Power to be efficient

Transmission and distribution technologies are the key to increased energy efficiency

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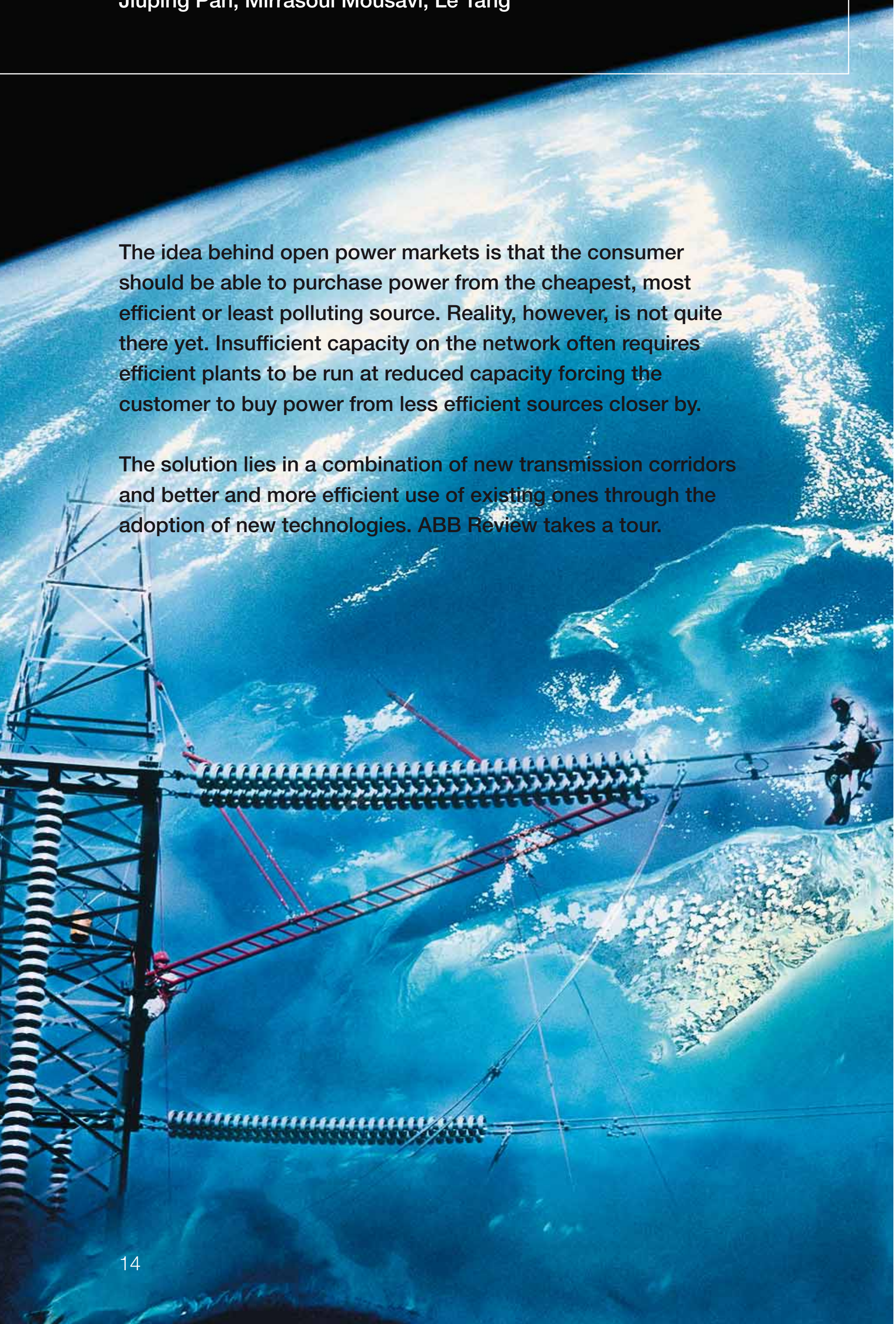
The idea behind open power markets is that the consumer should be able to purchase power from the cheapest, most efficient or least polluting source. Reality, however, is not quite there yet. Insufficient capacity on the network often requires efficient plants to be run at reduced capacity forcing the customer to buy power from less efficient sources closer by.

The solution lies in a combination of new transmission corridors and better and more efficient use of existing ones through the adoption of new technologies. ABB Review takes a tour.



