Resilient Electric Grid (REG)

Combining Transmission Level Power at Distribution Level Voltages with Fault Current Management to Enhance the Safety, Security and Load Serving Capability of Urban Electric Grids.

A white paper by AMSC®, September 2014

Executive Summary

Increasingly intense weather events, terrorist threats, and aging infrastructure… These are all challenges that the world is facing today. These challenges represent significant threats to the electric grid, which is fundamental to our way of life. Without reliable power, basic human needs, such as food, clean water, and protection from the elements would quickly become a challenge. The economy would grind to a halt without access to fuel, banks, and the Internet. In short, a reliable and resilient electric grid is central to our safety, security, and economy.

Consider just a handful of recent events:

- **Weather:** When Hurricane Sandy swept ashore in October 2012, 8 million utility customers along the Eastern Seaboard, including major centers of economy, were without power for days and weeks and fuel distribution networks were paralyzed.[1] The White House has estimated that power outages caused by severe weather between 2003 and 2012 cost the United States economy somewhere between $18 and $33 billion.[2]
- **Equipment Failure:** In March 2012, an event at a substation in Boston caused a fire and a two day blackout in one of the city's busiest residential and commercial neighborhoods. Equipment failure caused similar outages at the same substation again in May 2012 and in June 2013.[3]
- **Terrorism:** In April 2013, snipers opened fire on a substation in Silicon Valley. The former chairman of the Federal Energy Regulatory Commission (FERC) called the attack the most significant incident of domestic terrorism involving the grid that has ever occurred. In fact, the former chairman believes that if a surprisingly small number of substations were knocked out at once, the entire system could be destabilized enough to cause a blackout that could encompass most the United States.[4] Terrorist organizations around the globe were linked to 2,500 attacks on transmission lines or towers and at least 500 substations from 1996 to 2006.[5]
- **Cyber Security:** Beyond physical attacks, cyber attacks could take down the grid by disabling internet communications and important pieces of equipment. According to a Wall Street Journal analysis of emergency reports that utilities file with the federal government, 13 cyber incidents have occurred in the past three years.[6]

Beyond providing resiliency during calamitous events, urban utilities are also challenged with population growth. The population in "urbanized areas"[7] is growing at a faster rate (14.3% from 2000 to 2010) than the overall population growth (9.7% from 2000 to 2010).[8] In fact, 71.2% of the U.S. population now lives in urbanized areas. There are strong efforts underway to improve efficiency and add distributed generation where possible, however, this is likely not enough. Increasing load creates a substantial challenge for urban utilities. Adding facilities and equipment is more expensive in the urban environment because of the higher cost of land. Additionally, in the urban environment, reliability requirements are more strict and operating requirements, such as noise, safety, footprint, and access are more difficult.

The REG System

AMSC's Resilient Electric Grid system is designed to interconnect critical urban substations, enabling them to share transmission connections and excess station capacity, while controlling the high fault currents that naturally result from such connections. By enabling the sharing of assets, urban utilities can "keep the lights on" and ensure the safety and security of residents following calamitous events. Additionally, interconnecting substations can enable utilities to increase the load serving capacity of existing substation equipment.

Many times, current urban substation design provides for redundant capacity. However, that capacity is typically not accessible by the rest of the network. By interconnecting substations, utilities are able to utilize the redundant capacity that is already built into the system. This provides added reliability in the event that one substation is rendered unusable and increased load serving capability during normal conditions.

[1] Sandalow, D. (2012, November 30). Hurricane Sandy and Our Energy Infrastructure. Retrieved from: http://energy.gov/articles/hurricane-sandy-and-our-energy-infrastructure

[2] Executive Office of the President. (2013, August). Economic Benefits of Increasing Electric Grid Resilience to Weather Outages. http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf

[3] Young, C., Botelho, A. (2013, June 9). Power now restored to Back Bay residents after early morning outage. *Boston Globe.* http://www.boston.com/metrodesk/2013/06/09/power-outage-leaves-the-dark-back-bay-and-traffic-problems-should-restored-noon/Rog34GUpAW2BYOHroSLzZO/story.html)

[4, 5, 6] Smith, R. (2014, February 5). Assault on California Power Station Raises Alarm on Potential for Terrorism. *Wall Street Journal.* http://online.wsj.com/news/articles/SB10001424052702304851104579359141941621778

[7] Urbanized areas defined as 50,000 or more people.

