Transient Protection Of The SMART Grid:
An AC Power Perspective

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Introduction

The electrical grid has been the backbone of U.S. economic output for more than a century, allowing companies to produce various types of goods and to support technological innovation. While the electrical grid has served the U.S. well, many politicians, economists, and industrial leaders believe that the generation, delivery and utilization of electrical energy needs to be radically changed to meet the future needs of the country. The current proposal is to add intelligence and greater ecological-friendly electrical generating sources to the current electrical grid, thus creating the SMART Grid. The SMART Grid is being promoted as a method to decrease dependency on foreign energy sources, reduce the emission of global warming components, create a more reliable source of electricity, and allow consumers more choices in how and when they utilize electrical energy [1].

Currently, more than 1,000,000 MW of electricity is generated by more than 9,200 generators, and is connected to consumers with more than 300,000 miles of transmission lines [1]. The current system is 99.97 percent reliable, resulting in approximately 29 hours per year that electricity is not available to consumers [1]. While economic data associated with electricity reliability is difficult to obtain and verify, available information concludes that substantial losses can occur when electricity is interrupted.

- EPRI estimated in 1995 that workers were idle for a total of 37.2 million hours in 1991, for a productivity loss of $400 million [2]
- Sandia National Laboratories estimated in 1998 that electricity outages annually cost the U.S. $150 billion [2]
- A one-hour outage in 2000 caused the Chicago Board of Trade to delay $20 million in trades [1]
- The Northeast blackout of 2003 resulted in $6 billion of economic loss to the region [1]

To increase the reliability and availability of electrical energy, the SMART Grid will rely on substantially more generators. These new generators will be smaller in capacity than existing generators, located in both remote locations and local locations, and will produce fewer pollutants. In the near term, the new generators will consist of windmills and photovoltaic solar panels. These generators may be part of a large farm producing 5,000 MW of electricity; or small, single locations supplying a few hundred kilowatts to the electrical grid. While wind turbines and photovoltaic solar arrays are the most notable renewable energy sources, other generators using alternative energy sources may also be on-line (e.g. those supplied from agricultural waste, those supplied from landfill decomposition, nuclear, etc.).

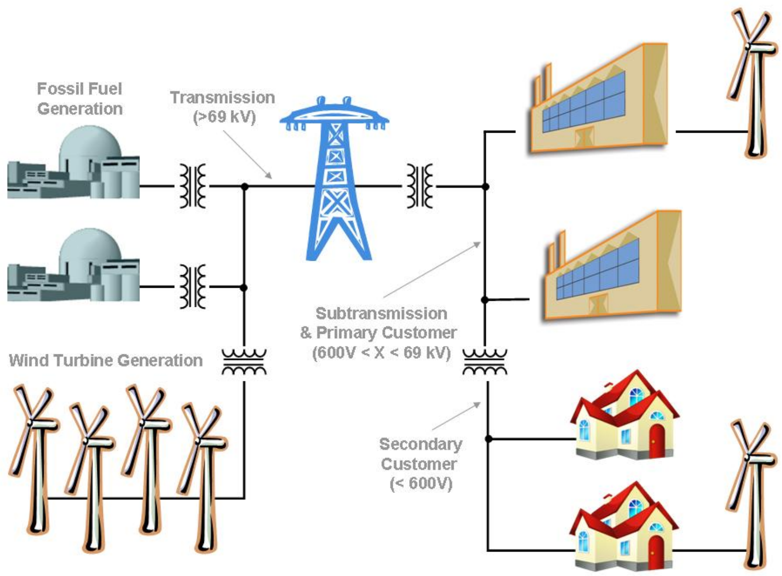
SMART Grid Network

In some aspects, the transient environment of the SMART Grid is the same as the electrical grid of today. That is, lightning will continue to produce direct and coupled transients that will propagate on the conductors until the transients are diverted to ground by either surge protective devices (SPDs) or through susceptible equipment. Other transient generators (e.g. capacitor banks, consumer equipment) will continue to directly couple switching transients onto the electrical grid.

