Smarter grids are more efficient

Voltage and Var Optimization reduces energy losses and peak demands

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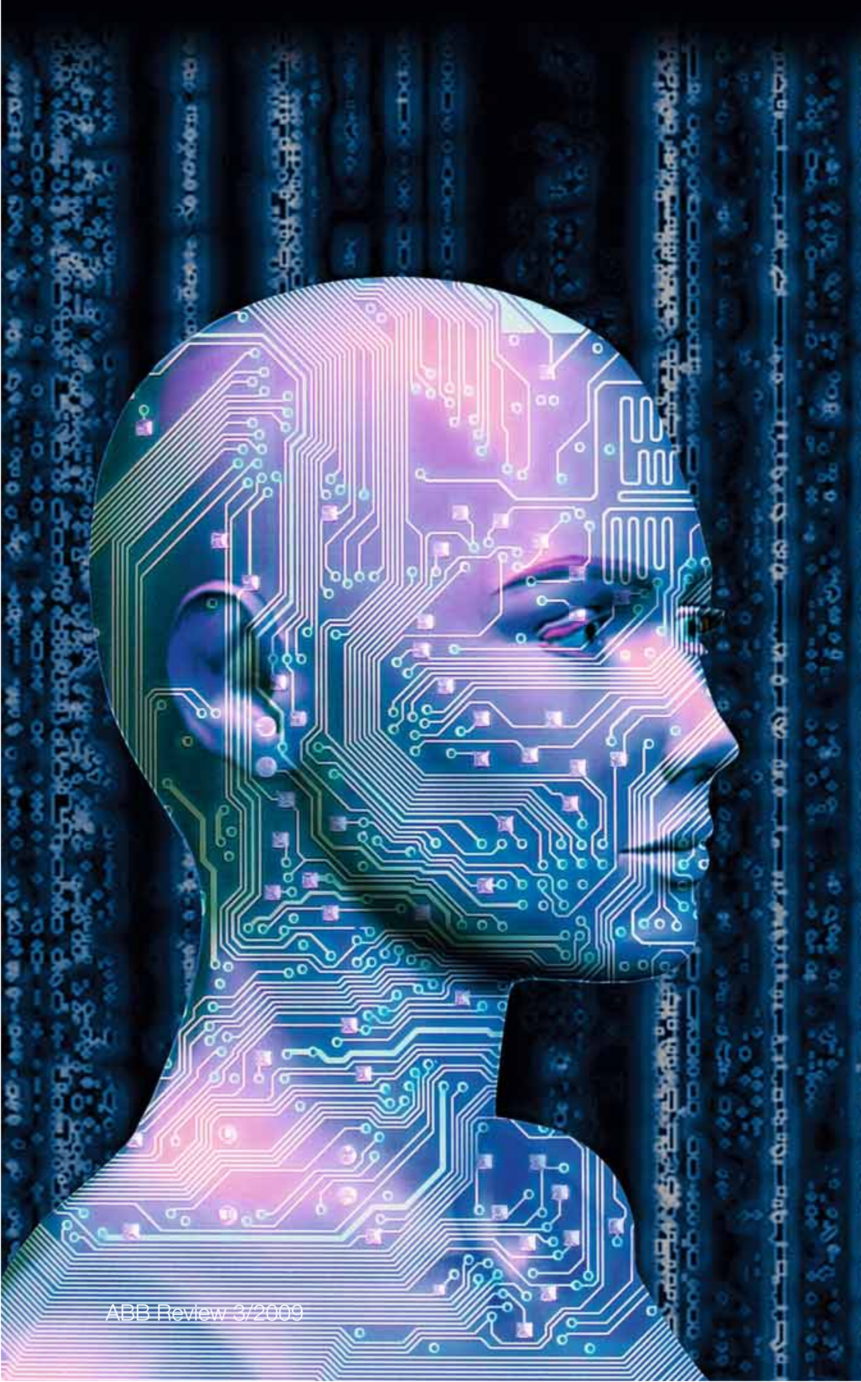


