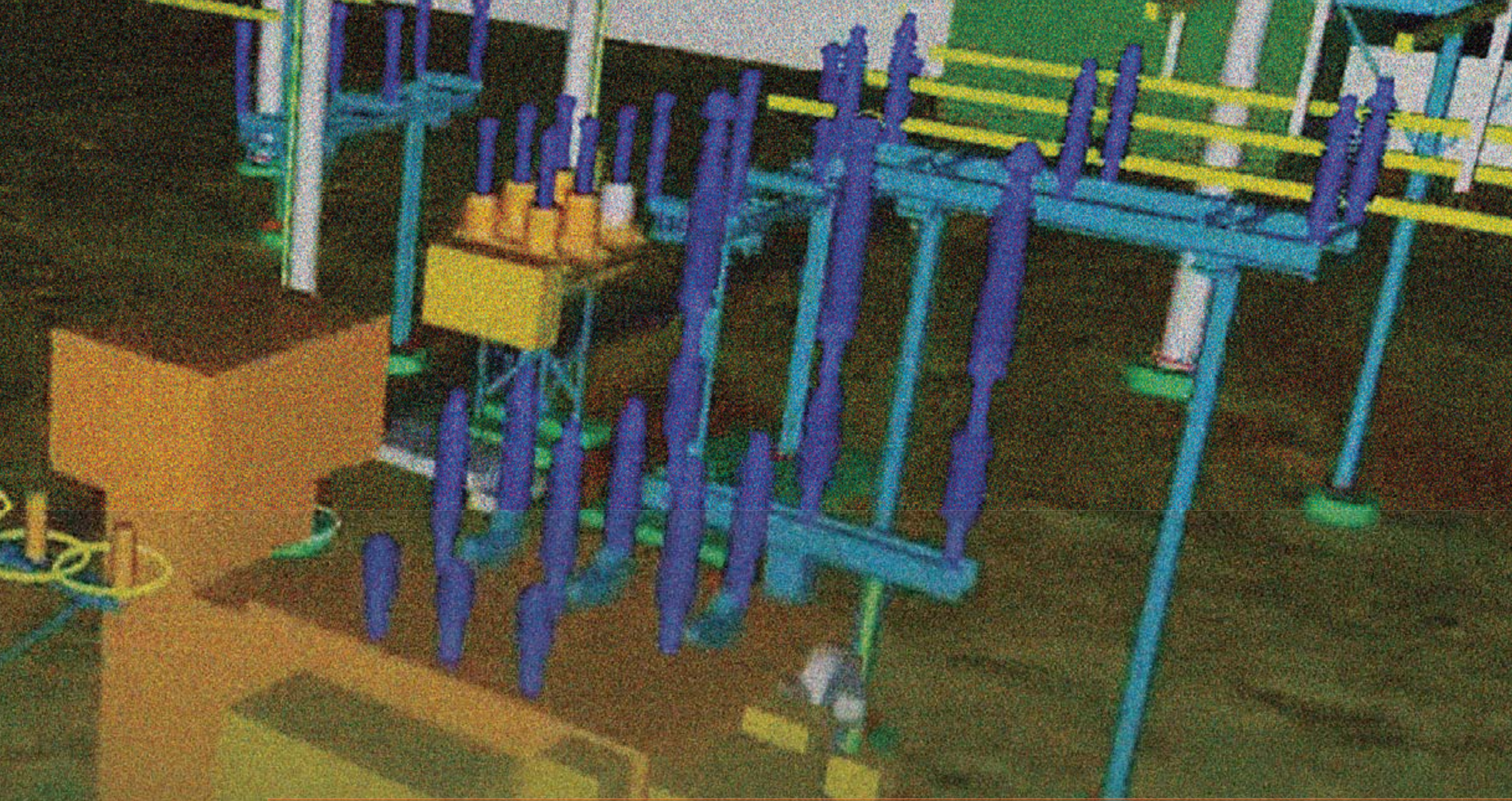


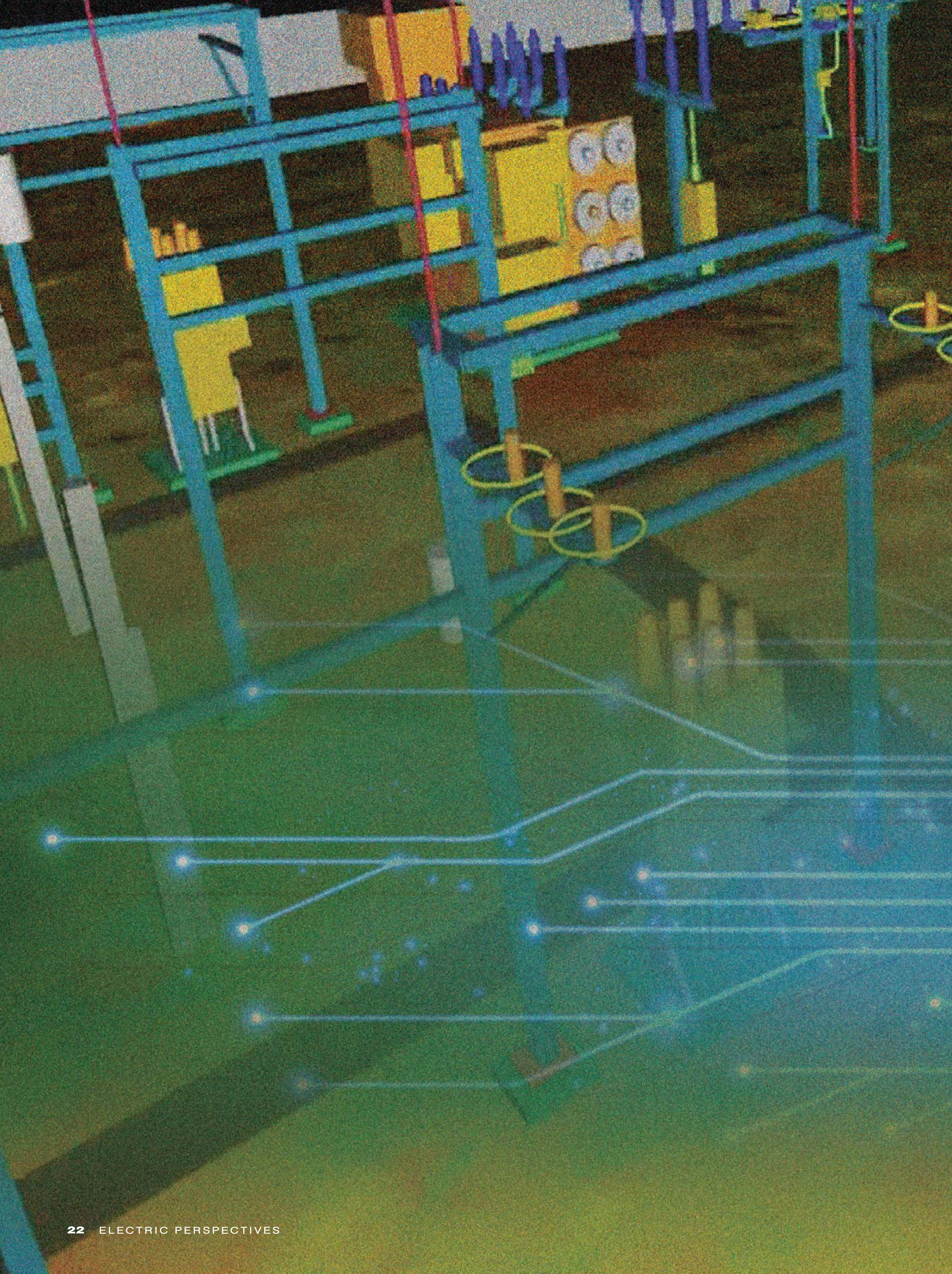
THE NEW SUBSTATION

Depending on the utility's needs, there are four different design approaches to the substations of the future. By Mladen Kezunovic

The electricity grid was invented in the 19th century and greatly expanded in the 20th. Recognizing the grid's complexity and relevance, the National Academy of Sciences declared the electricity system the world's largest "machine" and placed it at the top of the list of the greatest engineering achievements of the 20th century. The challenge facing electricity systems in future is to maintain the reliable and safe operation of this ever-expanding but already complex machine.

Technological, economic, and societal needs have driven most electricity system developments. And recently, a large emphasis has been placed on the use of renewable energy resources and the electrification of transportation, both affecting future development of the grid. As a result, grid expansion is

Bigstock



As the key to power system monitoring, control, and protection, the substation is the focus of many improvements that offer increased flexibility and higher reliability.

needed, but the reliability and safety challenges in an interconnected world expand as well. This concern was highlighted over the last decade by several widespread power system failures that had an enormous impact on the economy and livelihoods in both developed and undeveloped countries.