In other ways, the SMART Grid will not be the same. The SMART Grid will have large components capable of generating renewable electricity: windmills (wind turbines), photovoltaic solar arrays, hydroelectric turbines, etc. Renewable electrical generating equipment have smaller capacities than traditional coal or natural gas electric generators, which require more equipment networked together. Most photovoltaic solar arrays are capable of generating approximately 2 kW each [2]. The largest wind turbines available today are 6 MW [2]. In contrast, a modern fossil fuel electric generator is capable of generating between 500 MW and 1,300 MW [2]. For photovoltaic solar arrays or wind turbines to be viable substitutes for a fossil fuel generator, many devices must be networked.

Many electric generating organizations will have large wind turbines or photovoltaic solar arrays networked together, while smaller wind turbines or photo-voltaic solar arrays will be utilized by individual organizations or residential customers (owners) and connected to the SMART Grid when the energy is not required by the owner *(Figure 1)*. While these devices are much smaller in size and capacity, they will provide electricity to the SMART Grid when not needed by the owner.

FIGURE 1
SMART GRID DIAGRAM

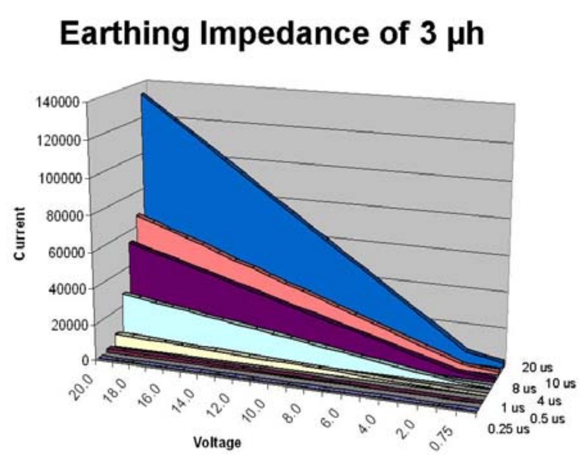


SMART Grid Transient Environment

With numerous large and small wind turbines and photovoltaic solar arrays networked to the SMART Grid, significant amounts of conductors will be utilized to connect the network. It is planned that these conductors will have lower impedances, which will allow electricity to flow with lower losses. However, lower loss conductors will result in higher frequencies, such as those associated with electrical transients, to propagate further through the electrical distribution network.

Lightning surges coupled onto electrical systems at the facility level shows surge currents can have varying amplitudes and durations. Calculations based on lightning rise times, breakover voltages (dielectric withstand) of distribution equipment, and impedance of the earthing system show that lightning currents could exceed 120 kA *(Figure 2)* [4]. Most transients coupled on the electrical distribution system will have less energy content, but the magnitudes of lightning-induced transients will be sufficient to damage most electronic equipment.

FIGURE 2
LIGHTNING INDUCED AMPLITUDES [4]



While switching transients are more common than lightning-induced transients, the data on switching transient is limited. The complexities of switching transients make predicting amplitude, frequency and duration difficult. Switching transients are determined by the characteristic parameters of the electrical system: inductance, capacitance, resistance, and conductance. In general, switching transients have a voltage that is less than two times the nominal system voltage, e.g. 480 V on a 240 V system.

With more equipment located in the environment and connected to the SMART Grid, there is a greater chance that lightning-induced transients will be coupled onto the SMART Grid. Equipment connected in close proximity of the induced transient has a higher probability of being subjected to higher amplitudes. In the SMART Grid, equipment that is normally connected deep inside a building or residence can now have direct exposure to the full energy capability of a lightning or switching transient.

Equipment Susceptibility

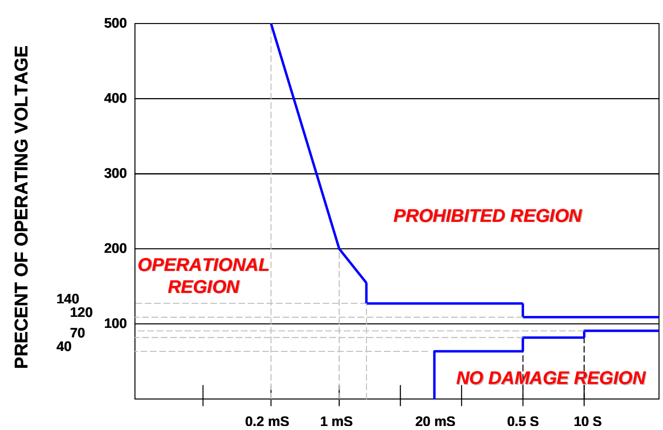
Semiconductor utilization in everyday commercial and industrial products and processes has dramatically increased. The electrical energy consumption of semiconductor devices in the early 1990s was minimal and mostly limited to computing or information systems. Today, it is estimated that electrical energy consumption of semiconductor-based equipment has risen to approximately 40 percent [4]. By 2015, it is estimated that semiconductor-based devices will further propagate into equipment, consuming approximately 60 percent of all electrical energy in the U.S. [4].