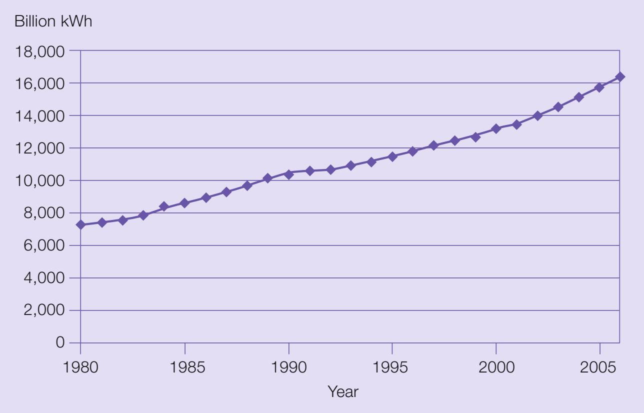
Have you ever wondered how much electric energy the world consumes or how much energy is lost on its way from the power plants to the end users? Have you wondered how much energy could be saved or greenhouse gas emissions could be cut if such energy losses were reduced by even a small amount? ABB is a world leader in the development of new technologies to help reduce electric energy losses and the demands made on electric distribution systems.

ABB offers a wide spectrum of products to increase energy efficiency and optimize demand management. Voltage and Var Optimization (VVO) is the latest addition to these applications. Differing from the traditional approach using uncoordinated local controls, VVO uses real-time information and online system modeling to provide optimized and coordinated control for unbalanced distribution networks with discrete controls. Electric distribution companies can achieve huge savings in the new frontier of energy-efficiency improvement by maximizing energy delivery efficiency and optimizing peak demand. VVO will help achieve these objectives by optimizing reactive resources and voltage control capabilities continuously throughout the year.

Transmission and distribution

The world has a huge appetite for electric energy, consuming thousands of billions of kilowatt-hours (kWh) annually, a figure that continues to climb as more countries become industrialized. The world's electric consumption has increased by about 3.1 percent annually between 1980 and 2006[1)], and is expected to grow to 33,300 billion kWh by 2030[2)] 1. The world's electricity consumption for 2008 was 16,790 billion kWh so by 2030 the world demand for electricity is expected to have almost doubled [1].

1 World electricity consumption (billion kWh)



Electric energy losses

Currently a significant amount (about 10 percent) of electric energy produced by power plants is lost during transmission and distribution to consumers. About 40 percent of this total loss occurs on the distribution network 2. In 2006 alone, the total energy losses and distribution losses were about 1,638 billion and 655 billion kWh, respectively. A modest 10 percent reduction in distribution losses would, therefore, save about 65 billion kWh of electricity. That's more electricity than Switzerland's 7.5 million people consumed in 2008 and equates to 39 million metric tons of CO_2 emissions from coal-fired power generation [1].

As the demand for electricity grows, new power plants will have to be built to meet the highest peak demand with additional capacity to cover unforeseen events. The peak demand in a system usually lasts less than 5 percent of the time (ie, just a few hundred hours a year). This means that some power plants are only needed during the peak load hours and their potential is utilized relatively infrequently. By active demand management on the distribution system, through demand response and VVO, the peak demand on the whole electric grid can be reduced. This eliminates the need for expensive capital expenditure on the distribution, transmission, and the generation systems. Even very modest reductions in peak demand would yield huge economic savings. For the United States in 2008, for example, the non-coincidental peak demand (ie, the separate peak demands made on the electrical system recorded at different times of the day) was about 790 GW. With every 1 percent reduction in the peak demand there would be a reduced need to build a 7,900 MW power plant 3.

Distribution system losses

The electric distribution network moves electricity from the substations and delivers it to consumers. The network includes medium-voltage (less than 50 kV) power lines, substation transformers, pole- or pad-mounted transformers, low-voltage distribution wiring and electric meters. The distribution system of an electric utility may have hundreds of substations and hundreds of thousands of components all managed by a distribution management system (DMS).

Most of the energy loss occurring on the distribution system is the ohmic loss[3)] resulting from the electric current flowing through conductors Factbox 1.

For any conductor in a distribution network, the current flowing through it can be decomposed into two components – active and reactive Factbox 2.

