Overcoming urban power distribution challenges with technology innovations

Executive summary

The people responsible for managing urban electric utilities are presented with a set of special challenges beyond those that face managers of suburban or rural substations. There are few pieces of distribution equipment designed specifically to meet the needs of urban substations. However, some technologies deliver solutions that are especially valuable to this market. This white paper presents suggestions for technology able to resolve the challenges of safety, increased power requirements, right of way and cost in urban substations.

The increased migration of people from rural settings to suburban/urban homes and workplaces continues to drive higher demand on municipal power distribution systems. Compounding the situation for the utilities is the fact that city dwellers also tend to be higher per-capita energy users. There are more users, and they each require relatively more power.

Our urban areas were originally electrified many decades ago. Like the water and sewer infrastructure, the power distribution network is showing its age. In coming years, utilities must devote increased attention to updating or replacing many elements of their urban grids in order to meet the growing demand and ensure availability.

Transmitting and distributing electrical energy within urban areas presents a number of special challenges that manufacturers are eager to solve. Whether installing new substations or maintaining existing locations, today's energy companies are using technology with features and functions able to address the unique needs of urban power users. Some of this technology represents step-wise enhancements to familiar equipment, while other devices represent functional leaps that require new ways of thinking.

This white paper will outline four special challenges faced by urban utilities: safety, "power density" or the ability to distribute more energy within the same physical space, right of way and, of course, cost.

After outlining each of the four power distribution challenges, this paper will go on to describe some of the technology options available to meet these challenges, including innovative features of traditional transmission and distribution equipment and non-traditional, hybrid devices that combine several pieces of equipment into a single, multi-function unit.

Challenge: Safety

In substations, as in most industrial environments, safety comes first. In suburban and rural settings, the main concern of utility managers is for the health of the technicians servicing the equipment. Because these substations are typically open-air and sited away from residential or commercial buildings, there is minimal danger to those living or working in the vicinity.

That is less true of urban substations. Because they are adjacent to or inside of buildings, or located below the sidewalks, their proximity to high-density pedestrian traffic puts the public at risk in the event of equipment failure.

"One of the greatest risks is a transformer fault and potential subsequent explosion, an event made more likely due to increased urban pollution and contaminant levels," says Joel Kern, an ABB product line manager for dry-type transformers. "Some transformers in under-sidewalk vaults spend much of their life partially or totally submerged by rainwater and runoff, creating an increased threat of a rusted transformer wall. If a short circuit or internal fault occurs on a transformer – a common failure mode in urban transformers under sustained high loads, the arc can create a large explosion that will blow through the top of the tank, sending up a geyser of pressurized, burning oil."

Then, there is the risk of arc flash incidents. On any day, there are between five and 10 serious arc flash incidents, with one or two people killed. When the flash occurs, it creates temperatures of approximately 30,000°F. That is hot enough to liquefy metal and create a superheated, shrapnel-laden pressure wave that will instantly ignite clothing and cause severe burns and blindness.

The life of urban maintenance crew members is even more at risk than their suburban and rural counterparts, because they typically work in closed vaults or confined spaces. In outdoor substations, any blast or oil discharge is widely dispersed to the atmosphere or the open yard area. In indoor electric rooms, those hazards are typically contained, and the potential harm from any sort of equipment failure is magnified for personnel in the area.

Solutions:

There are many technology solutions available to address the need for increased safety. In general, replacing or retrofitting equipment with more reliable devices creates some of the biggest strides in safety. Higher reliability means fewer maintenance visits, keeping technicians out of harm's way. So, as is often the case, equipment selected to address one challenge provides benefits by also addressing several other challenges.

Transformers

For transformers, safety is increased as the presence of insulating oil is decreased. Oil increases the likelihood of fire in the case of equipment failure. Because it is considered a hazardous material, an oil spill creates health issues and requires expensive cleanup.

Dry-type transformers eliminate insulation oil through a variety of technology approaches:

- Open-wound transformers that are vacuum-pressure-impregnated with a high-temperature polyester varnish.
- Vacuum-cast coil transformers, available with IEEE C57.12.0 and 180C Class insulation systems to protect them at the elevated temperatures often found in urban substations.
- Cast-resin transformers that feature windings hermetically cast in epoxy.

All of these dry-type transformer designs eliminate the chance of oil-related explosion. The absence of oil also makes them virtually maintenance free. They are an ideal solution for urban applications where transformers must be installed near or inside their place of use.

Where an oil-filled transformer is required or preferred, it is still possible to find safety-enhancing solutions. One example is the use of natural ester fluids which have a high fire point and are biodegradable. These fluids can be cleaned up and disposed of using standard cleaning methods rather than being treated as a hazardous material or toxic waste. It also provides greater risk mitigation on collateral damage from transformer explosion and fire. These and other traits enable it to be used safely indoors and in enclosed spaces, without additional fire safety measures.