The electrical energy generated by power plants is delivered to the end users hundreds to thousands of miles away via a network of interconnected transmission and distribution wires 1 2 3. Key components on this network include transmission towers, conductors/cables, transformers, circuit breakers, capacitors/reactors, HVDC/FACTS devices, and monitoring, protection, and control devices. In general, the network that delivers energy over long distances from power plants to substations near population centers and operates at high voltages is called the bulk power transmission network. The distribution system delivers energy from the substation to end users over shorter distances, is less interconnected and operates at lower voltages. The transmission and distribution (T&D) system is designed to ensure reliable, secure, and economic operation of energy delivery, subject to load demand and system constraints.

> The blackouts of recent years provide testimony to the lack of sufficient reliability and optimization capability in T&D systems on all continents.

A T&D system can be designed to provide three levels of services 4:

The first level of service provides the minimum level of connectivity and energy transfer capability under normal operation conditions. This is the most basic service. If this service fails to live up to its requirements, economic development of the areas served is compromised.

The second level of service allows for secure and reliable service to consumers in the event of plausible component failures. It requires redundant paths between power plants and consumers and thus a higher level of redundance in T&D capability.

The third level of services enables the optimization of geographically distributed and diverse energy resources to achieve maximum social and economic welfare. This can include optimizing the utilization of the various power plants to reduce the greenhouse gases that may contribute to global warming, and maximizing the overall economic efficiency of meeting the energy demand through market-based energy transactions. Such optimizations are simply not possible without sufficient T&D capabilities beyond the level required by the second level of service.

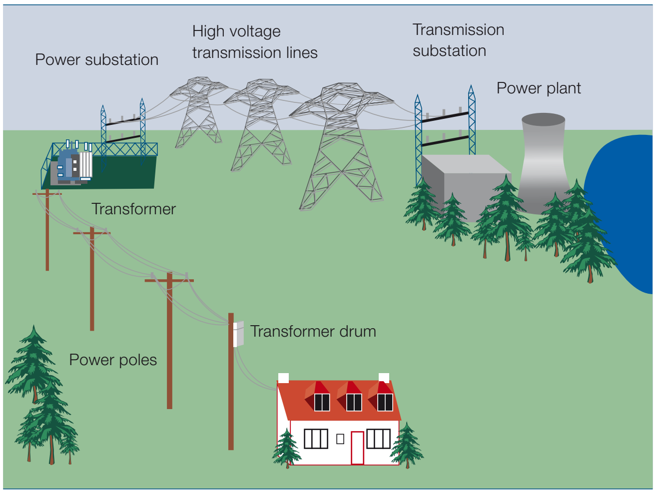
Unfortunately, most T&D systems in the world today achieve only the second level and partially the third level service. The blackouts of recent years Factbox provide ample testimony to the lack of sufficient reliability and optimization capability in T&D systems on all continents.

As is illustrated in the following section, a well built T&D system also affects the level of energy efficiency in power delivery.

Inadequate T&D hinders energy efficiency: An example from North America

Sufficient transmission and distribution capacities are an essential prerequisite for the efficient operation of electric power systems through the optimization of generation resources and loss minimization in the energy delivery system. Due to significant under-investment in network expansion and modernization, current T&D infrastructure in the United States often forestalls such measures 5.

1 Transmission and Distribution systems connect the power plants to the end users (source: www.howstuffworks.com)



Factbox Significant power outages in recent years

North America	14-Aug-03
London	28-Aug-03
Denmark/Sweden	23-Sep-03
Italy	28-Sep-03
Greece	12-Jul-04
Australia	14-Mar-05
Moscow	25-May-05
European blackout	4-Nov-06
Victoria, Australia	17-Jan-07
South Africa	18-Jan-07
Colombia	26-Apr-07

Transmission congestion issues in the United States

Transmission congestion occurs when flows of electricity across a line or piece of equipment must be curtailed to keep the flow levels under the limits required, either by physical capacity or by system operational security restrictions. Power purchasers always look for the least expensive source of energy available to transmit across the grid to the load centers. When a transmission constraint limits the amount of energy that can be transferred safely to a load center from the most desirable source, the grid operator must find an alternative and more expensive (or less efficient) source of generation to meet the system demand. An industry survey in 2003 examined the six operating ISOs[1] in the United States including New England, New York, PJM[2], Midwest, Texas, and California [1]. This survey found that the total congestion costs experienced by the six ISOs for the four-year period from 1999 to 2002 totaled approximately $4.8 billion. Public data available from the RTO-administered[3] energy markets have

