The existing electrical grid infrastructure is aging and based on century old systems and approaches to electrical delivery. Microgrid technology offers many advancements and benefits to the future of the electrical grid. This paper looks at the inner workings of microgrids and their implementation. This paper examines various storage methods within microgrids, a key benefit to their utilization, as well as a brief look at various microgrid control functions and issues. Regulatory issues are covered to address the potential wide spread expansion of microgrids and their ability to be the cornerstone of the electrical grid in the future.

Introduction

The electrical grid has grown over the decades of its existence from small independent systems with local power generation and consumption, to a large interconnected and very complex machine. Along with the growth of the grid, the need for the energy that is transported along its many millions of miles of wires has grown with it. High voltage transmission lines moved power generation to more remote locations and the growth of people connected to the grid has increased the grids interconnectivity across the map. Over the grids existence, however, innovation has been slow and many problems to date affect the grids ability to transform into the required system to power the fast advancing technological world. New technologies are available and can be utilized to tackle some of the obstacles that face the grid.

The grid has a reliance on fossil fuel produced energy. The production of energy from fossil fuel plants generates greenhouse gasses that adversely affect the environment. Peak demands and the overall peaking nature of the electrical grid have negative effects to the grid. It takes a lot of capital cost to maintain and update the grids infrastructure which is determined by the peaking loads. To date a large amount of the grids infrastructure is aging and not equipped to handle the continually increasing load. Also power plants need to be available to supply the energy during the peak times and by nature these plants tend to be fossil fuel driven. Renewable energy and the technology associated to producing it has advanced over the last few decades yet the ability to maximize its potential on the grid has not been achieved. By nature renewables are unpredictable at producing power, which makes incorporating them in the current demand driven grid system very difficult. The abundance of renewables are also generally not located near large areas of energy consumption and there is limited ability to transmit that energy over the required distances.

Though no one technology or fix will be able to correct all these problems that face the grid, smart effective uses of current technology can improve and significantly aid in the abilities and modernization of the grid. Energy storage is a crucial component to the future of the grid and its implementation needs to be expanded. Micro grid infrastructures utilizing storage can aid in the resiliency and stability of the larger grid. Smart controls are needed to incorporate the end user with the micro grid and the overall utility grid. Together these changes can not only improve upon the existing energy delivery system to the end user but also change the way power is produced and used which will have beneficial affects to the environment we live in as well.

Microgrid

People rely on energy in many forms every day. From the gasoline in the car you drive to the electricity that comes out of the wall outlet to power your appliances, energy is a vital necessity. 40% of energy consumption comes out of the wall outlet to power your appliances, energy is a vital necessity. 40% of energy consumption comes in the form of electricity. 30% of this is for commercial and residential needs. Even with energy efficiency initiatives and legislation, energy consumption is growing and with this the needs of an improved grid to get the electricity to the end user reliably and safely. Micro grids have shown to be a viable option in the grid system and come with many advantageous benefits. Microgrids are defined by the Microgrid Institute as “A microgrid is a small energy system capable of balancing captive supply and demand resources to maintain stable service within a defined boundary.” A notable benefit to a micro grid is its ability to be designed for its applicable purpose. Whether servicing a residential community or commercial shopping district a micro grid can be designed and implemented accordingly in various ways that also suit the geographical location. Microgrids are designed and built with one or more distributed energy resources (DER) in order to form a system. There are many variations of the microgrid to include how it is connection to the grid. They can be fully interconnected to the grid and consume and supply power, they can be fully isolated from the grid, often referred to as islanded, and they can be connected but only capable of consuming and not supplying power to the grid.

A common element to microgrids is the local DER which often utilizes environmentally friendly renewable energy sources such as solar and wind. Generally microgrids are implemented in order to provide reliable power
to an area that does not have power, or power is not reliable, and in some cases this can also minimizes the energy cost from grid consumption. In all cases, local power generation would be a requirement. There are many draws to using renewable energy sources for microgrid applications. Renewables are a fast growing industry with costs associated with their implementation dropping yearly. Compared to fossil fuels, which are re-sourced from concentrated areas around the world, almost any place a microgrid can be installed will have a source of renewable energy that can be used for a DER. Renewable sources are also environmentally friendly and do not have carbon emissions when producing electricity. The lack of emissions from renewables greatly reduces the overall production of greenhouse gasses.