Semiconductors are not just limited to computing, information or communication systems. Semiconductor devices can be found in a plethora of industrial equipment including variable frequency drives (VFDs); programmable logic controllers (PLCs); uninterruptible power supplies (UPSs); automatic transfer switch (ATS) equipment; electrical metering devices; fire alarm systems; heating, ventilation and air conditioning (HVAC) systems; etc. Semiconductor devices are also found in equipment used in critical locations: healthcare facilities, traffic control systems, emergency 911 centers, etc. Additionally, semiconductor devices are found in a lot of electrical distribution equipment, including ground fault interrupters (GFIs), adjustable trip circuit breakers, electrical metering equipment, etc.

Equipment susceptibility is difficult to determine as the source of transients varies, and the distances and impedance variations between the transient source and affected equipment also significantly varies. In addition, the mode of coupling can also affect the susceptibility of equipment.

The Information Technology Industry Council (ITIC), with help from Electric Power Research Institute (EPRI), adopted the Computer and Business Equipment Manufacturers' Association (CBEMA) curve to accurately reflect the performance of 60 Hz single-phase information technology equipment *(Figure 3)* [6]. While this does not reflect all electronic equipment containing semiconductor devices, it does provide a first-pass approximation to determine equipment susceptibility. Transient voltages that exceed those defined by the ITIC can result in process interruptions, as equipment can be interrupted or damaged.

FIGURE 3
ITIC Curve for Single-phase Electronic Equipment [6]



Another method of determining the transient immunity of equipment is to determine the dielectric withstand. The dielectric withstand of equipment as detailed in UL Standards, regardless of a product's listing status (i.e. Listed or Recognized), is 1000 vac plus two-times the rated voltage from any phase (line or neutral) to ground [6, 7]. For equipment designed for a 240 volt system, the dielectric withstand is 1480 vac or 2093 volts peak. Transients in excess of the dielectric withstand capability of equipment make the equipment prone to damage or failure.

The best method for determining the susceptibility of equipment is to obtain this information from the manufacturer. Transient susceptibility is typically tested to standards from the Institute of Electrical and Electronics Engineers (IEEE) or the International Electro technical Commission (IEC). Typical testing includes subjecting to lightning-induced surges with a maximum voltage of 6,000 volts, and a maximum current of

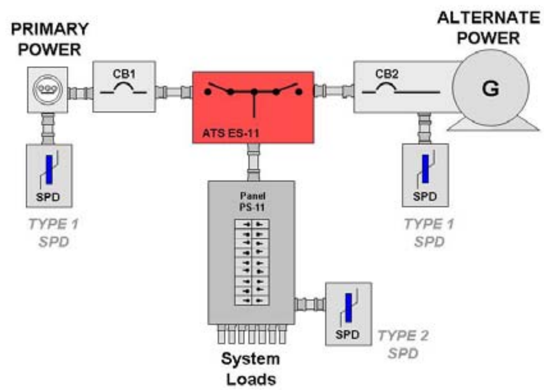
3,000 A (IEEE Category B Combination Wave) [8, 9]. Since most electronic equipment is only evaluated to the IEEE Category B Combination Wave that has a maximum current of 3,000 A, additional protection is required.

It is important to note that equipment located in applications where lightning-induced transients exceed these amplitudes, or equipment that is subjected to low-frequency switching surges, are not properly protected. Unprotected or improperly protected equipment can result in process interruptions, as service can be interrupted or equipment damaged.