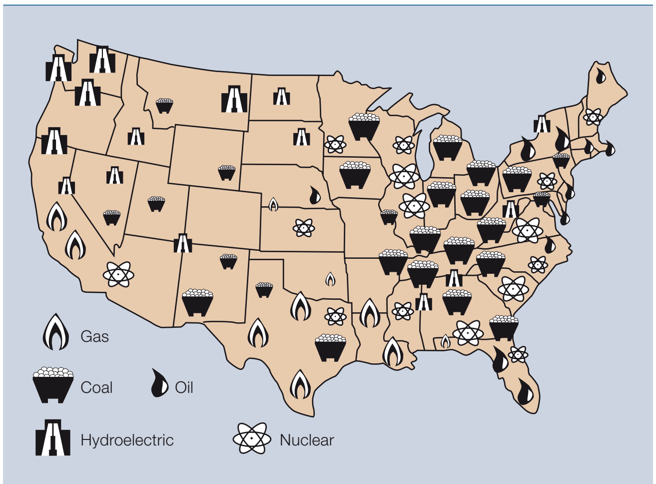
Footnotes

[1] ISO: Independent System Operator

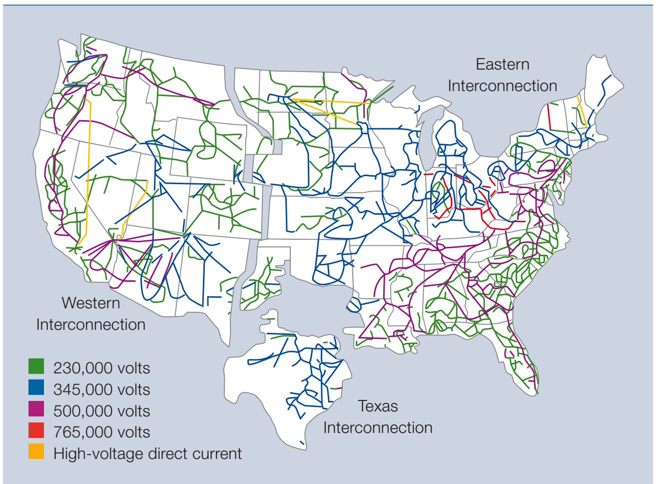
[2] PJM: Pennsylvania New Jersey Maryland Interconnection

[3] RTO: Regional Transmission Organization

2 Power plant locations in the United States (source: US Department of Energy)



3 Transmission grid in the United States (source: US Department of Energy)



shown increased congestion costs over time. A more recent study has indicated that, based on the reported congestion costs for New York ISO and PJM from 2001 to 2005, the total congestion costs are nearly $1 billion per year in New York and more than $2 billion per year in PJM [2]. Transmission congestion also calls for frequent transmission load relief actions 6. When demands are very high and local generation is limited, grid operators may have to curtail service to consumers in some areas to protect the reliability of the grid.

HVDC transmission is more efficient for long distance bulk power transfer when using overhead lines. HVDC systems can carry 2–5 times the capacity of an AC line of similar voltage.

Electricity losses in T&D systems

Transporting power from the generation source to the load always involves some losses. These losses add to the total electrical load and so require additional generation, hence wasted resources. Overall, the losses in transmission and distribution systems account for 6 to 7.5 percent of the total electric energy produced [3]. Typical losses are about 3.5 percent in the transmission system and about 4.5 percent in the distribution system. Losses vary greatly in terms of network configuration, generator locations and outputs, and customer locations and demands. In particular, losses during heavy loading periods or on heavily loaded lines are often much higher than under average or light loading conditions. This is because a quadratic relationship between losses and line flows can be assumed for most devices of power delivery systems. The annual monetary impact of T&D losses is estimated at over $21 billion (based on the average national retail price of electricity and the total T&D losses in 2005 [3]).

In recent years, T&D losses in the United States have been marked by an increasing trend, mainly due to increased power transactions and inefficient T&D system operations 8.