As the key to power system monitoring, control, and protection, the substation is the focus of many improvements that offer increased flexibility, higher reliability, and reduced lifecycle cost. The role of the substation is to connect major elements of the power system, such as transmission lines and power transformers, and to route power from one line to the next, thereby allowing the flow of electric power from generation point to customers. To reduce line losses (among other things), substations also use power transformers to change the voltage level between the transmission line and other parts of the system, such as distribution and generation. Last but not least, substations contain switching devices (circuit breakers) that are used to disconnect power system elements that experience faults; and they contain other control equipment, such as protective relays and voltage regulators.

To accomplish all these tasks, substations house high-voltage equipment, often called power apparatus or primary equipment, as well as low-voltage monitoring, control, and protection equipment, often called secondary equipment. The two types of equipment are interconnected in one physical location—the primary equipment located in the substation switchyard, and the secondary equipment located in a control house. Substations vary in size and voltage levels and can cost anywhere from a few hundred thousand to tens of millions of dollars.

Substation Design Challenges

An analysis of substation design criteria can demonstrate the benefits of improving substations. (See Figure 1.) And it should be noted that cost, reliability, operational flexibility, and environmental impact offer the most opportunities to improve the design to gain the highest returns on investment since such design features result in direct monetary benefits.

The key requirement is to provide integration along three leading design goals: implementation of improved design criteria; use of advanced technology; and an ability to upgrade in meaningful deployment stages. The challenges in improved design criteria

Mladen Kezunovic is a professor with the Department of Electrical and Computer Engineering at Texas A&M University. The views expressed here are the author's.

Modern substations have advanced equipment, some of which is highly dependent on such ever-changing technology as computers, sensors, and communications.

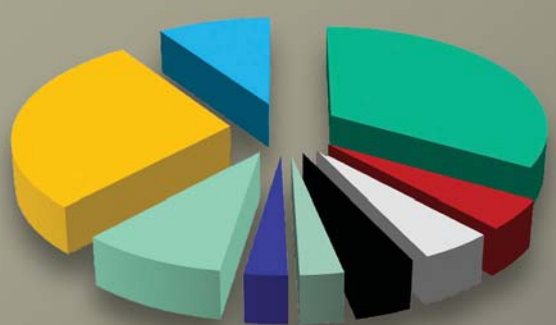


FIGURE 1

THE CRITERIA FOR SUBSTATION DESIGN

are to achieve multiple design features, such as operational flexibility and reliability, while reducing cost and making the design interoperable. Advanced technologies are readily available, but their integration in the existing design may not be straightforward due to fundamental incompatibility. This highlights the difficulty of proceeding in stages that allow both the upgrade of legacy solutions and the introduction of new designs in new substations.

Cost Factors

Cost considerations are not simple and depend on many factors.

What is the location of the substation, both electrically and geographically? The location determines substation importance in reliability of power system operation and environmental considerations, both having potentially huge cost impact.

What is the age of the substation? In general, the older the legacy design the more costly upgrades will be. Older substations not only may need a retrofit to achieve more operational flexibility, but also may require improved monitoring of aging assets.

What is the role of the substation in delivering power for a market-contracted power delivery transaction? Some substations have more elaborate connections to transmission lines in the system making them potentially a major bottleneck and risk for transfer of power among the connecting lines, which can have huge impact on reliability and the cost of operating the system. Upgrading such substations often generates a higher return on investment.

What is the operating experience from the past? If a substation has continuously experienced maintenance and reliability issues, the cost of upgrading may be easy to justify since a history of high expenses can be documented.

You need to have a long-term outlook. Modern substations have more advanced equipment, some of which is highly dependent on such ever-changing technology as computers, sensors, and communications. These factors certainly impact the substation's life-cycle cost, since future upgrades may cost as much as the original design and, if not managed properly, can introduce prohibitive costs down the road. Similarly, the designs that are not open to easy upgrades may create stranded assets that will be costly to replace in the future.

Technological Enhancements

Generally speaking, the technology for substation upgrades is well ahead of the ability of the substation users to gain its full advantages. Typical examples are new sensors and intelligent

The key cost savings in substation updates is in the substation wiring, including converting copper wires into multiplexed optical cables.

electronic devices that could offer tremendous benefits in enhancing operational flexibility, reliability, and safety, but are not yet fully explored.