[8] United States Census Bureau. 2012. Growth in Urban Population Outpaces Rest of Nation, *Census Bureau Reports.* [Press Release]. Retrieved from: https://www.census.gov/newsroom/releases/archives/2010_census/cb12-50.html

HTS – The Enabling Technology

The REG solution is enabled by AMSC's second generation (2G) high temperature superconductor (HTS) wire, an inherently smart material. A superconductor wire has extremely high levels of power density, which means that it can carry extremely large amounts of power within a very small cross section of material. It is also inherently fault current limiting. Traditional copper material does not have the power density or the fault current limiting features required to interconnect substations.

AMSC's superconductor wire is made up of HTS material, which is sandwiched between two layers of metal laminate. When the wire is running in its normal state, the power flows through the superconductor element of the wire. When fault current passes through a superconductor wire, the current moves from the superconductor material to the outer metal layer. This causes the wire to instantaneously become resistive, which limits the fault current and can eliminate the risk of fault currents causing damage to expensive pieces of equipment and power outages. Once the fault is cleared, the wire returns to a normal, superconducting state.

AMSC is uniquely able to provide an HTS cable system with inherently fault current limiting capabilities. The Company has designed and patented the HTS fault current limiting cable design and also has a portfolio of fundamental 2G HTS patents. AMSC has completed nearly a dozen HTS projects around the world, including a 138 kV, 610 meter transmission voltage installation with Long Island Power Authority (LIPA) and 22.9 kV Alternating Current (AC) cable system with Korea Electric Power Corporation (KEPCO).

Alternatives to REG System

Traditionally, if a utility wants to increase capacity, the standard option is to build a new substation or expand an existing substation. Building or expanding a substation often requires the acquisition of land which is an expensive proposition in the urban environment. New substations require new transmission lines into the substation, new transformers, and all the associated protection and switchgear. Depending on the city, expanding an existing substation or building a new substation can cost anywhere from the tens of millions to over one billion dollars.

If a utility wants to increase reliability, there are two traditional options. The first is to build new substations. This will break the city up into more, smaller pieces from a service standpoint. If one substation goes down, then a smaller section of the city is impacted. This marginally minimizes the risk at a high cost. The second option is to add more transmission circuits and distribution transformers, meaning the utility's reliability will go from N-1 to N-2 or from N-2 to N-3, and so on. However, this will result in increased fault current levels on the system. To protect against faults, the utility will have to replace breakers or rebuild large sections of the grid to a higher voltage. Both of these options can cost into the billions of dollars.

The Resilient Electric Grid system is unique because it is expected to benefit both reliability and capacity without the high cost of land acquisition and challenges such as higher fault current risk that come with the traditional solutions.

The REG System

REG systems provide utilities an option to increase urban reliability and capacity that is better performing, easier to site and install, and is ultimately lower in cost than traditional options. This is achieved via two major applications: interconnecting urban substations and allowing for simplified new urban substations.

a. Interconnecting Urban Distribution Substations

REG systems allow utilities to interconnect urban substations at the distribution level to provide higher levels of reliability than is possible otherwise. In most urban distribution systems, many substations are used to each serve a particular part of the grid, whether via a secondary network, radial distribution feeders or a combination of the two. While these substations are generally interconnected at the transmission voltage side (69kV, 115kV, 345kV, etc.) they are not typically interconnected at the distribution voltage side (12.5kV, 13.8kV, 34.5kV, etc.). The number of transmission interconnections and transformers at each substation are such that if there is a failure of one or two of these components, loads will continue to be served. In other words, these grids are operated with an "N-1" or "N-2" level of reliability. However, if more components are lost, there is no "backup system" to continue to serve load and blackout conditions may occur.

REG systems allow urban substations to be interconnected at distribution levels, just as the transmission system is interconnected, because they allow the movement of transmission level power at distribution level voltages. This means that with a REG solution, a "backup system" is created by allowing urban substations to support each other in the event of a large number of transmission or transformer outages, resulting in N-3 or N-4 levels of reliability. In addition, REG systems effectively allow existing components, such as transformers,