Technologies to improve efficiency in transmission and distribution systems

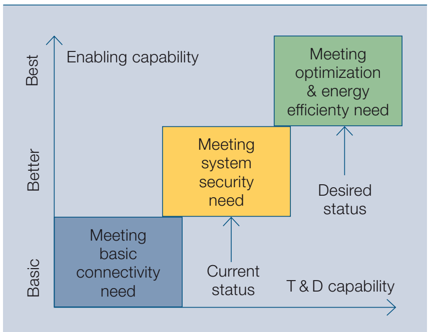
Technology options for improving efficiency of transmission and distribution systems may be classified into the following three categories:

- technologies for expanding transmission capacity to enable optimal deployment and use of generation resources
- technologies for optimizing transmission and distribution system design and operations to reduce overall energy losses
- new industry standards for energy efficiency power apparatus

Expanding transmission capacity to enable optimal deployment and use of generation resources

There are three major technology options that permit transmission capacity to be augmented: building new lines – AC or DC, upgrading existing lines, and utilizing existing lines closer to the thermal limits.

4 The three levels of services provided by transmission and distribution systems



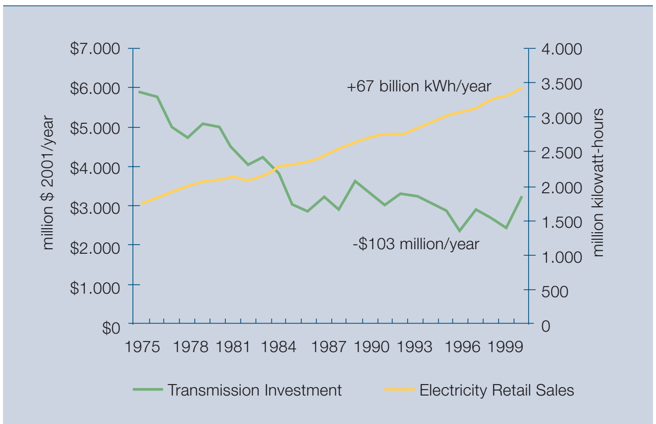
Constructing new lines

There are two technological options for new lines: high voltage AC (HVAC) and high voltage DC (HVDC). Thermal constraints typically limit transmission capacities of HVAC lines to 400 MW for 230 kV, 1100 MW for 345 kV, 2300 MW for 500 kV and about 7000 MW for 765 kV. However, in addition to these thermal constraints, the capability of AC transmission systems is also limited by voltage constraints, stability constraints and system operating constraints. As such, the power handing capability of long HVAC transmission lines is usually lower than these values.

HVDC

HVDC transmission is more efficient for long distance bulk power transfer (eg over 600–1000 km) when using overhead lines 9. HVDC systems can carry 2–5 times the capacity of an AC line of similar voltage 7. The environmental impact of HVDC is more favorable than AC lines because less land is needed for the right-of-way[4]. HVDC transmission has been widely used to interconnect AC systems in situations where AC ties would not be feasible on account of system stability problems or different nominal frequencies of the two systems. In addition, HVDC transmission is also used for underwater cables longer than 50 km where HVAC transmission is impractical because of the high capacitances of the cable (otherwise intermediate compensation stations would be required). A recent development in HVDC transmission utilizes a compact voltage source converter with IGBT[5] technology permitting an improved quality of supply in AC power networks. The technology uses small and

5 Transmission investment is falling behind electricity demand growth (source: EEI)



Footnotes

[4] See also "Light and invisible, Underground transmission with HVDC Light", Dag Ravemark, Bo Normark, ABB Review 4/2005 pp 25–29.

[5] IGBT: Integrated Gate Bipolar Transistor (a power electronic switching device).

low profile converter stations and underground cable transmission – reducing environmental impact. This technology, which is called HVDC Light™, opens up new possibilities for improving the quality of supply in AC power networks with rapid and independent control of active and reactive power, emergency power support and black start possibility.

Efficiency of HVDC

Losses in an HVDC system include line losses and losses in the AC to DC converters. The losses in the converter terminals are approximately 1.0 to 1.5 percent of the transmitted power. This is low compared to the line losses, which are a function of conductor resistance and current. Since no reactive power is transmitted in DC lines, line losses are lower for DC than for AC. In practically all cases, the total HVDC transmission losses are lower than the AC losses for the same power transfer 7.

Obstacles to new lines

One significant barrier to line construction, whether AC or DC, is the cost allocation controversy. Lines frequently cross regions in which the local benefits are questionable. Should these costs be socialized or should they be allocated directly to the benefactors only? This remains an area of disagreement in politics and society.

Even if a line has financial support, the issue of permitting and siting can become a long, arduous process that many utilities struggle with for years. By the time permission is finally granted, the requirements may have changed and additional studies be needed.

