system for the collection of data on the status of the interconnected network system. The security of the cyber network is essential for the security of the grid system. Figure 2 illustrates such a future system.

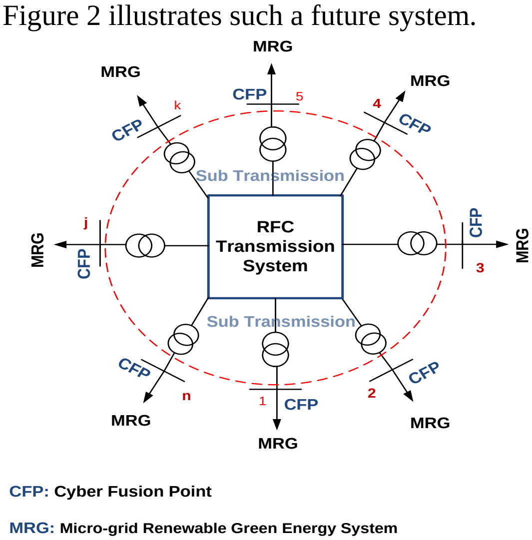

Figure 2. A Cyber-Controlled Smart Grid of the Future with High Renewable and Green Energy

The MRG's energy management system (EMS) communicates with individual smart meter**s** located at residential, commercial, and industrial customer sites. The smart meters can control loads, such as air conditioning system**s**, electric ranges, electric water heaters, electric space heaters, refrigerators, washers, and dryers using Ethernet TCP/IP sensors, transducers, and communication protocol, as shown in Figure 3.

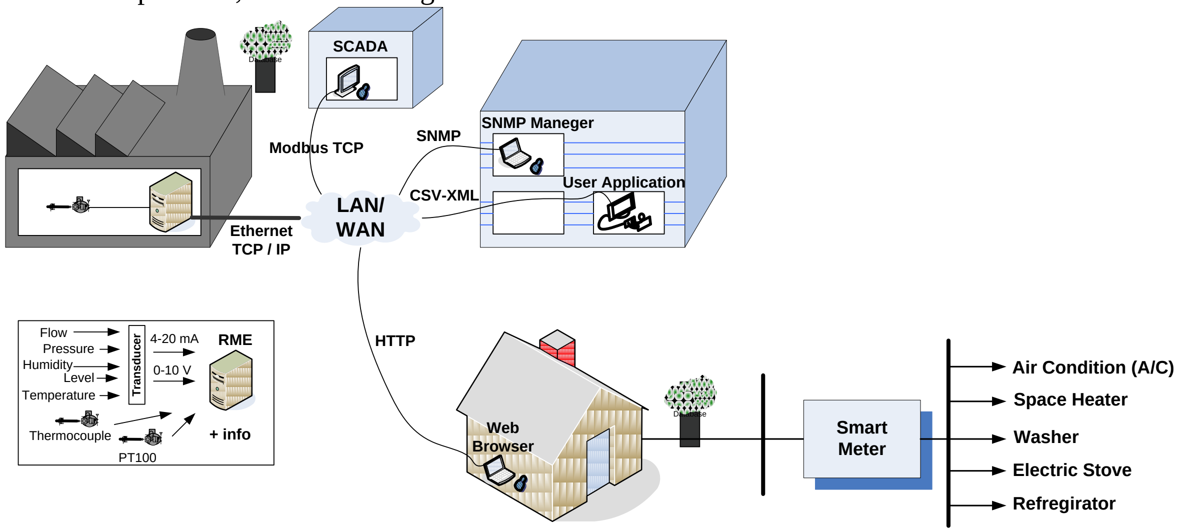

Figure 3 Ethernet TCP/IP Sensors, Transducers, and Communication Protocol for Load Control

The intelligence of the EMS of the MRG system will receive information on the status of connected loads from local smart meters. The EMS of the MRG system will control various customer loads, based on real-time pricing signals and grid normal, or alert, or emergency, signal**s**. In general, the EMS takes information from the utility and the Open Access Same-Time information System (OASIS). Based on real time pricing, smart meters are programmed to control loads on the customer sites. The EMS's control of loads will depend on input signals from its EMS or and the customer's pre-established contract criteria. The EMS of the MRG would have the capability to shed customer load and respond to local utility operating conditions.