The key cost savings in substation updates is in the substation wiring, including converting copper wires into multiplexed optical cables. With optical sensors, you can realize significant cost advantage through a direct transfer of all measurements in a digital form from the source to the destination using either optical or cooper cable.

Looking from the primary equipment side, many new power apparatuses are available now to enhance operational flexibility and meet demands for large power throughput and better controllability.

You can use new dry-type power transformers to minimize environmental contamination and fire hazards.

A static compensator, also known as "static synchronous condenser," is a regulating device that can be either a source or a sink of reactive power and hence may be used to control the flow of power.

The flexible alternating current transmission system control device may be used to control power flow, too, and relieve congestion on transmission lines.

Instrument transformers, such as voltage and current transformers used for relaying and revenue metering, can bring the high-level voltages and currents from the power apparatus to the low-level voltages used by the control and measurement equipment.

Optical cabling allows utilities to monitor power lines and interact with substations.

Electronic instrument transformers may use electronic components and connect directly to the fiber-optic cables to transfer the measurements from the substation switchyard to the control house without any isolating or auxiliary transformers.

Energy storage is typically battery-based but may use other technologies, such as ultra-capacitors, as well.

Video cameras and infrared cameras may be used to monitor security perimeters of the substation or to observe

A gas-insulated substation (GIS) in Saudi Arabia. GIS is used mostly where space is expensive or not available, or where harsh weather requires it.

potential heat sinks indicating potential equipment failures.

Design Conflicts

One conflicting regulatory and technological requirement is to make substations as flexible and elaborate as possible but at the same time comply with the stringent placement permits and environmental conditions. This often leads to designs for compact spaces, such as underground sheds or basements of high-rise buildings. To achieve such designs, the builder may have to use a sulfur hexafluoride (SF_6) gas-insulated substation (GIS). SF_6 is an inert, nontoxic, colorless, odorless, and nonflammable gas that is about five times as dense as air and provides two to three times the insulating ability of air at the same pressure—but it also is the most powerful greenhouse gas. A GIS is mostly used where space is expensive or not available or where environmental conditions require protected enclosure from harsh weather or environments.

This design conflict also exists in the mitigation of power transformer noise, vibrations, fire hazards, etc., that may have to be confined in an isolated place but require a more costly approach to make the substation equipment compact enough to fit into dedicated enclosures or building structures.

Substations in rural areas are much easier to handle, since the space and environmental hazards are not as stringent. This helps with the cost of the equipment and maintenance approaches because the open-air substations with exposed equipment are much more accessible.

Security Issues

Still, exposed open-air substation designs are also open to malfeasance—they are relatively easy to attack and inflict damage on. If you consider the cyber vulnerability exposed by the remote access to the all-digital secondary equipment in the substations, then you must take special care to protect this important power system physical-cyber infrastructure. While a cyber attack may be mitigated with an effective IT solution, perimeter security remains an issue since substations are frequented by a variety of utility maintenance and technical support staff.

One option to reduce a substation's vulnerability to physical attacks is to introduce a compact hybrid substation design where the wiring of the power apparatus is less exposed, the circuit breaker and measurement transformers are enclosed, and the control house contains the secondary equipment.

Future Design Approaches

As electric utilities look to the future, they may consider four different design

This design creates an opportunity for better correlating the market activity with the physical system in real time.