Reactive power compensation devices are designed to reduce or eliminate the unproductive component of the current, reducing current magnitude – and thus energy losses. The voltage profile[4)] on the feeders[5)], depending on the types and mixture of loads in the system, can also affect the current

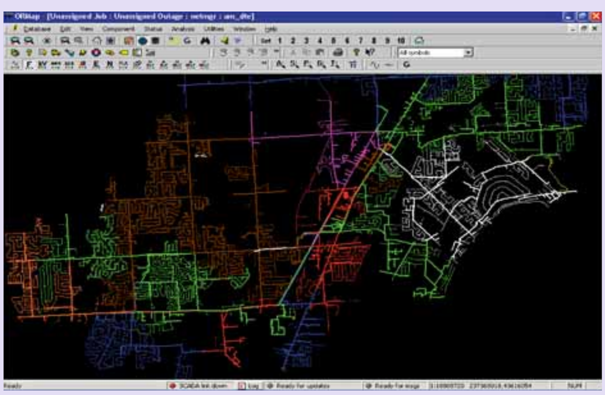
Footnotes

1) US Energy Information Administration, International Energy Annual 2006

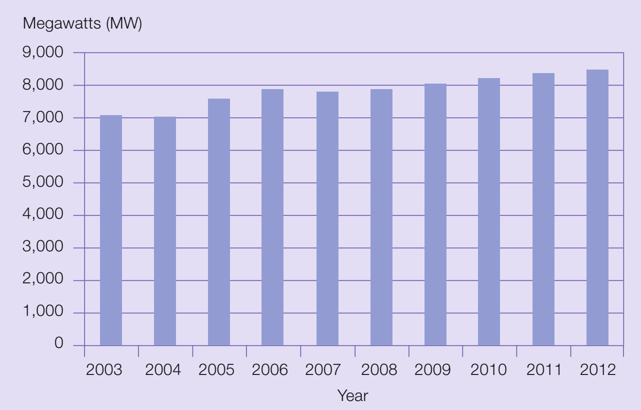
2) US Energy Information Administration, World Net Electric Power Generation: 1990–2030

3) The voltage drop across the cell during passage of current due to the internal resistance of the cell

2 Distribution system overview from network manager system (DMS)



3 Annual peak demand reduction of 1 percent for the United States



distribution, although indirectly and to a smaller extent, thus affecting power loss.

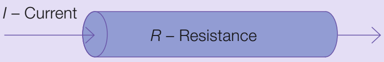
Voltage and var control devices

Voltage regulating devices are usually installed at the substation and on the feeders. The substation transformers can have tap changers, which are devices that can adjust the feeder voltage at the substation, depending on the loading condition of the feeders. Special transformers with tap changers called voltage regulators are also installed at various locations on the feeders, providing fine-tuning capability for voltage at specific points on the feeders.

Reactive compensation devices, ie, capacitor banks, are used to reduce the reactive power flows throughout the distribution network. The capacitor banks may be located in the substation or on the feeders.

Factbox 1 Energy losses

The energy loss is due to the resistance in the conductor. The amount of loss is proportional to the product of the resistance and the square of the current magnitude. Losses can be reduced, therefore, either by reducing resistance or the current magnitude or both. The resistance of a conductor is determined by the resistivity of the material used to make it, by its cross-sectional area, and by its length, none of which can be changed easily in existing distribution networks. However, the current magnitude can be reduced by eliminating unnecessary current flows in the distribution network.



$Loss = I^2 R$

A modest 10 percent reduction in distribution losses would save about 65 billion kWh of electricity.

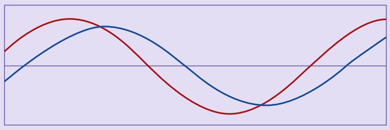
Traditional control verses VVO

Traditionally, the voltage and var control devices are regulated in accordance with locally available measurements of, for example, voltage or current. On a feeder with multiple voltage regulation and var compensation devices, each device is controlled independently, without regard for the resulting consequences of actions taken by other control devices. This practice often results in sensible control actions taken at the local level, which can have suboptimal effects at the broader level.