Breakers

In extra-high-voltage (EHV) circuit breakers, it is possible to eliminate the risks associated with insulating oil by relying instead on gas-insulated breakers. The oil is replaced with sulfur hexafluoride (SF_6), an inorganic, non-conductive and non-flammable gas. This gas reduces the chance of explosion and subsequent oil-fueled fires to the extent that gas-insulated breakers are often referred to as being "explosion-proof."

One of the major operating benefits of many modern EHV circuit breakers is that they are engineered to operate over a wide range of transient recovery voltages. As an example, for many SF_6 gas-insulated dead-tank breakers, the traditional solution to interrupting what's referred to as a 90% short-line-fault included the addition of an external line to ground capacitors mounted at the breaker terminal or within three hundred feet or so of the breaker. As an alternative, there are circuit breakers engineered to perform these operations at interrupting ratings as high as 63,000 amps, without the need for additional external capacitors.

Switchgear

In switchgear, the greatest safety improvements are gained by replacing air-insulated with gas-insulated equipment, garnering the same benefits as described previously for transformers. In addition, gas-insulated switchgear is inherently a safer choice because live parts are enclosed in metallic, grounded vessels that require less maintenance. This reduces the amount of time workers are exposed to the equipment. In fact, gas-insulated switchgear cuts maintenance requirements in half while reducing the mean probability of equipment failure compared to air-insulated – a real technological advantage to critical power urban substations that cannot afford unplanned outages. Obviously this also reduces operating costs.

There are several, recent safety enhancements for medium-voltage, air-insulated switchgear – including design changes that contain or reduce the potentially deadly forces of an arc flash. These design changes include enhanced enclosures that better contain the gas and pressure resulting from an arc flash, protecting people working in or near the lineup. Interior ventilation openings are outfitted with specially hinged louvers that remain open to provide air flow during normal operation but are pushed closed by the high pressure of an arc flash. Sturdier hinges and enhanced latches keep the doors secure. The cabinets are vented using plenums that direct gas, heat and pressure safely to an exterior "safe zone."

"The chance of injury to maintenance crews can also be minimized by selecting new switchgear that incorporates protection from accidental contact with energized components," explains Ulf Andersson, ABB's Director of Engineering - Substations. "Switchgear is available with enhanced Ingress Protection Ratings achieved by embedding the bussing and enclosing of most or all of the active components. When someone touches the surface, it's not energized. To me, that makes tremendous sense in terms of the highest possible safety."

Retrofit safety solutions are also available that reduce or eliminate arc flash, making even older switchgear much safer to work around.

"For example, fault-current-limiting technology relies on an extremely fast-activating device to interrupt a fault current," explains Dr. Mietek Glinkowski, Director of Technology at ABB. "There are devices available that can detect and limit short-circuit current during the first current rise (i.e., in less than a millisecond). This is more than ten times faster than a conventional medium-voltage circuit breaker."

Another approach is exemplified in ABB's arc-suppressive Ultra-Fast Earthing Switch (UFES) that initiates a 3-phase short circuit to earth in the event of a fault. The extremely short switching time of the primary switching element, less than 1.5 milliseconds, in conjunction with the rapid and reliable detection of the fault, ensure that an arc fault is extinguished almost immediately after it arises – a huge safety advantage.

Another retrofit for older, medium voltage metal-clad switchgear is the use of remote racking systems. These electro-mechanical devices are used to operate, trip and release the circuit breaker at a distance, removing the technician from proximity to the equipment. Crew members can work more quickly and efficiently, because they don't need to suit up in cumbersome, full-body arc flash-protective Personal Protective Equipment (PPE).

Multi-function devices

Multi-function devices are becoming more common in the power transmission and distribution power industry. Adoption is far from widespread, due in part to unfamiliarity with the concept of two-in-one technology. Consider, though, that the idea of a phone and camera combination would have sounded outlandish just a few years ago. Today, that feature-merge is taken for granted.

”In transmission equipment, the disconnecting (power) circuit breaker (DCB) is one example of a multi-function device with a safety advantage,” says Andersson. “It has an inherent interconnect between the circuit breaker and disconnect elements of the device. Separate devices rely on operating procedures or external interlock systems, which provide less certainty of safety.”

“It’s interesting to consider the fact that most of today’s breakers require maintenance every 15-plus years or so,” observes Andersson, “yet we install disconnect switches that require maintenance every two-to-five years to isolate that breaker. The isolation of lines, transformers, etc., for operational or maintenance purposes, can be readily handled by the DCB, with a much longer service interval, creating the second, and probably bigger, safety benefit.”