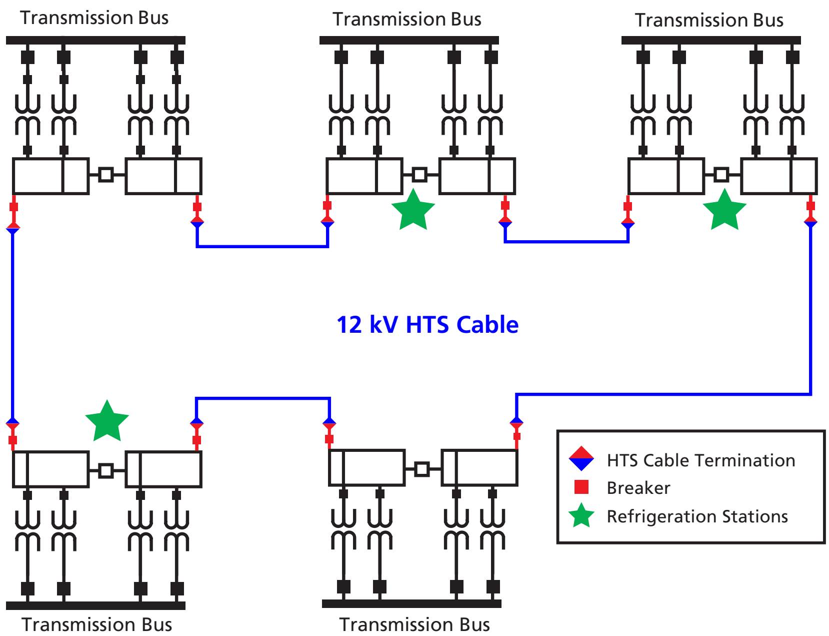

Fig. 1

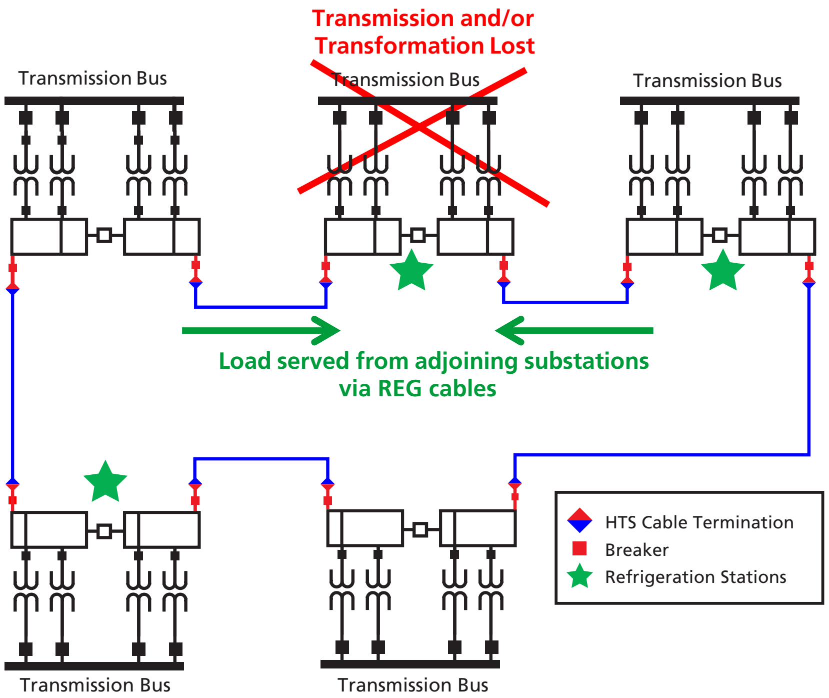

Fig. 2

that are underutilized (due to redundancy or deviations from load forecasts) at one substation to help serve load at another substation, effectively increasing the overall load serving capability of the grid.

An example of using REG to interconnect urban substations is shown in Figure 1. This example shows five urban, distribution substations interconnected by REG cables to form a loop.

This configuration is more reliable because in the event of multiple transformer failures or the transmission system serving any one of the substations becomes unavailable, the load at that station can be served directly from the adjoining stations (Figure 2).

In addition, because each substation has redundant transformers to provide N-2 reliability individually, the act of networking the substations at the distribution side allows the spare capacity of those transformers to be utilized for load capacity, while still maintaining redundant transformers. That is to say that before the REG cables are installed, each substation required two spare transformers to provide N-2 reliability, resulting in ten spare transformers among the five stations. However, once the substations are interconnected, only two spare transformers are required for all five substations combined. This means that the additional eight spare transformers are now available to serve load.