Upgrading existing lines

There are three ways to upgrade the capacity of existing lines: raise the voltage, increase the size and/or number of conductors per phase, or use high-temperature conductor materials. Increasing a line's voltage reduces the current required to move the same power. An upgrade from, 230 kV to the next voltage level of 345 kV for example, increases a line's capacity from about 400 MW to 1100 MW.

A high-temperature conductor is capable of transmitting two to three times more current than conventional power lines of the same diameter without increasing structure loads.

Reconductoring

Since a conductors' resistance is approximately inversely proportional to its cross-section, increasing this cross section or adding parallel conductors increases the line's current-carrying capacity. For instance, A 230 kV line can be increased from 400 MW to 1100 MW by adding new, larger and bundled conductors.

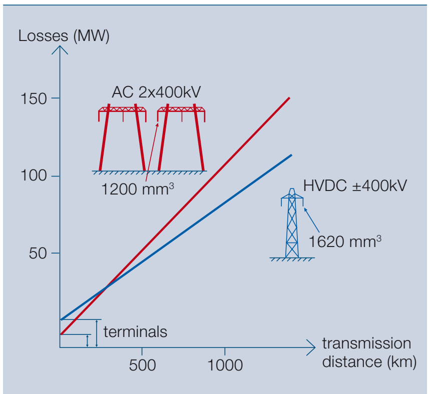
Recent technological development in the area of high-temperature conductors provides an effective way of mitigating thermally constrained bottlenecks for short- and medium-length lines. A high-temperature conductor is capable of transmitting two to three times more current than conventional power lines (ie, aluminum-steel reinforced conductors – ACSR) of the same diameter without increasing structure loads.

For both of the above options (raising voltage or reconductoring), the same right-of-way is used and new land use is normally not required. However, because of the increased weight of the new conductors or increased insulation requirements, the towers may need to be strengthened or rebuilt. The major substation equipment, such as transformers and circuit breakers may also need to be changed.

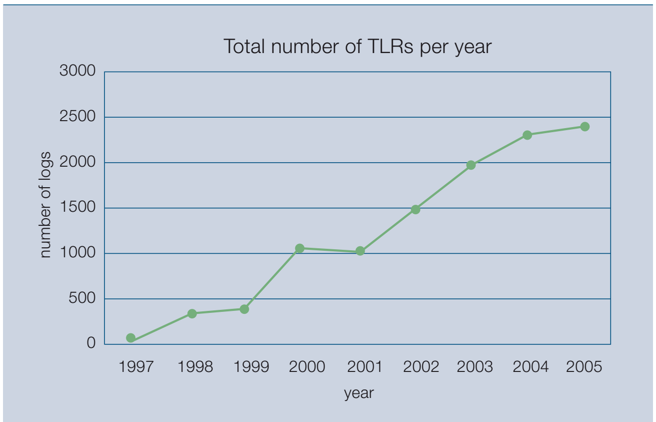
New lines or upgrades?

The issue of constructing new lines versus upgrading existing corridors is

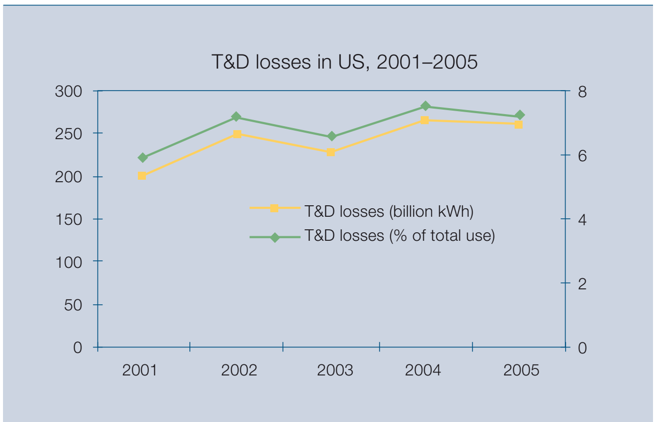
7 HVDC lines have lower transmission losses over long distances than HVAC lines



6 Transmission loading relief (TLR) incidents are on the increase (source: NERC)



8 Transmission and distribution losses in the USA, 2001–2005 (source: EIA)



Energy efficient grids

9 An HVDC station: HVDC is seeing increasing use in bulk transmission over long distances and other applications

10 FACTS equipment increases the capacity and stability of AC lines

certainly not determined by technical questions alone. As mentioned earlier, the process of obtaining permission to build a line takes many years in the U.S., and there is no guarantee of success. However, the DOE[6] recently issued two draft designations for national interest electricity transmission corridors as part of the implementation of the EPACT 2005[7]. This is intended to simplify the permit-granting process in order to speed up the construction of large lines in the most critically congested areas.