Challenge: “Power density”

Urban utilities are under constant pressure to deliver higher levels of electrical energy but without any expansion of the substation or transformer space footprint. Because the equipment is typically housed in underground vaults or inside buildings, it’s tremendously expensive to increase the square footage to accommodate larger transformers and other hardware. In order to increase the power, utilities need solutions that provide greater power density.

“To deal with space constraints while accommodating increased power demands, utilities in many urban networks simply operate their transformers at loads above their rating,” says Kern. “It’s not uncommon to routinely run a transformer at 130 percent of the rated capacity, with occasional sustained higher loads, for the entire life of the transformer. This solves the requirement for serving increased demands in the same space but at the cost of greatly shortened equipment life.”

When replacements are required, utilities are eager to purchase equipment with higher ratings but only within a footprint comparable to the existing equipment. Aside from increasing overall output, up-rating may allow the utility to reduce the number of devices, potentially providing a significant footprint reduction.

Solutions:

Transformer

The best path to improved power density may be dry-type transformers and new EHV circuit breakers. In the case of dry-type transformers, one of their advantages is that they require less space than conventional, oil-filled units. With the conservator and other oil-system-related apparatus eliminated, the transformer footprint shrinks tremendously. Because of the greatly reduced risk of fire or explosion, less space is required in the electrical room for fire-suppression or firefighting equipment.

Breakers

There are several space-saving benefits created by gas-insulated EHV breakers. The first comes from the recent availability of 362 kV breakers that are actually rated to 420 kV. The ability to handle higher-voltage spikes makes it possible to install a relatively smaller breaker and still handle the higher voltages.

The other footprint reduction opportunity is created by the availability of EHV circuit breakers engineered to minimize transient faults in a substation, without the need for external ground capacitors. These capacitors, typically used to provide protection for maintenance crews when a breaker is shut down, are eliminated.

Multi-function devices

Multi-function devices like the disconnecting circuit breaker are especially valuable to urban utilities trying to get more power from every square foot of electrical room. These new hybrid devices create as much as a 50% space reduction compared to traditional power circuit breaker solutions.

Cables

“When we look at increasing capacity, cables are also a big deal,” Kern explains. “If you can push higher voltages through the cables, you become more efficient. Cities have a legacy of 5 kV systems but are switching to 15 kV systems, so the higher rated cables allow them to serve higher loads.”

Fiber optic current sensors

Utility managers also gain a space advantage by replacing traditional current transformers with fiber optic current sensors (FOCS) that measure current with a fiber optic loop placed around the conductor. This new technology creates footprint reductions of approximately 50% while increasing availability and reliability.

Additionally, replacing copper wire bundles with a fiber optic pathway also simplifies right-of-way issues.

Challenge: Right of way

While urban utility managers deal with many issues that would be foreign to their rural counterparts, perhaps the most city-specific challenges relate to right of way. Every utility must deal with obtaining the appropriate permissions and privileges, but that process can be especially vexing for big city utilities.

From a purely physical perspective, altering existing equipment or the spaces they occupy is comparable to adding a basement to a house that’s already built – with the occupants still living in it. It can be done, but it requires a major, costly construction effort with careful coordination of building operations and traffic and pedestrian flow.

The required permitting can literally take a decade or longer to complete as all of the various municipal entities, regulators and private property owners are brought into the process. Electrical projects are often delayed so they can be accomplished in conjunction with planned water, sewer or other infrastructure projects. Once the street is torn up and the hole opened, all work can be accomplished at once.

In addition to the hardware, there is also cabling to consider. Most urban installations won't permit new aboveground cabling, current building tenants aren't eager to have cables running through their spaces, and creating new holes below ground means safely navigating through a labyrinth of pipes, cables, conduits and other buried infrastructure.

Solutions:

"In a conventional communication environment, multiple copper wire connections are required to conduct the signals from sensors or instrument transformers back to the control house," explains Alejandro Schanakovsky, an ABB applications and support manager. "Each device needs its own set of wires, so the control cable bundle can be substantial. Installing or modifying these bundles creates significant right-of-way issues with potentially large engineering and construction costs, not to mention the cost of the physical copper wires. Instead, it's possible to rely on an IEC 61850-9-2 compatible merging bus unit to consolidate those signals and broadcast the data via a single fiber optic cable over an Ethernet network. This also creates tremendous labor reduction, because you don't have to run miles of control wires."

When used in conjunction with the FOCS described earlier, right-of-way issues are further minimized. For a three-phase power line, at least three groups of measuring cables are eliminated when FOCS are used with an intelligent merging unit interface. The cable and related auxiliaries can be done away with, simplifying connections to the primary equipment. Finally, since there is no magnetic saturation in FOCS, one set of FOCS can be used for monitoring, protecting, or even metering. In this way, cabling requirements are again reduced.