Microgrids and their associated DER also provide benefits to the main grid. With the traditional grid setup, generation is done at large scale and in remote locations from the energy end user. This means long distance transmission and energy losses along the way. The losses can be as high as 10 percent. The close proximity of microgrid power generation minimizes losses over long distance. The grids transmission capabilities is designed and built around peak demand for the associated loads. This means added cost in infrastructure to build capacity for areas. This capacity is only then utilized for a short time out of the year. Due to microgrids serving a small designated area, the infrastructure can be built accordingly and at relatively significantly less cost. Proper operation will also reduce peak demand energy taken from the main grid and therefore reduce the required capacity the main grid is required to handle. The main grid has to balance electrical supply with demand over large service areas with a constantly fluctuating demand. This poses challenges and difficulty to the grid operators. Microgrid generation and storage alleviates this fluctuation and allows for a more predictable energy demand from the grid as the microgrid is seen as one overall load. The microgrid can handle various changes in demand by controlling various DER and relying on the main grid for a constant supplemental supply.

Energy Storage on the Microgrid

A critical aspect of a well-designed microgrid is energy storage. To date the current grid system has very limited energy storage. The lack of energy storage and sufficient large scale energy storage technology is a pressing matter with the electrical grid. Building and implementing microgrids allows for the implementation of energy storage, utilizing various technologies, near the consumption of the energy. Storage on the microgrid, or distributed storage, aids the DER in meeting the needs of the microgrid. Microgrids have both an energy need and a power need. An energy need is for mid to long term electrical supply and a storage system would have a good energy density to supply this to the microgrid. A power need is for short term needs and is how much power the energy system can supply per unit volume. The energy and power density comprise the storage systems storage capacity which is sized and designed to the overall microgrid and how it operates.

Though energy storage is not required within a microgrid it does have advantages. If the microgrid is connected to the main grid, storage allows time for DER to start up and supply the microgrid should the main grid go down. If the microgrid is an island microgrid, or has become islanded, storage allows stable operation of the DER independent of system load. If the microgrid utilized renewable energy sources, storage can supply needed power during the times that renewables are not able to generate power. Finally storage can be used to peak shave and therefore reduce the demand on the main grid and demand charge for the customer for grids connected to the main grid.

The most prevalent form of storage is the battery. Batteries designed to support microgrids come in various forms and materials.

- Lead acid batteries have been used for nearly a century in automobiles and have also been applied to individual house applications, however, they have a low energy density and therefore large and heavy for the amount of energy they can store. They also do not hold up well to repeated charging-discharge cycles.
- Sodium-sulphur batteries have been used in microgrid applications as well. They offer higher energy density then lead acid batteries and are capable of thousands of charge-discharge cycles.
- Sodium-sulphur batteries suffer from high cost per kW however. They also operate at 300°C, with the sodium and sulphur in the molten state, and will suffer irreparable damage if they are completely discharged and grow cold.
- Over the last few years a large amount of research and development has gone into Lithium-ion batteries. Most prevalent in the automobile industry to power the new wave of electric vehicles, lithium-ion batteries have proven to be very capable batteries. Lithium-ion battery technology is the fastest growing battery chemistry technology today. Advantages of lithium-ion batteries that make them suitable for microgrid applications are their high energy density, and low maintenance. Lithium-ion batteries do have disadvantages as well. Lithium ion batteries have highly flammable electrolytes and pushing the boundaries on Li-ion technology poses the risk of fires caused by these batteries. They are also still very expensive to manufacture. Using lithium-ion batteries in electric vehicles for grid storage is also a possibility known as vehicle to grid (V2G).
• Another form of battery that is being revitalized from 200 year old technology is the saltwater battery. Produced for microgrid and energy management systems, Aquion Energy is manufacturing an aqueous hybrid battery based on this technology. Aqueous Hybrid Ion (AH1) battery chemistry is centered on a saltwater electrolyte. This allows the battery to be nontoxic and non-combustible. This makes the battery well suited for microgrids and being a distributed storage source because it is environmentally friendly and safe to handle.