Make full use of transmission capacity

In many cases, transmission lines are operated well below their thermal loading capacity due to voltage constraints, stability constraints, or system operating constraints. Several technologies are available and are being applied to improve the utilization of the transmission capacity. The phase-angle regulator (PAR) is the device most often used to remove thermal constraints associated with "parallel path flow" or "loop flow" problems. Series capacitor compensation is another commonly used technology for increasing transfer capability of long-distance HVAC transmission lines. A family of devices based on power electronics technology, often referred to as FACTS devices (Flexible AC Transmission System)[8] can be used to enable better utilization of lines and cables and other associated equipment such as transformers 10. The simplest of these devices are the thyristor controlled capacitor and reactor banks (SVC) that have been widely used to provide quick reactive power compensation at critical locations in the transmission grid. Another commonly used device is thyristor-controlled series capacitors (TCSC) that can provide reactive compensation as well as damping of power system oscillations. More sophisticated use of power electronics is employed in what is called static synchronous compensators (STATCOM). This device can absorb and deliver reactive power to the system based on the variations of the system voltage fluctuations. The most sophisticated of these devices is the Unified Power Flow Controller (UPFC). The UPFC can regulate both real and reactive power in a line, allowing for rapid voltage support and power flow control. It is estimated that FACTS devices can boost the transmission capacity of lines now limited by voltage or stability considerations by as much as 20 to 40 percent.

11 Distribution transformers account for a considerable part of total transmission and distribution losses. New materials help reduce these losses

Potential benefits of building and operating unconstrained transmission grids

Reduce the prices for electricity

The operation of unconstrained transmission grids provides cost effective generators access to the load and so increases the efficiency of the electric power market. The operation of an unconstrained transmission grid has the potential advantage that it may permit full use of the regional load shape diversity that may result from weather condition differences and time zone differences. As a result, efficient generation resources can be dispatched at full capacity for more hours, permitting the usage of less economic resources to be reduced.

> Losses vary greatly in terms of network configuration, generator locations and outputs, and customer locations and demands.

Improve system reliability

Unconstrained transmission grids will potentially improve overall system reliability. At the given level of capacity

Footnotes

[6] DOE: Department of Energy (USA)

[7] EPACT: Energy Policy Act

[8] See also "Grid flexibility, FACTS: novel means for enhancing power flow", Rolf Grünbaum, Johan Ulleryd, ABB Review 4/2005 pp. 21–24.

reserve, an unconstrained transmission grid can provide adequate emergency power from adjacent (interconnected) regions to the region that is experiencing catastrophic multiple outages, such as the simultaneous losses of several generation units and transmission lines.

Promote emission reduction and fuel diversity

Unconstrained transmission grids provide opportunities to use generation sources with lower pollution, and to use more renewable energy sources located remotely from major population centers. The opportunity for greater fuel diversity will also contribute to national security goals to increase reliance on domestic fuel sources. It will also be helpful to keep a balanced regional generation resource mix such that a temporary shortfall of one type of resource will not cause significant problems.

> The use of superconducting conductors to replace copper in transformer windings can reduce the load losses significantly.

Reducing T&D energy losses through optimized system design and operation practices

The following are some of the most widely recognized loss reduction techniques in T&D system design and operation resulting in higher efficiency.

- Reconducting – replace a conductor with a larger conductor or add additional conductors in parallel.
- Voltage upgrades – upgrade a portion of the transmission or distribution network to a higher voltage level.
- Voltage optimization through reactive power compensation – install reactive power resources at chosen locations to minimize reactive power transfer on the T&D grids.
- Direct delivery of power to mega load centers through HVDC.
- Equalizing phase loading – improve the balance of phase currents of distribution systems.
- Superconducting materials at or near liquid nitrogen temperatures have the ability to conduct electricity with zero resistance. High temperature superconducting (HTS) cables now under development can carry three to five times the power of conventional cables with copper conductors. These cables can be used instead of overhead transmission lines or cables in places where environmental and space constraints prohibit the use of overhead lines. The load losses of HTS cables will be significantly lower than those of overhead lines or conventional cables, even when the power required for refrigeration is included. A major vendor of superconductors claims that HTS cable losses are only 0.5 percent of the transmitted power compared to 5 to 8 percent for traditional power cables. Furthermore, the use of superconductors to replace copper in transformer windings can reduce the load losses significantly. For the case of a 100 MVA transformer, the total losses (load losses, core losses and refrigeration power) can be 65 to 70 percent of that of a conventional transformer.