Challenge: Cost

Cost is a never-ending concern for all utilities that face constant scrutiny of their rates and revenues. It is common knowledge that prices for everything are higher in urban areas, and that is also true of power transmission and distribution system improvements.

Transportation, site, permit and labor costs all make improvements to urban utilities more expensive than similar improvements in suburban or rural settings. Utilities are eager to purchase solutions for the many challenges they face, but only to the extent that tight budgets allow. The pressure from consumers for the lowest possible energy costs, reflected in directives and regulations from various governing commissions and boards that must approve a rate hike, often makes it difficult to acquire the capital funds required.

Utility managers need to look beyond the first cost for new technology. A big-picture view, considering total lifecycle costs of new technology, can provide a readily supportable case for often making the needed investment in equipment with a higher first-cost price.

Lifecycle costs include all the factors listed in this paper, in addition to the operations and maintenance costs of old versus new equipment. Also part of the lifecycle costs are the penalties for outages. Residential outages are clearly irritating to users and may result in fines for the utility. The penalties for an outage that cripples urban data centers, corporate headquarters, or communication and transportation systems can incur much higher fines for the power provider.

Solutions

Transformers / switchgear

Dry-type transformers and gas-insulated switchgear, as an example, come with higher initial purchase price tags. However, they offer other cost savings benefits related to safety and installation.

For example, dry-type transformers do not require the same fire prevention measures (fire suppression systems, fire walls, oil containment basins, and the need to maintain a 25-50 foot clearance), reducing initial costs and insurance premiums.

“Compared to air-insulated equipment, gas-insulated equipment has a greatly reduced footprint,” Andersson says. “If I am building a substation using air-insulated devices, I may need two acres of land, while comparable gas-insulated devices may require only a half acre. Also, there are savings in the site acquisition and preparation costs. So when you look at the whole picture, GIS in an urban environment is absolutely a more cost effective approach.”

Applications - FDIR

“Fault detection, isolation and restoration (FDIR) applications also offer potential cost reductions,” Glinkowski says. “These applications directly address the huge headache and expense of precisely and quickly repairing faults that lurk somewhere in the spider web of underground vaults, channels and trays. FDIR can be a powerful tool supporting cost reduction in the more complex distribution arrangement found in urban areas.”

Monitoring

“Another source of maintenance cost reduction is the addition of asset health monitoring and automation technology, whether retrofitted to existing equipment or specified on new,” Kern says. “Data delivered by these newly-intelligent devices gives system managers instant, at-a-glance status reports on transformers, breakers, switchgear and other substation devices. Rather than having to respond urgently to a failed device, they receive an alert when operating parameters begin to deviate from what’s expected. This allows for a lower-cost, scheduled-maintenance response, with a higher likelihood that the issue can be cleared in a single visit. Having device-level operating data also reduces the need to dispatch crews to

make routine check visits on sites. Instead, system managers can remotely assess asset heath."

Multi-function devices

The multi-function devices mentioned earlier regarding space savings also create a significant reduction in operating costs. Disconnecting circuit breakers are a perfect example of how fewer installed devices mean fewer pieces of equipment to install and maintain, and a smaller number of stocked replacement parts required.

"Today's relays are an interesting example of multifunction devices," Andersson says. "If you look back at the 1960s, 1970s and 1980s, we used mostly electromechanical relays. They were single-function, hard-wired devices. There was an over-current relay, a differential relay, an over-voltage relay and so on. Today these devices are computers programmed with the algorithms to provide any one of multiple control, monitoring and protection modes. Because they are computers, you don't need as many copper wires for signals. This goes hand-in-hand with IEC 61850, which defines substation communications between devices and relays. Instead of thousands of wires carrying control signals, your communications are via much more compact fiber-optic channels."

Conclusion

The typical lifecycle of urban distribution equipment is significantly shorter than comparable equipment in a suburban or rural environment. Higher loads and harsh environments mean that an urban transformer may provide only five years of service before it needs to be replaced.
As utility managers specify replacement equipment, the typical approach is to simply look at the size or function of the existing device and write a spec for a close-match replacement. This is a relatively risk-free approach, but it fails to capitalize on the tremendous potential of today's technology.

Utilities might want to instead consider a clean-slate analysis focused on four key challenges: safety, power density, right of way, and total cost of ownership. Based on that analysis, the benefits of the using new power technologies becomes clear. These new devices and retrofits meet the increased power demands of urban markets utilizing a smaller footprint — saving first-costs and ongoing operational costs over the lifecycle of the substation. Further, technology now offers a variety of options to increase safety for workers and residents within substations located in densely populated areas, underground and inside buildings.

Urban utility managers can look to the latest technology as they look for ways to ensure reliable power for the bright lights of the big cities.

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