• Flow batteries are being utilized for grid and microgrid storage. A flow battery is a rechargeable device serving a microgrid. The construction of the flywheel consists of a large rotating cylinder on magnetic bearings within a vacuum chamber. The motor spins the flywheel and the energy is stored within this kinetic energy. When electrical power is required the flywheel spins the generator. The construction of the flywheel consists of a large rotating cylinder on magnetic bearings within a vacuum chamber. The amount of energy stored in a flywheel is proportional to its inertia and speed. Flywheels have a long life span and require little maintenance which makes them useful in microgrid systems. They have a fast response; ability to absorb energy within seconds or minutes, and give it back to the grid just as fast. This makes them well suited for frequency regulation, to support the operation of the microgrid, and not the overall storage device of the microgrid. Therefore in microgrid application flywheels can be used to support battery storage. Also, there are multiple flywheel approaches in which “flywheel farms” have been implemented to store megawatts of electricity for minutes of discharge time. Another drawback to the flywheel is the overall cost.

Microgrid Control

To make the most out of environmentally friendly renewable energy sources and energy storage technology within a microgrid system, a sophisticated microgrid control or management system is required. One of the most important aspects of the microgrid control system is safety. The control system must be able to supply power to the loads of the microgrid safely when it is attached to the main grid and also when it is not. If power is ever lost from the main grid, the control system must be able to manage the distributed generation, energy storage, and loads on the microgrid to maintain the reliable power. Current microgrid control systems use either a central controller or distributed controller among the various electrical components of the microgrid. Communication between the electrical components are done via their electrical connection or by network communication connections. Voltage, Frequency, and active and reactive power are the main variables used to control microgrid systems. A microgrid control system allows for the optimization of the distributed energy resources associated within that microgrid.

Challenges to the design and implementation of microgrid control systems include:

• Network communication limitations
• Variable power supplies
• Predicting power generation from variable supplies
• Integration of various technologies
• Variability in design

All these aspects need to be accounted for when implementing a microgrid control system. Important features of a microgrid control system include:

• Control of DER supply
• Integration of DER supply with main grid
• Control load/ demand
• Economic use of DER
• Smooth ability to transition between modes of operation

During operation with the microgrid attached to the main grid, loads will get power from both the DER installed in the microgrid and the main grids supply. During this mode of operation, the frequency, of the microgrid is controlled by the main grid. If the microgrid is disconnected from the main grid, either on purpose, due to an outage, or malfunction of equipment, the microgrid control system needs to balance loads with supply to maintain frequency. This operation is more challenging than being connected to the main grid. Energy storage systems can be used during temporary mismatches between power generation and demand, allowing for stable microgrid operation in all modes as well as transitions from one mode of operation to another.