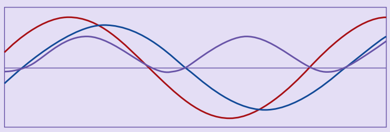
Ideally, information should be shared among all voltage and var control devices. Control strategies should be comprehensively evaluated so that the consequences of possible actions are consistent with optimized control objectives. This could be done centrally using a substation automation system or a distribution management system. This approach is commonly referred to as integrated VVO. The accelerated adoption of substation automation (SA), feeder automation (FA) technology, and the widespread deployment of advanced metering infrastructure (AMI) have over the last few years laid the foundations for a centralized control approach, by providing the

Factbox 2 Active and reactive power

The voltage and current waveforms on an AC power line are typically sineshaped. In an “ideal” circuit, the two are perfectly synchronized. In the realworld, however, there is often a time lag between them. This lag is caused by the capacitative and inductive properties of attached equipment (and of the lines themselves).

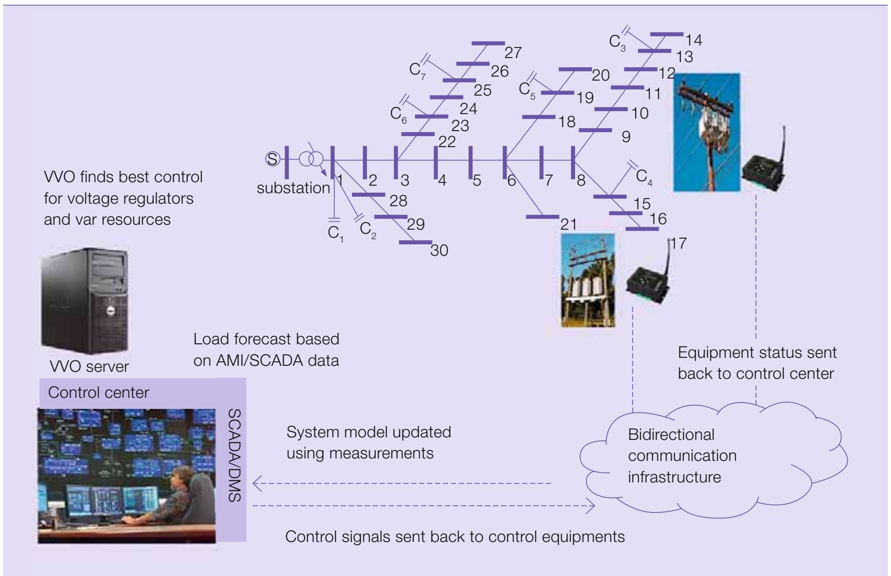


The momentary flow of power at any time is the product of the momentary current and voltage. The average value of this power is lower than it would be without the time lag (for unchanged magnitudes of voltage and current). In fact the power even briefly flows in the “wrong” direction.



The greater the time lag between the curves, the lower the energy delivery. This lag (expressed as phase angle) should thus be minimized. The average energy delivery per time unit is called active power (measured in W). Reactive power (measured in VAr) is a measure of the additional power that is flowing on the line but cannot be put to effective use.

4 A schematic showing how VVO works



Footnotes

4) Voltage profile refers to the spatial distribution and voltage magnitudes at different locations or nodes throughout the network.

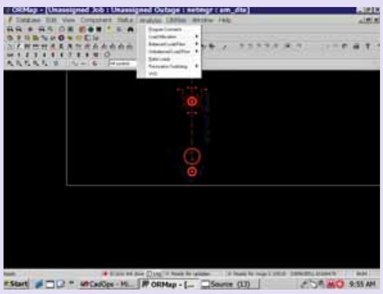
5) Any of the medium-voltage lines used to distribute electric power from a substation to consumers or to smaller substations.

necessary sensor, actuator, and reliable two-way communications between the field and the distribution system control center. Until recently, however, a key technology has not been available that can take advantage of advanced sensing, communication, and remote actuation capabilities that can be used to continually optimize voltage and var. Prior generations of VVO technologies have been hindered by their inability to model large and complex utility systems, and by their unsatisfactory performance in solution quality, robustness and speed.