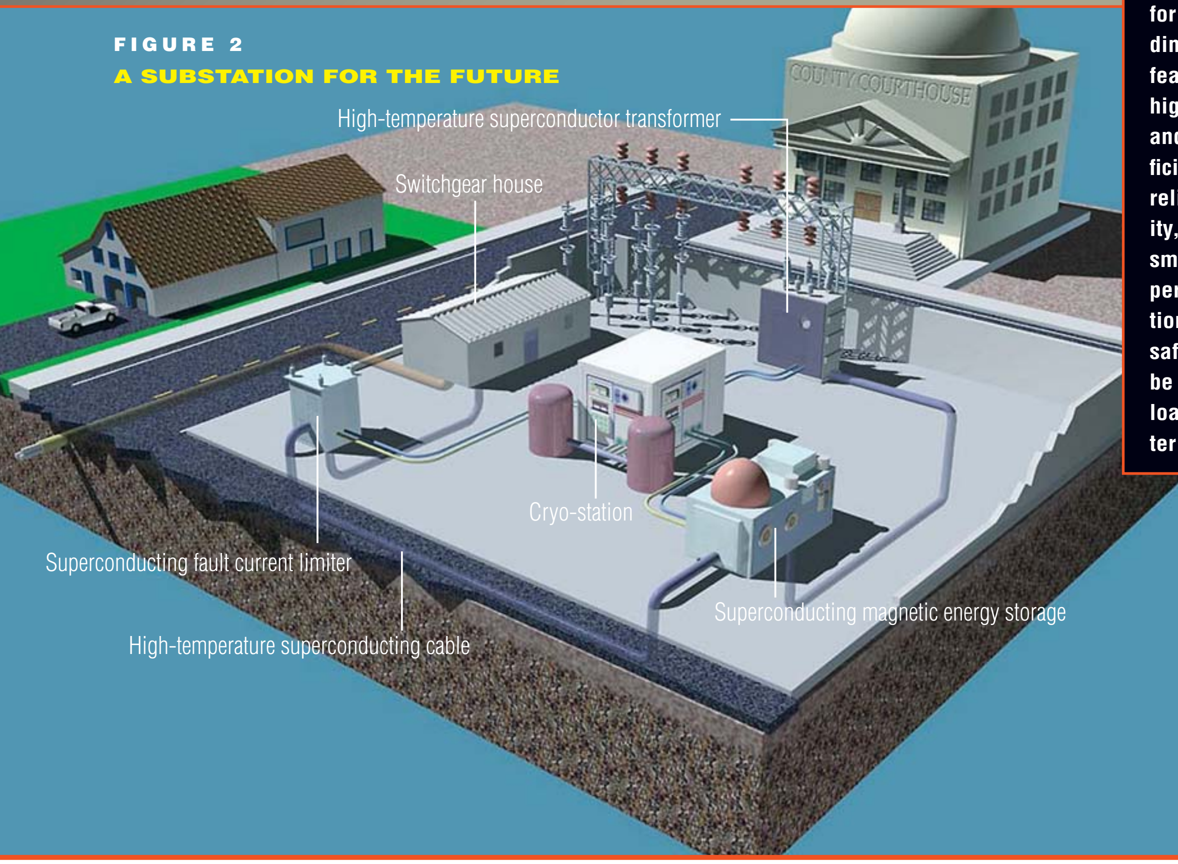


FIGURE 2

A SUBSTATION FOR THE FUTURE

Future substation designs will be based on superconducting technology and cost more due to an elaborate system for insulation coordination. Special features will include: high transmission and distribution efficiency; increased reliability, quality, and flexibility; smaller size (50-70 percent size reduction); heightened safety level so it can be located closer to load areas; and better aesthetics.

approaches to meet varying scenario requirements, as well as changing and evolving needs.

Maintain current substation design. Decide on the most important design criteria that need to be met immediately. This most likely will be the least expensive option to resolve the most pressing need to monitor the primary aging equipment and return the investment by extending that equipment's life.

Retrofit existing substation design. Project what the most important requirements are 5-10 years down the road. This design will require a major upgrade of the secondary equipment to achieve an increase in operating flexibility, reliability, and security, and will return the investment through value-added applications. For this purpose, a comprehensive survey of new technologies and a cost-benefit analysis should be completed. Particular emphasis might be given to the use of wireless and optical fiber communication media when adding new equipment and using software integration of data.

Implement new substation design. By assuming certain regulatory and technology developments, this approach would look at the replacement strategy that will occur within the next 20-40 years. This design will return the investment through its ability to push more power through the system more reliably. This approach requires field implementation that is different from the current practice and assumes availability of newly designed software modules for data acquisition and information extraction. It will include new communication infrastructure to support the exchange of information with control systems and neighboring substations and the use of power flow controllers of various designs.

Greenfield design. The most risky approach is to try to predict the design technology and operating practices that will include regulatory constraints for environmental compliance with a horizon of 50 years. This design will return investment primarily based on regulatory and environmental grounds. It will include two novel technologies (high temperature superconductor cable and solid-state transformers), as well as an intelligent economic alarm processor that combines the physical asset state and the electricity market function into one solution in the future. (See Figure 2.) This creates an opportunity for better correlating the market activity with the physical system in real time and sharing such information among market participants. Future "intelligent" substations should play an important role in the overall smart grid and be capable of providing such information. ◆