Other notable technologies and design practices that can increase the efficiency of the grid include:

- more underground distribution lines – these could save up to 80 percent of distribution losses
- DC distribution networks
- microgrids to eliminate long distance transmission
- intelligent automated grid design
- real-time online control systems
- load management through smart metering
- energy storage devices

The estimated potential for improving energy efficiency directly through transmission and distribution loss reduction is higher than 1 percent of total delivered energy. This will result in an annual savings value of $3 billion dollars[9].

Footnotes

9) Assuming the 2005 U.S. national average retail electricity price.

10) 1 Quad = 10^{15} BTU = $2.931 \cdot 10^{11}$ kWh = $1.055 \cdot 10^{18}$ J

Improvements of energy efficiency of power apparatur

Another key to upgrading the efficiency of T&D systems lies in the improvement of the energy performance of power apparatus. This could be implemented as part of a program to better manage energy demand, contribute to the security of energy supply, and mitigate climate change.

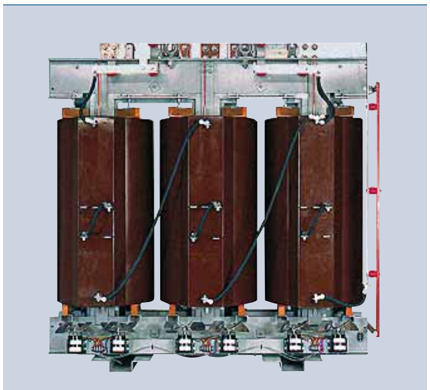
Transformers

Distribution transformer losses in particular make up a considerable fraction of the total loss incurred in transmission and distribution systems 11 12. Based on a study of the Pacific Northwest transmission and distribution systems, it was found that distribution transformers accounted for over 30 percent of losses while substation transformers contributed only 2 percent [4]. With their widespread application and long life span, distribution transformers represent a great energy saving potential. From the energy savings point of view, even a minor increase of one-tenth of one percent in transformer efficiency leads to significant energy savings as most transformers are energized around the clock.

Using currently available technologies, transformer losses can be reduced by at least 15 percent in a cost-effective manner.

Two types of losses are commonly evaluated for loss reduction: core losses and coil losses. Core losses are often referred to as no-load losses

12 Transformer load losses can be reduced through appropriate choices in the materials and geometry of windings



because they occur in the core of an energized transformer regardless of its loading conditions. When a transformer is energized 24 hours a day, every day, this loss amounts to substantial energy consumption over the transformer's life (typically 20–30 years). Coil losses, on the other hand, occur in the transformer windings and vary with loading conditions 13. Hence they are referred to as load losses.

Transformer no-load losses can be reduced by using magnetic core steel materials or optimizing their geometries. Increasing the core cross-section or decreasing volts per turn reduces the core losses by decreasing the core flux density. Decreasing the conductor cross-section also reduces the no-load losses by decreasing the path length of the magnetic flux. The caveat involved in these steps is that they typically result in increased load losses. Load losses can be reduced in a number of ways including the application of higher conductivity materials such as larger cross-section conductors or adopting copper conductors instead of aluminum conductors. Utilizing lower loss winding methods reduces the length of the winding conductors. Smaller magnetic core cross-sections and fewer turns also reduce the winding losses. Superconducting transformers, in particular, have minimum winding losses.

These explanations show that steps to reduce no-load losses often result in increased load losses and vice-versa. Hence, the transformer loss reduction is an optimization process involving physical, technological, and economical factors tempered by some form of life-cycle economic analysis. Most often, a trade-off has to be considered with respect to the core/winding material, design, and how the buyer evaluates the Total Cost of Ownership (TCO) of the transformer. Such an evaluation takes into account the initial cost of the transformer as well as the life cycle cost including losses.

The TCO is most often evaluated by electric utilities during the procurement process. Although industrial and commercial consumers directly pay for their energy losses, they are ironically less enthusiastic about TCO evaluations, due in part to their procurement practices and the relatively short transformer life cycles.

In many cases, transmission lines are operated well below their thermal loading capacity due to voltage constraints, stability constraints, or system operating constraints.