How does VVO work?

VVO is an advanced application that runs periodically or in response to operator demand, at the control center for distribution systems or in substation automation systems. Combined with two-way communication infrastructure and remote control capability for capacitor banks and voltage regulating transformers, VVO makes it possible to optimize the energy delivery efficiency on distribution systems using real-time information 4.

5 VVO prototype screen capture



6 VVO compared to prior method

Prior method	ABB VVO capability
Single phase equivalent model	Multi-phase, unbalanced model
Balanced load	Unbalanced load
Single source	Multi-source
Radial system	Meshed system
Ganged control	Unganged control
Academic system size	Real utility system size
Offline performance	Online performance
Heuristic	Optimization theoretic

VVO attempts to minimize power loss, demand, and voltage/current violations[6] in meshed, multi-phase, multi-source, unbalanced electric distribution systems.[7] The control variables available to VVO are the control settings for switchable capacitors and tap changers of voltage regulating transformers.

Main benefits of VVO

The main benefits of VVO for distribution system operators are:

- Improved energy efficiency leading to reduced greenhouse gas emissions.
- Reduced peak demand and reduced peak demand cost for utilities

General problem definition for VVO

VVO must minimize the weighted sum of energy loss + MW load + voltage violation + current violation, subject to a variety of engineering constraints:

- Power flow equations (multi-phase, multi-source, unbalanced, meshed system)
- Voltage constraints (phase to neutral or phase to phase)
- Current constraints (cables, overhead lines, transformers, neutral, grounding resistance)
- Tap change constraints (operation ranges)
- Shunt capacitor change constraints (operation ranges)

The control variables for optimization include:

- Switchable shunts (ganged or unganged[8])
- Controllable taps of transformer/voltage regulators (ganged or unganged)
- Distributed generation

Technical challenges

VVO in essence is a combinatorial optimization problem with the following characteristics:

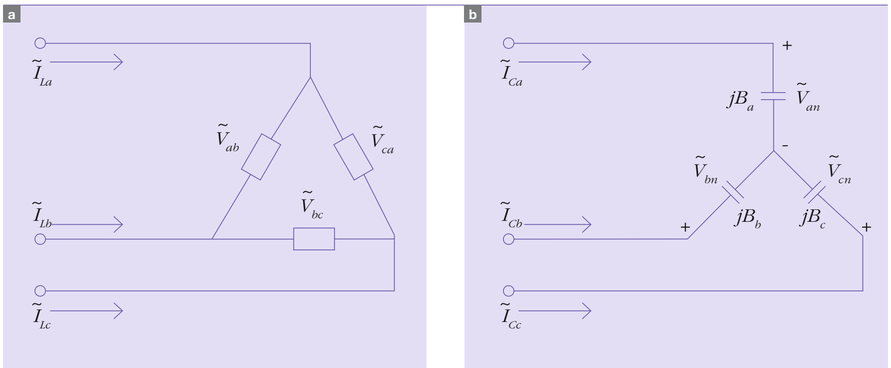
- Integer decision variables – both the switching status of capacitor banks and the tap position of regulation transformers are integer variables.
- Nonlinear objective being an implicit function of decision variables – energy loss or peak demand are implicit functions of the controls.
- High dimension nonlinear constraints – power flow equations numbering in the thousands in the multi-phase system model.
- Non-convex objective and solution set.
- High dimension search space – with un-ganged control, the number of control variables could double or triple.

Anyone who has tackled optimization problems will tell you that mixed-integer nonlinear, non-convex (MINLP-NC) problems are the worst kind to solve (See "Simply the best," *ABB Review* 1/2009, page 54).

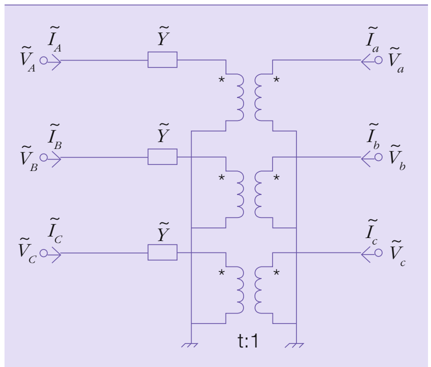
> VVO improves energy efficiency and reduces greenhouse gas emissions. It reduces peak demand, which reduces peak demand cost for utilities.