The benefits to the grid as a result of this application include:

- General increase in reliability of the electric grid serving the urban area from "N-2" to "N-4"
- Ability to supply the load at any substation in the event of loss of the incoming transmission lines or transformers serving any single substation
- Increase in load capacity by allowing transformers that were previously kept as "emergency spares" to be utilized to serve load
- Allow planned or emergency maintenance at critical urban substations without interrupting service

b. Simplified New Urban Substations

In some cases the correct answer to increasing reliability and load serving capability is the addition of a new substation. However, a new substation traditionally requires multiple transmission feeds from separate sources and multiple transformers to achieve the desired level of reliability. This results in a large and expensive project that can easily reach into hundreds of millions of dollars.

REG provides an alternative approach. Instead of installing a traditional "transmission to distribution" substation near the urban center, REG systems allow the distribution transformers to be installed at a remote substation where space is less expensive and available and associated construction work is also less expensive and disruptive. Power can then be brought into the urban area via REG cables at distribution voltage levels. This results in an urban substation that requires neither transmission feeds nor power transformers and their associated switchgear, protection and other equipment. The net result is a far more compact substation at a lower cost. Further redundancy can be achieved by utilizing additional REG cables to connect between existing urban substations, resulting in increased reliability not only for the new station but also for the existing stations.

Again, the high power density (resulting in compact right-of-ways) of REG technology provides a new solution option to utility engineers that is not possible with copper cables.

New Urban Substation Scenario

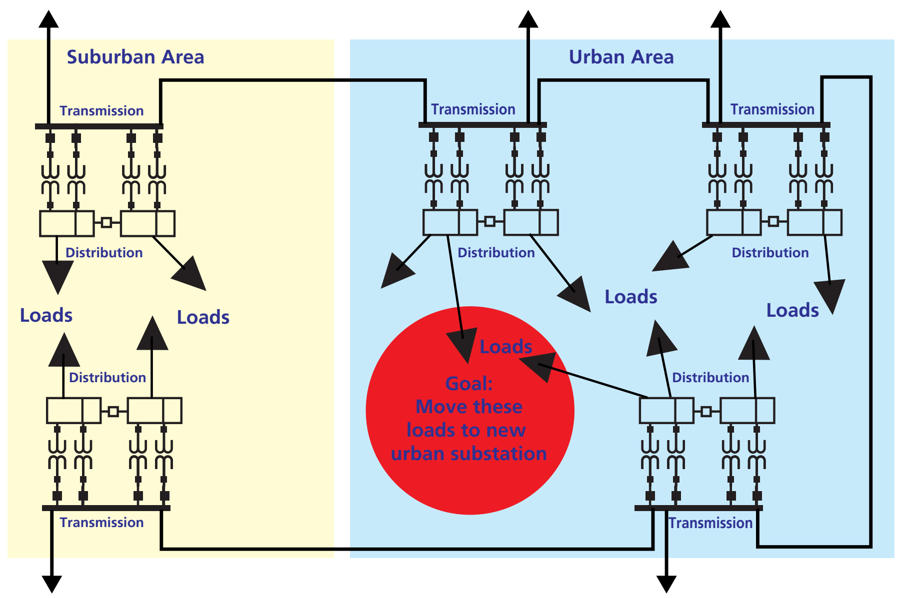

Fig. 3

Traditional Solution: New Full Transmission/Distribution Urban Substation with Similar Transmission Connections

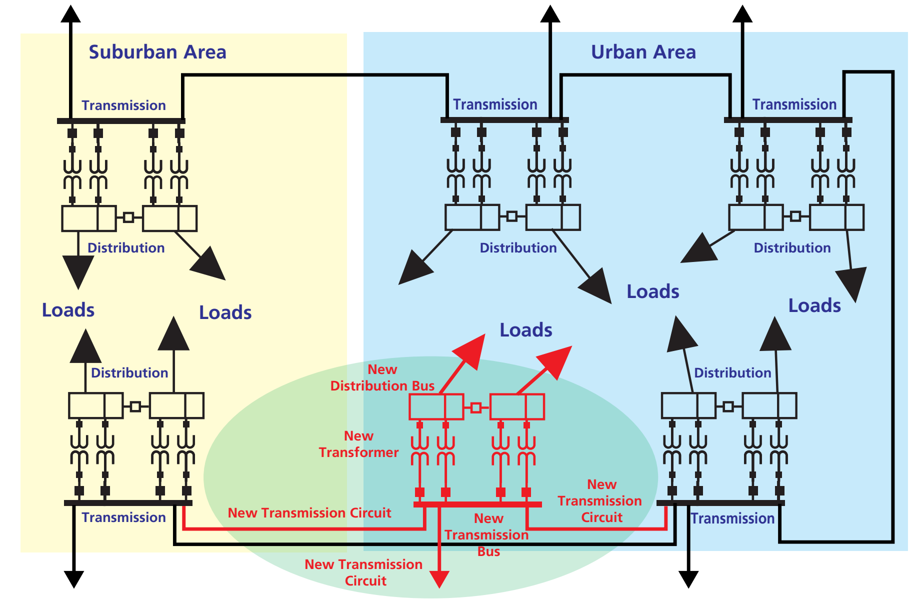

Fig. 4

REG Solution: Transmission & Transformation in Suburban Area, Distribution Only Substation in Urban Area