The energy efficiency of transformers is improving in many markets due in part to government policies and initiatives and market forces. The US Energy Act of 1992 required the DOE to provide a cost-benefit analysis of increasing energy efficiency for distribution transformers. The study performed by the Oak Ridge National Laboratory (ORNL) found that energy efficiency gains are technically feasible and may lead to substantial energy savings of 3.6 to 13.7 quads[10)] of energy over the period from 2000-2030 [5]. In 1995, the Environmental Protection Agency (EPA) launched the Energy Star Transformer program in partnership with electric utilities to promote and support the use of high-efficiency, cost-effective distribution transformers. This program is raising public awareness of energy efficiency as a means to reduce greenhouse gas emissions.

Energy efficient distribution transformers have recently been put in the spotlight worldwide 14. Canada, Mexico, and states of California, Massachusetts, New York, Minnesota, Vermont, Wisconsin, and Oregon have already adopted energy efficiency programs. Such programs are further supported and promoted by the Consortium for Energy Efficiency (CEE), a North American, nonprofit organization that promotes energy-efficient products and services.

Although no mandatory efficiency standards have been implemented to date, there are various industry standards for energy efficiency evaluation of distribution transformers. The National Electrical Manufacturers Association (NEMA) standards eg, TP-1, 2, 3 may be voluntarily adopted by transformer vendors for determining energy efficiency and measuring energy consumption of distribution transformers. NEMA TP-3 provides labeling guides for energy efficient transformers. The IEEE standard PC57.12.33 provides guidance for distribution transformer loss evaluation. This standard is in draft status and more detailed than NEMA TP-1.

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy recently issued a Notice of Proposed Rule Making (NOPR) that sets minimum energy-efficiency standards for liquid-immersed and medium voltage dry-type distribution transformers. The new efficiency requirements are expected to impact around 50 to 60 percent of the distribution transformers produced today. These transformers normally use the least costly and most readily available steel grades known in the industry as M4, M5, and M6. The proposed energy efficiency improvement requires the use of more efficient M2 and M3 steel grades for the grain-oriented silicon core steel. Furthermore, this requirement places additional demand on highly efficient core material as dry-type transformers are typically produced with non-grain-oriented core steel. As a result, the final cost of the transformer and availability of supply commodities for energy efficient transformers will be evident challenges in the implementation phase. The DOE will eventually mandate energy efficient transformers, but the implementation is unclear at present. Following the DOE mandate, NEMA documents will be adopted in some form in line with a worldwide energy efficient effort that is taking place in North American as well in IEC markets.

The way forward

The foregoing sections introduce technologies that can be applied individually or in combination to increase the efficiency of the power system. The world wide potential for energy saving is enormous. In the US alone, the potential for energy saving through transmission and distribution loss reduction is higher than 1 percent of total delivered energy, which has a market value of around $3 billion dollars. In addition, the savings in congestion costs amounting to billions of dollars annually can be achieved with enhanced T&D systems.

In addition, electric transmission and distribution is also the main enabler for optimizing the generation portfolio and reducing fossil fuel consumption through access to clean and renewable energy sources.

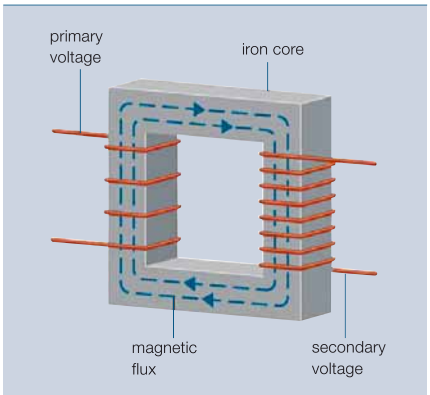
The following roadmap has been developed by the Business Roundtable Energy Task Force T&D working group that included leading U.S. utilities and T&D vendors.

The operation of unconstrained transmission grids provides cost effective generators access to the load and so increases the efficiency of the electric power market.

- Adequate investment is needed to expand the network capacity and controllability to enable optimal deployment and use of power generation resources.
- Optimal network design and operation with advanced technologies and practices are essential to save energy.
- The establishment of new industry standards for energy efficient power apparatus is needed to reduce consumption.

Technologies to significantly improve the world's T&D system efficiencies are available today. Deployment of these technologies is not only an issue of balancing long-term benefits with costs but also an issue of conventional utility practices, supportive regulatory environments and societal support. ABB's advanced technologies and best design and operations practices will play a major role in improving the efficiency of the energy systems of the world.

13 Transformer principle (source: Precision Graphics)



14 An NA pole-top three phase transformer

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