Smart microgrid systems will be comprised of several components. These components include green and renewable energy sources with their associated power converters, efficient transformers, and storage systems. Figures 4 and 5 present such DC and AC architectures. Microgrid Systems will also include cyber communication systems consisting of smart sensors for monitoring, controlling, and tracking the normal, alert, emergency, and restorative states of systems. Cyber-controlled smart microgrids provide a new paradigm for defining the operation of distributed generation (DG). The smart microgrid concept assumes a cluster of loads and micro-sources, operating as a single controllable system. To the utility, this cluster becomes a single dispatchable load which can respond in seconds. The point of interconnection in the smart microgird is represented by a node where the microgrid is connected to the utility system, as shown in Figures 4, 5. This node is referred to as the locational marginal pricing (LMP), where the node price (cost) represents the locational value of energy. Electric utilities (energy serving entities) try to provide reliable supplies of electric power to their customers. Maximum benefits require low cost, sufficient supply, and stable operation. The architectures shown in Figures 4 and 5 are of interest to smart grid technology since they facilitate "Plug and Play" capabilities. In these architectures, green energy sources, such as fuel cells, microturbines, or renewable sources, such as photovoltaic (PV) generating stations and wind farms, can be connected to a DC bus or an AC bus, using uniform interchangeable converters. The smart grid system must be able to operate in two modes of operation, 1) in synchronized operation with the local utility system, and 2) in the Island mode of operation, upon the loss of the utility system. When a smart microgrid is connected to a utility, the smart microgrid is operated, using a master and slave control technology. The master referred to is EMS of the utility system. If the smart grid is suddenly separated from its local utility and system stability is maintained, then the slave controller takes over load frequency control and voltage control. For high power microgrids, there is a purchasing agreement between the utility and microgrids, regarding active and reactive power transfer. The word "smart" refers to microgrids that can control their loads and accept a ("price signal") and/or an "emergency operation signal" from its local utility, in order to adjust active and reactive power generation. Smart microgrids have hardware in place to shed loads, in response to a price signal, and they can rotate nonessential loads, to keep on critical loads. However, since disturbances in a utility system cannot be predicted with current technology, it is quite possible, upon the loss of the utility system, that microgrids would not be rapidly disconnected from the utility system. Therefore, the stability of the microgrids would not be maintained. Future research in cyber monitoring and control will seek to provide predictive models to track states in the system and to provide distributed intelligence and self-healing control technology.

In Figure 4, the EMS controls the infinite bus voltage and the system frequency. The slave controller controls the AC bus voltage of the inverter and the inverter current. Therefore, the slave controller of the microgrid inverter must be able to control active and reactive power, at leading or lagging power factor, or operate at the unity power factor. In small, renewable energy systems, the inverter is controlled at the unity power factor, and it leaves the voltage control, that is, the reactive power (Vars) control, to the EMS of the utility system.

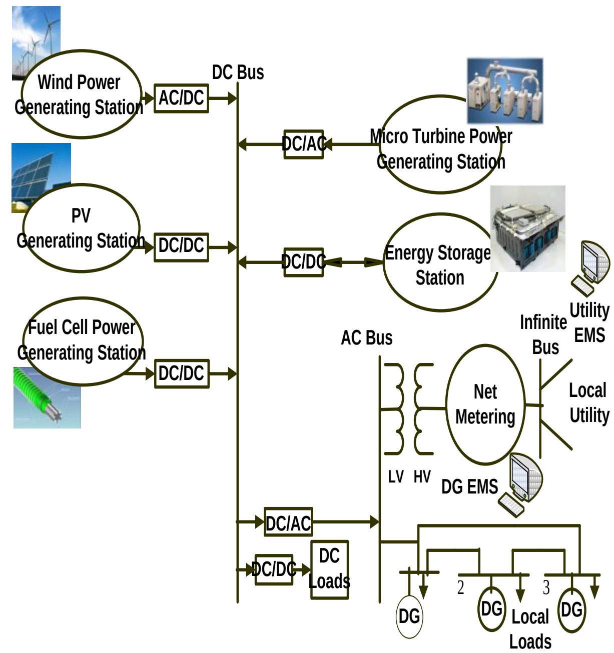

Figure 4. The DC Architecture of a Smart Microgrid DG Power System

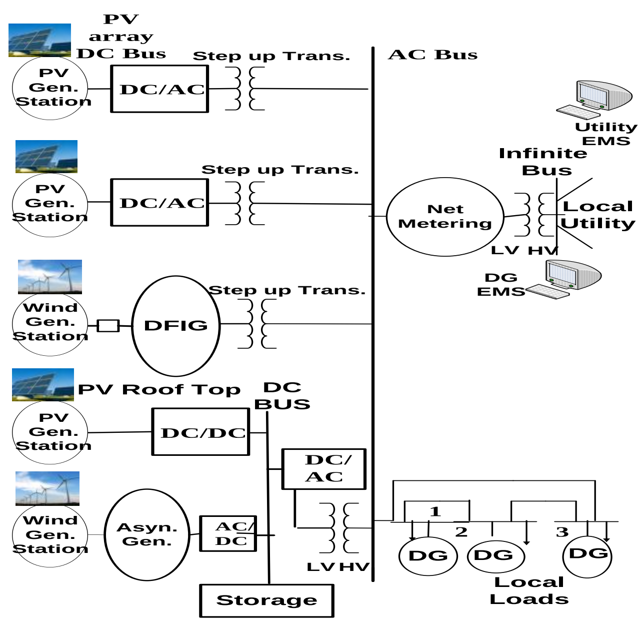

Figure 5. The AC Architecture of a Smart Grid DG Power System

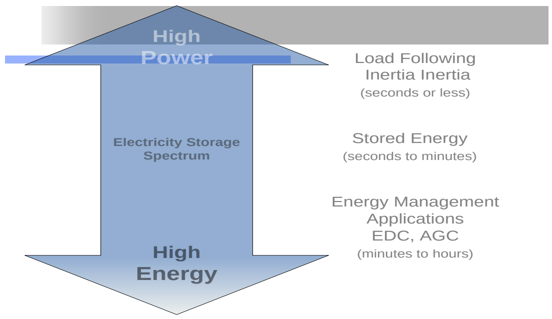

Figure 6. The Energy Management Time Scale of Power System Control [5]