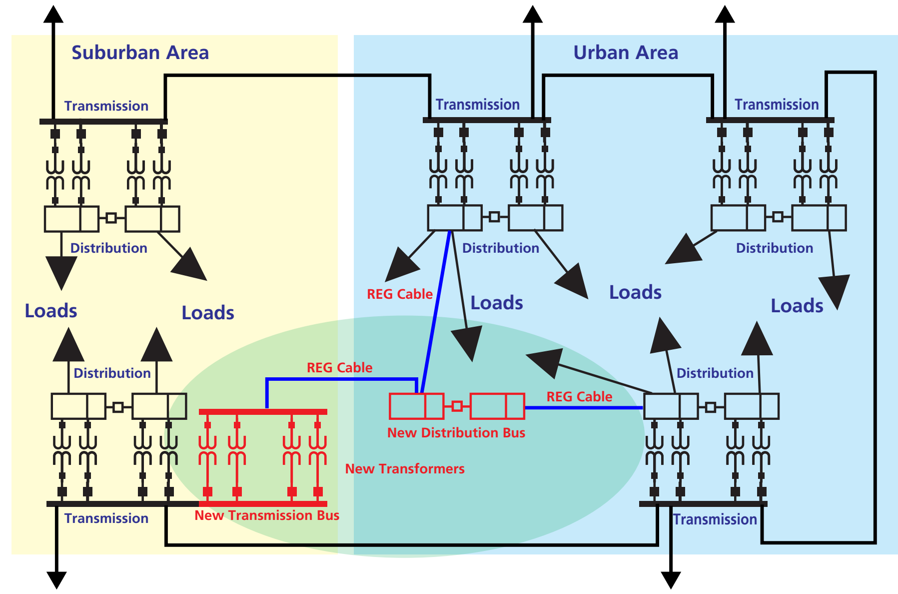

Fig. 5

Figure 3 shows an example scenario where additional load serving capacity is needed in an urban area. Note that current level of reliability for the urban substations is "N-2", meaning that for any substation, two transmission circuits can be removed and the load could still be served, which is common in major U.S. cities (compare this to the suburban area which has only "N-1" reliability).

Figure 4 shows the traditional solution of installing a full transmission to distribution substation in the urban area, which is then connected to the greater transmission grid via three circuits in order to maintain the same level of N-2 reliability as in the existing urban substations. This approach requires three transmission circuits, all of which are fully or partially located in the urban environment as well as four transformers and associated protection and switchgear, again, all of which are installed in the urban environment.

Figure 5 shows an alternative solution using REG technology. In this scenario, the new transformers are installed at a suburban substation, no new transmission circuits are installed, and the new urban substation is only a simple distribution bus interconnected to the greater system via three REG cables. This solution has significant advantages. It reduces the equipment and work needed in the urban environment, which substantially reduces the cost of the project. This solution also minimizes disruption and maintenance requirements in the urban area. Finally, the solution increases the reliability of two of the three existing substations at the distribution level by including them in the REG network. The addition of another REG circuit from the new substation to the fourth urban substation would result in blanket increase in the reliability of the entire urban area to N-3 in addition to increasing the load serving capability of the area by a similar amount as the traditional solution.

While the REG solution described above makes the assumption that the transmission feed to the suburban substation is sufficient to serve the new load and that there is sufficient room at the existing substations to install a REG system, it is clear that the REG system is likely to be less expensive than the traditional solution, especially in areas with very high property values and where performing major construction is costly and disruptive. Also, the installation of the transformation at the existing suburban substation will likely allow for better optimization of the transformers by reducing redundant components needed to achieve desired reliability levels and therefore ensuring better utilization of new and existing assets. This could result in a reduction in the total number of transformer units (and associated protection and switchgear) required.