Applying SPDs to the SMART Grid

Facilities that contribute to the supply of electricity to the SMART Grid have two service entrance locations: primary power source and alternate power source (Figure 4). Primary power is supplied from the utility. Alternate power is supplied from on-site resources (e.g. wind turbine, photovoltaic solar array, etc). Facilities with dual source power capabilities require an automatic transfer switch (ATS) device to ensure coordination of both sources. As shown in *Figure 4*, the system loads of the facility can be powered by the primary source (utility) or the alternate source (e.g. wind turbine, photovoltaic solar array, etc). The ATS also allows for the alternate power source to be networked into the SMART Grid.

FIGURE 4
ILLUSTRATION OF DUAL SOURCE FACILITY WITH SPDs INSTALLED



Providing surge protective devices (SPDs) has become a “best engineering practice” for protecting equipment and processes from transients. Intercepting transients at the incoming point of a facility has shown to be the best method of protection [10]. This requires the placement of SPDs at the electrical service entrance of a facility. Once the transient has been significantly reduced at the service entrance, additional protection is required at distribution panels and at the point of use [10].

Protecting equipment within a facility from transient conditions requires SPDs to be applied at the service entrance of the primary power and alternate power. To provide the best protection, SPDs should be placed as close to the service entrance as possible. In most cases, this requires the SPDs to be placed on the input of the service disconnect. SPDs intended to be installed upstream of the service disconnect are required to be classified as a Type 1 SPD [11]. To mitigate any remnant overvoltage within the facility, a Type 2 SPD should be located on each subsequent distribution panel.

Connecting an SPD to the electrical distribution must be accomplished in accordance with the National Electric Code and all local codes. The primary requirements for connecting an SPD in accordance to the National Electric Code are:

- Article 285.3 – SPDs shall not be used on ungrounded, impedance grounded, or corner-grounded systems unless approved for use
- Article 285.4 – Where used, SPDs shall be connected to each ungrounded conductor
- Article 285.5 – SPDs shall be Listed
- Article 285.6 – SPDs shall be marked with a short circuit current rating (SCCR), and shall not be installed at a point on the system where the available fault current exceeds the SCCR of the SPD
- Article 285.11 – SPDs can be connected indoors or outdoors, and shall be inaccessible to unqualified persons
- Article 285.12 – Conductors used to connect the SPD to the system shall be as short as possible
- Article 285.26 – Conductors used to connect the SPD to the system shall be greater than 14 AWG copper, or 12 AWG aluminum

- Article 285.27 – SPDs shall be permitted to be connected between any two conductors of the system: grounded, ungrounded, or grounding conductors; connection of the grounded and grounding conductors shall only be interconnected during a surge

Conclusion

The electrical grid is poised to transition from a system that was conceived more than 100 years ago, into a modern engineering marvel. The SMART Grid will revolutionize generation, distribution and utilization of electrical energy similar to how the Internet has revolutionized communications. Proponents of the SMART Grid tout that this complex network of fossil fuel and renewable energy sources will be capable of generating and distributing electricity at lower costs and lower levels of pollutants. In addition, the SMART Grid will reduce our dependency on foreign sources of fuel and be more reliable.

The renewable energy sources will consist of wind turbines, photovoltaic solar arrays, hydroelectric plants and other futuristic systems. These systems will be networked together using advanced conductors that have lower losses, allowing for high efficiencies to be obtained.

To protect the SMART Grid, and all the advanced electronic devices that will be connected to it, high quality surge protective devices (SPDs) with proven performance, demonstrated safety, and unprecedented reliability are required. The SPD must be capable of connecting to service equipment to limit lightning-induced transients from entering the facility or being coupled onto the SMART Grid. Additional SPDs will be required to limit any transient overvoltage that propagates into the facility.

For SPDs to be effective on the SMART Grid, they need to be:

- Installed in accordance with the National Electric Code and all local codes
- Classified as Type 1 SPDs for use upstream of service equipment
- Classified as Type 2 SPDs for use downstream of service equipment
- Capable of diverting transient currents that can be reasonably expected at the point of application
- Have voltage protection levels, including connecting conductors, that are sufficient to protect electronic equipment
- Have proven performance characteristics, demonstrated safety, and unprecedented levels of reliability

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