An Inverter Operation as a Steam Generating Unit. For a smart microgrid to participate in energy management, voltage, and frequency control, its inverter must be controlled to operate as a steam generator. Recall that, by adjusting the field current, the operator decides the operating power factor of a generator, that is, active and reactive power production. An inverter can be made to operate in the same three modes to provide only active power or reactive power, or both active and reactive power. Therefore, the inverter can be controlled to deliver energy, based on the "price signal" received from a system operator, and it remains stable.

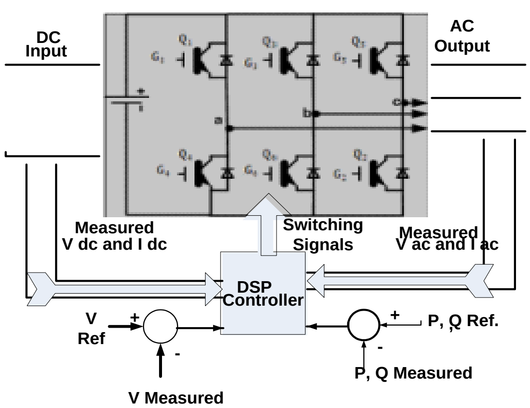

Figure 7: The Operation of an Inverter as a Steam Generator

The problem of power injection into the local utility system must be investigated by modeling the storage system and by developing an equivalent coherent generator model of the utility power network. The development of a coherent model for the external system is important since it will provide the characteristic impedance of the utility network that determines the ability of the smart microgrid to deliver power into a local utility system.

When the smart microgrid can respond to the local utility system during emergency operation, this would be very valuable to the local utility, since excess power can be used as "Real-Time Spinning Reserve." Then the microgrid qualifies as a provider of real-time spinning reserve. Such a system would receive payment from its local utility, even if its generated power is not used.

The steam power plant has stored energy in its boiler and stored energy in its inertia of rotor. This allows the power system operator to control the frequency of the system. In a power system, the loads are controlled by end users. The power system operator controls the system frequency and voltage to follow the system load demand. We can make the storage system act as a boiler; however, this must be accomplished by following the limits on the discharge rate of battery storage systems, that is, the state of charge (SOC). However, it is necessary to make sure that storage systems will not be subjected to excessive discharges which damage battery systems, or reduce their life. We can use a battery storage system with a flywheel, or a supper-charging capacitor to create the combination of a battery-flywheel or supper-charging capacitor, with its inverter acting as a steam power plant. In this architecture, the fly wheel system would provide inertia energy, rapidly, as DC voltage bus drops; then the storage system would take over, under appropriate control, to keep the system stable.

Research Issues. Smart microgrid research issues include 1) determining a secure cyber system for monitoring the status of the grid system; 2) creating a firewall to stop intruders from the intentional sabotage of the cyber system; 3) determining a cyber system that will have open architecture at customer load sites and, at the same time, have a secure cyber communication system with the interconnected grid system; 4) modeling microgrid systems for the control and reliability assessment of future cyber-physical energy systems; **5**) modeling and controlling fuel cell based flow batteries and combined heat, hydrogen, and power (CHHP) systems to provide storage systems; 6) developing control technology for the efficient operation of storage systems, such as flow batteries, battery- flywheels, or battery-supper-charging capacitors, to supply power for several applications, including plug-in, hybrid electric vehicles, and hydrogen fuel that can be used for multiple fuel cell applications; **7)** developing secure micro-grids through the predictive modeling and monitoring of self-healing (adaptive systems) diagnostics control technology; **8)** developing interactive smart metering to improve load model profiles; **9)** developing control technology for future cyber-interconnected smart microgrids, in which every node in the system will be adaptive, controllable, price-smart, operable as a microgrid, and functioning as an island or a synchronized system.

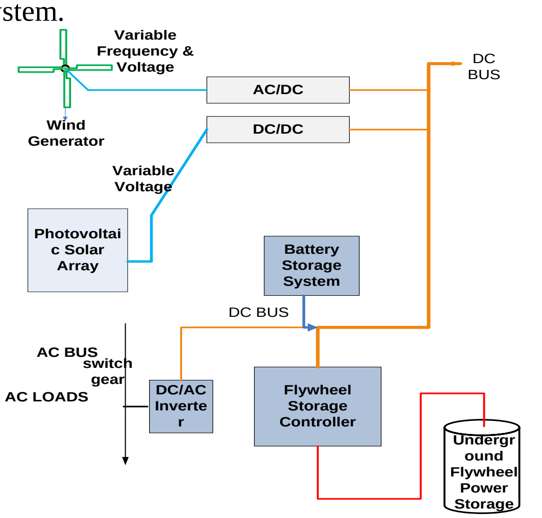

Figure 8. A DG Generating Station Acting as a Steam Unit

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