The benefits of a REG solution in this scenario include:

- The general increase of load serving capability in the urban area (primary goal of the project)
- Substantially reducing the size of the urban installation
- Minimizing the cost and disturbance of urban construction
- Replacing difficult-to-site transmission

circits with easier-to-site REG distribution voltage cables

- The general increase in reliability of all substations connected to the new substation via REG
- Potential reduction in the total amount of transformation needed to achieve desired reliability levels

HTS – The Enabling Technology

The applications of REG systems described above take advantage of the key features of REG cables:

a) Power density

b) Ease of siting

c) Fault current limiting

a. Power Density

While technically, the current carrying capability of a REG cable can be extraordinarily high, the actual capability in AC power grids is typically limited by the availability of ancillary equipment such as circuit breakers and other switchgear, metering equipment, and so on. Therefore the practical limitation is generally 4000A, but in some cases can be 5000A or higher if gas insulated switchgear is utilized. While modern, 5000 kcmil XLPE cables can have base rating as high as 2300A in ideal conditions (90°C operating temperature, 20°C ground temperature, and depth, phase spacing, circuit spacing, and thermal backfill all per manufacture specifications), these ideal conditions are often very difficult to achieve in urban environments often resulting in a need to derate the cables by more than half. It is typical to consider REG cables as capable of carrying approximately 3-5 times the current as a conventional cable in a realistic (i.e. non-ideal) application. Figure 6 compares the rating of REG cables vs. typical XLPE cables (cross-linked polyethylene, the most common type of power cable used by utilities for today's projects) applications. The figure clearly shows that REG cables can provide transmission level power transfers at distribution voltages.

b. Ease of Siting

Unlike XLPE cables, REG cables are thermally isolated from the environment where they are installed, meaning that the current carrying capability of the cable is unaffected by the surrounding environment. This is an important factor for comparing the technologies from an installation perspective. The resistance in XLPE cables results in heat generation that must be dissipated into the environment. If the heat is not properly dissipated, then

Power Transfer Equivalency of REG Cables vs. XLPE Cables

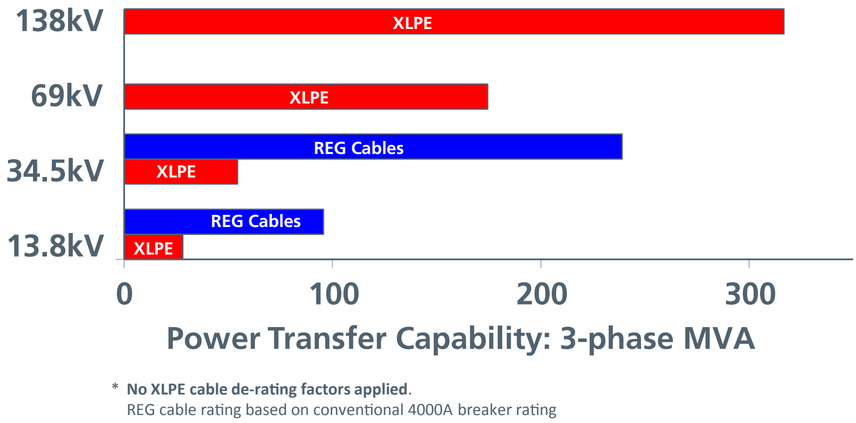

Fig. 6

the cable temperature will rise to a point where damage may occur. Heat dissipation is a function of many factors including depth of burial, type of soil, proximity to other heat sources (such as other cables), and ambient temperature. Generally, if any of these factors result in heat dissipation that is not as efficient as assumed by the cable manufacturer (i.e. the cable is buried deeper than intended or the spacing between phases is smaller than intended), then the cable must be operated at a lower-than-rated current (i.e. de-rated). This is not a concern for REG cables, meaning that there are fewer constraints when siting and installing REG cables. Furthermore, REG cable configurations typically have all three phases of the circuit in a single cryostat, meaning that only a single "cable" is installed per circuit, rather than three separate single-phase cables per circuit as is required for medium and high voltage XLPE cables. Finally, like all shielded superconductor cables, REG cables emit extremely low electromagnetic fields relative to a typical copper cable or overhead line. This further reduces siting limitations as the electromagnetic field from non-superconductor cable can interfere with certain communication systems or create other siting challenges.

Installation of only a single cable and fewer installation requirements are particularly important features to consider in urban environments where, below the city streets, there is often a maze of utility infrastructure such as power cables, telecommunications, water, steam, gas, etc. (See Figure 7). As a result, minimizing the amount of equipment installed and the additional flexibility in the siting requirements of REG cables is expected to result in lower installation costs than that of equivalent XPLE cables.