In September 2014, the United States Department of Energy announced $8 million in funding to improve resiliency of the grid. The funding is going to seven projects around the country that focus on microgrid technology and deal with microgrid control in one way or another. Each project is receiving $1.2 million and they will bring together regional and state entities, private sector...
business and universities. Commonwealth Edison, known as ComEd, the local utility for the northern Illinois area recently obtained the $1.2 million grant to build a master microgrid controller that will be able to operate multiple microgrids.\textsuperscript{14} Along with other entities, ComEd will work to build a controller that will be able to optimize the relationship of one or multiple microgrids with the main grid.\textsuperscript{13} Alstom Grid, Inc. and Burns Engineering, Inc. received the $1.2 million in funding also for work on microgrid controls. The project will use the former Philadelphia Navy Yard to perform the work.\textsuperscript{15} The Electric Power Research Institute, located in Knoxville, Tennessee, is slated to develop generic microgrid controller.\textsuperscript{13} General Electric will develop an advanced microgrid control system for Potsdam, New York.\textsuperscript{13} TDX Powers, Inc. located in Anchorage, Alaska will install a microgrid control system on Saint Paul Island.\textsuperscript{13} The University of Californias Advanced Power and Energy Program will develop and test a standard microgrid controller utilizing the University microgrid as a test bed.\textsuperscript{15} Finally Burr Energy was selected to construct and test microgrid control systems for two Maryland suburbs.\textsuperscript{13} All these projects are important as the controlling capabilities and operational features of microgrids will ultimately determine the degree of proliferation in the utility power industry.\textsuperscript{16} Depending on the infrastructure and operational characteristics of the microgrid, the required control and operation strategies can be significantly different then that of the conventional power system.\textsuperscript{16} These projects can aid in speeding up the development and commercialization of microgrid controllers.

Microgrid control brings new questions of grid security. Physical grid security has always been a concern with the grid, however, with implementation of microgrids and their control architecture, cyber security is a growing issue.\textsuperscript{17} Physical grid security is comprised around the physical components that make up the grid such as power plants, transmission and distribution lines, and sub stations. While this is still a threat with microgrids, having distributed infrastructure makes it more difficult for large scale affects from attacks. This same distributed infrastructure also aids the microgrid set up from large scale effects of cyber-attacks to the grid. Microgrid control systems rely on software based programs and communication networks to perform their functions.\textsuperscript{17} This makes them targets for directed cyber-attacks. Therefore cyber security and cyber hardening is very important parts to the design and construction of the microgrid control systems.\textsuperscript{17}

### Microgrid Implementation

Currently in the United States there is about 1,051 megawatts of microgrids deployed.\textsuperscript{18} The majority of these are located and facilitate factories, college campuses, hospitals, and military bases.\textsuperscript{18} Most of the current installed capacity and microgrid programs have stemmed from the benefits of reliability and resiliency.\textsuperscript{18} The overall benefits of renewable integration has not been in the forefront of microgrid implementation. After the devastating effects of Hurricane Sandy many policy makers examined ways to fortify and make the electric grid more reliable during times of extreme weather when reliable electrical power was crucial. States along the east coast, such as New York and Connecticut, have developed incentive programs for microgrid deployment due to the impact of recent hard hitting storms including Hurricane Sandy.\textsuperscript{19} Microgrids also provide the ability to deploy renewable energy sources, decrease emissions per unit of power used, and allow the grid and institutions that depend on the microgrid to become more efficient and resilient.\textsuperscript{20} Storage on the microgrid is a key element of utilizing the benefits of renewable and California recently put in place a 1.3 gigawatts of energy storage program by 2020 that could ultimately lead to financial incentives for microgrids.\textsuperscript{18,19} California also allocated $26.5 million to microgrid projects that focus on integration of renewables.\textsuperscript{18} The widespread implementation of microgrids still faces many challenges and obstacles. Technical, financial, and regulatory issues must all be addressed.\textsuperscript{19} Three prevalent barriers to the more rapid and universal deployment of microgrids are: convincing the public that the overall benefits outweigh the costs required to install them, figuring out how to put cost value on reliability, and updating current regulations.\textsuperscript{20} Though challenges do exist, the overall benefits are profound and microgrid advancements are being made.