The major challenge is to develop optimization algorithms that are efficient for large problems. Since a certain amount of computation (ie, CPU time) is needed to evaluate the loss and demand for a single specific control solution (a single functional evaluation), an algorithm that requires fewer functional evaluations to find the optimal solution is generally regarded as more efficient than one that requires more functional evaluations to achieve the same objective. In the case of VVO, a single function evaluation involves solving a set of nonlinear equations, the unbalanced load flow, with several thousand state variables. The nonlinear, non-convex combinatorial properties of the VVO problem coupled with high dimensionality (large number of state variables) are the reasons why VVO has been a long standing challenge in the industry. In the last decade many in the research community have increasingly begun to resort to meta-heuristic approaches (eg, generic algorithms, simulated annealing, particle swarming, etc) to avoid the modeling complexity. The meta-heuristic approach has shown limited academic value in solving small-scale problems and in offline applications where online performance is not required.

7 Delta-connected load a and wye-connected capacitor bank b



8 Wye-wye-connected transformer model



ABB's next generation VVO
ABB developed a new-generation VVO in 2008 capable of optimizing very large and complex networks with online application speed. An innovative solution methodology enables the detailed and accurate modeling of the distribution system components and connections. It rapidly identifies the optimal voltage and var operation strategy from millions, if not billions, of operation possibilities using advanced mixed-integer optimization algorithms.

A prototype has been developed, which integrates directly with ABB's DMS. The prototype performed very well in the lab with distribution network models of a real utility system. Both the solution quality and speed robustness met or exceeded design criteria for online applications 5.

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The size of the test systems range from 1,600 to 7,800 nodes and 1,600 to 8,100 branches per circuit. Optimization improved the loss from 2.5 percent to 67 percent[9] and demand reduction from 1.4 percent to 5.8 percent.[10]

The following table is a brief summary of the key features that differentiate ABB's VVO technology from prior methods 6.

To accurately model a distribution network's behavior a detailed network model is used. Phase-based models[11] are used to represent every network component. Loads or capacitor banks can be delta 7a or wye connected 7b.

Transformers can be connected in various delta/wye and various secondary leading/lagging configurations with or without ground resistance, with primary or secondary regulation capability 8.

Both voltage and var controls can be ganged or unganged. The method works on radial as well as meshed networks, with single or multiple power sources. Voltage controls are enforced for each individual phase, using phase-to-ground or phase-to-phase voltage, depending on the connection type of the load.

One smart technology at a time
With the accelerating deployment of advanced sensor network, smart metering infrastructure, and remote control capability, there is a growing need for smart applications like VVO that optimize the operation of the distribution system. The development of the next generation of VVO technology is a demonstration of ABB's ability to bring smart grid technology to its customers.

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Footnotes

6) Voltage/current violations refer to the undesirable excursion from normal operating range, eg, current exceeding the maximum limit safe for a given conductor type, or voltage exceeding a limit unsafe for the consumer or falling short of a limit needed for normal operation for end users.

7) A distribution system model may have the following features: meshed (looped, with multiple paths between some nodes), multi-phase (each of the A, B, C phases explicitly modeled, rather than modeled as a single phase), multi-source (a load can get electric supply from multiple sources), unbalanced (asymmetric construction, such as a single-phase feeder, and/or asymmetric loading, ie, unequal loading on each phase)

8) Ganged control means multiple phases operated in unison, and unganged control means each phase operated independently.

9) The amount of loss reduction depends on the controllable voltage and var resources in the system, the system loading condition, and the initial control strategy.

10) The amount of demand reduction depends on the factors that affect loss reduction as well as the load model. For 100 percent constant load, demand reduction can only be achieved through loss reduction.

11) Exact component model includes the information of all existing phases.

References

[1] *CIA Online Factbook.* Retrieved June 2009 from http://www.cia.gov/library/publication/the-world-factbook/