Photo courtesy of Consolidated Edison

Fig. 7

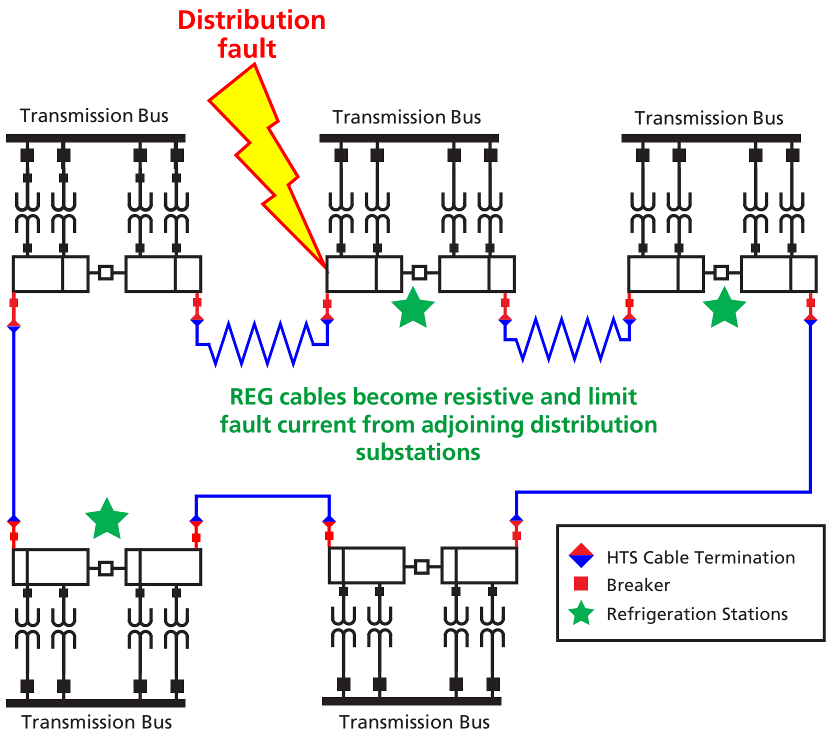

Fig. 8

c. Fault Current Limiting

The fault current limiting aspect of REG cables is a truly unique and very important aspect of the technology. Like all superconducting cables, REG cables only operate in the superconducting state (i.e. zero resistance) when the current in the cable is below a maximum current level. The exact value of the maximum current is designed into the cable by AMSC and our cable manufacturing partners.

In the event that the current in the cable exceeds the maximum current, which generally happens if there is a system fault nearby, the cable will instantaneously become resistive, effectively adding a significant amount of impedance to the system. The addition of this impedance results in lower system fault current levels than would be seen if the cable did not have this feature. AMSC designs REG cables using techniques and materials to maximize the resistance of the cable during fault conditions, maximizing the benefit.

This fault current limiting feature of the cable is the final unique attribute that makes REG cables a very powerful solution to improve reliability on urban grids.

It should be noted that there are two primary reasons that substations are not typically interconnected at the distribution level. First, the amount of power that would be needed to fully backup an entire urban substation at distribution voltage levels would require many conventional copper cable circuits, which is simply not practical in areas of very high costs for right-of-way and construction. Second, interconnecting distribution substations will result in a significant increase in fault current levels, often well beyond the limits of the existing breakers. This would result in the need for a very expensive upgrade and the creation of a more dangerous and expensive system to operate and maintain.

Recall the previously discussed application of interconnecting urban substations. If conventional copper cables were used to make the interconnections, the fault currents at the newly interconnected distribution buses would increase dramatically, requiring expensive upgrades and equipment replacements. However, if interconnected with REG cables, this issue is resolved by their fault current limiting capability (see Figure 8).

Alternatives to REG System

Compared to the alternatives provided by REG technologies, traditional solutions to increase reliability and load serving capability in urban environments have significant drawbacks. They often require significant land or right of way acquisition, significantly increase fault current levels, increase system vulnerability during construction and/or can be very expensive.

The traditional solution options generally include:

a. New Transmission Assets

b. New Conventional Substations

c. Rebuilding to Higher Voltage Levels

a. New Transmission Assets

The most readily available solution to increase reliability in urban areas is to add transmission overhead lines or cables. Overhead lines are often not an option in urban areas due to the inability to obtain right-of-way and, even if right-of-way is available, there may be public opposition to the aesthetics of a new transmission line in a densely populated area. Traditional transmission cables are less problematic in terms of obtaining right of way and public opposition but have the disadvantage of carrying far less current. This is particularly true if underground space constraints require the cable phase to be near each other or another electric circuit or placed deep underground or near some other source of heat. All of these scenarios require the cable to be derated to avoid overheating.