Many different rules may apply depending how a microgrid operates and many state’s laws are not clear about the legal status of microgrids.\textsuperscript{21} In much of the United States the electric utility system is owned and operated by a monopoly distribution system operator (DSO).\textsuperscript{22} This makes it hard for independent microgrid developers to install infrastructure and make any modifications that would allow the microgrid and the main grid to operate optimally together.\textsuperscript{22} Issues that need to be addressed include: the connection of the microgrid to the main grid, the location of the microgrid infrastructure, how is the microgrid funded, the regulation of the power generated on the microgrid, and how the utility adjusts procurement and resource adequacy with consideration to microgrid deployment.\textsuperscript{22} There is a growing number of research projects that are being done in the development of microgrid technology and some states are addressing the regulatory issues. However, due to the current regulatory environment this is a slow process and until the regulatory framework makes microgrid development simpler, microgrids simply will not grow beyond niche applications.\textsuperscript{23}

### The Micro-Microgrid or Nanogrid

Critical facilities such as hospitals, fire stations, and data centers depend on a reliable source of electrical
power. To ensure consistent electrical supply critical facilities will often install their own equipment to facilitate the generation of electrical power should the main grid go down. Along with improving the reliability, microgrid technology provides the opportunity and desired infrastructure for improving the efficiency of energy consumption in buildings. Commonly referred to now as a nanogrid, a nanogrid may range from a laptops battery and plug to a buildings onsite storage and generation or just the energy management system. Many of the same benefits that come with microgrids can be found with installing nanogrids. Increased reliability is the largest factor leading to nanogrid installation. Another large benefit to nanogrid installation is peak shaving. With current technology in energy management systems (EMS) coupled with a storage device, usually a battery system, there is potential for customers to save substantially on electrical usage.

One company moving this technology forward on the grid and building scale is Stem Inc., a start-up based out of California. Stems system uses storage and management software to lower peak demand and therefore the customers energy bill. Stem is taking a different approach to marketing the microgrid and nanogrid by focusing on the customers cost of electricity and their ability to reduce peak demand, a significant factor to business energy bill. Stem also promotes the added benefit of the customers overall peak shaving on the main grid as well as offering utility services. Recently Stem received a $1 million dollar grand for a project that includes installing 1 MW of storage and control systems on the island of Oahu to help with the integration of renewables. With the proliferation of renewables in the commercial and residential markets solutions such as Stems will increasingly become essential to maximize the benefits as well as protect the main grid.

Energy efficiency within buildings can also be achieved through the use of a nanogrid. Renewable energy sources can be installed for building microgrid DER in areas that have an abundance of resources. The buildings electrical and thermal loads can also be supplied by a combined plant within the building. Combined heat and power (CHP) plants supply a building heat loads as well as a good amount of the electrical load. By combining the thermal and electrical loads the efficiency of energy generation can increase by as much as 25 percent.

Conclusion

Over the next few years and decades the energy industry will be at the forefront of change and innovation. With strong pushes due to environmental concerns the methods of generating the electricity the world uses will be forced to ever cleaner sources. Also with the aging electrical transmission and distribution infrastructure concerns over grid reliability will grow. The electrical distribution system will be required to undergo advancements utilizing the latest technologies and practices. Microgrids provide a means to ultimately balance the needs of the future with the technology of today. A properly deployed microgrid provides improved grid reliability and resiliency. The use of storage on the microgrid allows for the full utilization of environmentally friendly renewable sources of energy such as solar and wind. Challenges are still prevalent in the wide spread implementation of microgrids throughout the United States and the world, however, the benefits are sound and progress is currently underway. From the nanogrid to the microgrid all the way to the macrogrid the way electricity is delivered to end users is changing. The science is being developed in full force. The regulation controlling the implementation of that science needs to follow suit.

References

8. Battery University, Is lithium-ion the ideal battery? (2014), http://batteryuniversity.com/learn/article/is_lithium_ion_the_ideal_battery.
14. ComEd, ComEd awarded grant from Depart-
15 Burns-Group, 14. alstom and burns team wins department of energy grant (2010), http://
eteam-wins-department-of-energy-grant.
17 Cyber secure microgrid (2012), http://iper.com/?page=
cyber_secure_microgrid.
18 J. St.John, California ready to fund the next wave of microgrids paired with renewables and storage (2011).
microgrids_power_and_regulations/.
22 C. Villarreal, D. Erickson, and M. Zafar, Microgrids: A regulatory.
23 S. Lacey, Here’s what utilities really think about microgrids (2012), http://