Regardless whether overhead or underground solutions are selected, new transmission assets will result in an increase in fault current within the urban area. Dealing with the increase in fault current may require replacing protective devices, rebuilding substation bus work, or splitting up the system (resulting in reliability reductions).

Furthermore, by themselves, new transmission assets generally don’t increase load serving capability, as this is typically limited by the number and size of transformers in the urban area.

Compared to new transmission assets, REG solutions require less right-of-way, are easier to site without derating, limit any increases in fault current, and can provide increased load serving as well as reliability increases all while carrying a similar amount of power. The net result is that REG technology provides a more cost effective and higher performing installation.

b. New Conventional Substations

This option involves construction of a new substation and increasing load serving capability by transferring a portion of the existing load from existing substations to the new one. This is typically a large, complex, and expensive option because the new substation must have the same level of reliability as the existing substations, meaning it cannot simply be a single transformer fed by a single transmission line. Instead multiple transmission lines (generally a minimum of two) and multiple transmission to distribution transformers (generally a minimum of three) are needed. This means that the substation must be large and multiple transmission rights-of-way are needed.

In most urban areas, the most severe limitation on new substations is the requirement to acquire the significant amount of land needed for the substation and public opposition of the substation in the neighborhood. In one specific case, Consolidated Edison of New York indicated that a new substation in their service territory was estimated to cost $1.1 billion.

Further, new substations only provide minor increases in reliability. They do further segment load so that outage events affect a smaller percentage of customers, but they do little to increase the reliability standard of the grid.

REG solutions can provide new load serving capability in urban areas at a price that is likely to be much lower than this traditional solution. This is because REG technology will allow the utility to install the largest parts of new substations – the transmission voltage switchyard, transformers and associated protection equipment – outside the urban area in a location where land acquisition and the cost to perform construction is much less expensive. Further, REG solutions can allow for substantial increases in the reliability standard of the area which is generally not provided by a new traditional substation.

Rebuilding to Higher Voltage Levels

This option involves the utility increasing the rated voltage of a portion of the system to the next voltage class. For example, a utility could increase the operating voltage of an existing circuit from 13.8kV to 34.5kV. However, such efforts are often extraordinarily expensive, difficult and risky in urban environments due to constraints on space and other circumstances which may require the components to be removed and then rebuilt. A particular concern is that while components are taken out of service during the construction phase of the project, there is increased risk that an additional event or equipment failure will result in a system outages.

Rebuilding also requires a utility to replace all substation transformers, switches, protective devices, metering devices, overhead lines, underground cables and customer distribution transformers that make up the system that is being rebuilt. The effort to do this is immense and such programs can easily take many years and over a billion dollars to execute.

REG technology can provide many of the benefits of a system rebuild, such as higher load serving capability while managing fault currents, and also increase the system reliability standard - all at a much lower cost.

Conclusion

REG systems offer unique capabilities and a major value proposition for electric power utilities facing the need to provide increased reliability and power capacity in the densely populated, urban environments that are home to centers of finance, trade and government, where reliable power is critical to security of any nation.

All electric utilities must be constantly aware of the possibility of failures from aging equipment and many electric utilities are dealing with increases in the frequency of severe storms and very often a threat of attack, whether physical or cyber, from those who would attempt to intentionally damage the city's infrastructure.

As our economies and technologies advance, so does the expectation of, and reliance on, a resilient power system. Higher levels of reliability are not just desired, they are expected and required. AMSC's Resilient Electric Grid systems can help utilities to meet these expectations and requirements, ensuring the safety and security of our critical infrastructure.

About AMSC

AMSC (NASDAQ: AMSC) generates the ideas, technologies and solutions that meet the world's demand for smarter, cleaner … better energy. Through its Windtec Solutions, AMSC enables manufacturers to launch best-in-class wind turbines quickly, effectively and profitably. Through its Gridtec Solutions, AMSC provides the engineering planning services and advanced grid systems that optimize network reliability, efficiency and performance. The company's solutions are now powering gigawatts of renewable energy globally and enhancing the performance and reliability of power networks in more than a dozen countries. Founded in 1987, AMSC is headquartered near Boston, Massachusetts with operations in Asia, Australia, Europe and North America.

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