Distributed Energy Resource (DER) Using FACTS, STATCOM, SVC and Synchronous condensers for Dynamic Systems Control of VAR

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Presented
at
2005 National Association of Industrial Technology (NAIT) Convention
St. Louis, Mo
November 16-19, 2005

Keyword Search:
Electricity,
Energy,
Electronics,
Design

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ABSTRACT

Distributed energy resource (DER) may acquire a fractional, but significant, share of future electricity generation requirements. Utility restructuring provides an economic driver, but DER also promises ancillary technical benefits to the distribution system infrastructure. However a number of coordination issues [covering protection, harmonics, transients, voltage and frequency control presently require analysis in order to understand the benefits, costs and technical limits to the penetration of DER on a given distribution line. This report aims to quantify these limits as well as pointing the reader towards appropriate modeling methods and simulation software. The report also provides simplified formulas and guidelines for analysis of other generic problems which will be fine tuned as more sample feeders are studied.

Voltage control and reactive-power management are two aspects of a single activity that both supports reliability and facilitates commercial transactions across transmission networks. 1996, 1997a) recognized the importance of voltage control by including it as an ancillary service in Order 888, Reactive Supply and Voltage Control from Generation Sources.

1. INTRODUCTION

Distributed energy resource (DER) may acquire a fractional, but significant, share of future electricity generation requirements. Utility restructuring provides an economic driver, but DER also promises ancillary technical benefits to the (Hingorani and Gyugyi 2000) distribution system infrastructure. However a number of coordination issues covering protection, harmonics, transients, voltage and frequency control presently require analysis in order to understand the benefits, costs and technical limits to the penetration of DER on a given distribution line. This report aims to quantify these limits as well as pointing the reader towards appropriate modeling methods and simulation software. The report also provides simplified formulas and guidelines for analysis of other generic problems which will be fine tuned as more sample feeders are studied.

Voltage control and reactive-power management are two aspects of a single activity that both supports reliability and facilitates commercial transactions across transmission networks. The Federal Energy Regulatory Commission (FERC 1996, 1997a) recognized the importance of voltage control by including it as an ancillary service in Order 888, Reactive Supply and Voltage Control from Generation Sources. FERC differentiated generation-based activities from transmission-system-based activities, with the latter to be addressed under the basic transmission tariff.

On an alternating-current (AC) power system, voltage is controlled by managing production and absorption of reactive power. There are three reasons why it is necessary to manage reactive power and control voltage. First, both customer and power-system equipment are designed to operate within a range of voltages, usually within ±5% of the nominal voltage. At low voltages, many types of equipment perform poorly; light bulbs provide less illumination, induction motors can overheat and be damaged, and some electronic equipment will not operate at all (EPRI TR-111490 1998 *and* Florida Reliability 1996). High voltages can damage equipment and shorten their lifetimes.

Second, reactive power consumes transmission and generation resources. To maximize the amount of real power that can be transferred across a congested transmission interface, reactive-power flows must be minimized. Similarly, reactive-power production can limit a generator's real-power capability.

Third, moving reactive power on the transmission system incurs real-power losses. Both capacity and energy must be supplied to replace these losses. Voltage control is complicated by two additional factors. First, the transmission system itself is a nonlinear consumer of reactive power, depending on system loading. At very light loading the system generates reactive power that must be absorbed, while at heavy loading the system consumes a large amount of reactive power that must be replaced. The system's reactive-power requirements also depend on the generation and transmission configuration.

Consequently, system reactive requirements vary in time as load levels and load and generation patterns change. The bulk-power system is composed of many pieces of equipment, any one of which can fail at any time. Therefore, the system is designed to withstand the loss of any single piece of equipment and to continue operating without impacting any customers. That is, the system is designed to withstand a single contingency. Taken together, these two factors result in a dynamic reactive-power requirement. The loss of a generator or a major transmission line can have the compounding effect of reducing the reactive supply and, at the same time, reconfiguring flows such that the system is consuming additional reactive power. At least a portion of the reactive supply must be capable of responding quickly to changing reactive-power demands and to maintain acceptable voltages throughout the system. Thus, just as an electrical system requires real-power reserves to respond to contingencies, so too it must maintain reactive-power reserves.

Loads can also be both real and reactive. The reactive portion of the load could be served from the transmission system. Reactive loads incur more voltage drop and reactive losses in the transmission system than do similar-size (MVA) real loads. Vertically integrated utilities often include charges for provision of reactive power to

loads in their rates. With restructuring, the trend is to restrict loads to operation at near zero reactive power demand (a 1.0 power factor). The California independent system operator (ISO) proposal limits loads to power factors between 0.97 lagging (absorbing reactive power) and 0.99 leading (generating reactive power) (Pacific Gas and Electric et al. 1997) (Chapman 2003 and Dandachi 1996). This would help to maintain reliability of the system and avoid the problems of market power in which a company could use its transmission lines to limit competition for generation and increase its prices.

2. Purpose of Reactive Power

Synchronous generators, STATCOM, SVC and various types of other DER equipment are used to maintain voltages throughout the transmission system. Injecting reactive power into the system raises voltages, and absorbing reactive power lowers voltages. Voltage-support requirements are a function of the locations and magnitudes of generator outputs and customer loads and of the configuration of the DER transmission system. These requirements can differ substantially from location to location and can change rapidly as the location and magnitude of generation and load change. At very low levels of system load, transmission lines act as capacitors and increase voltages. At high levels of load, however, transmission lines absorb reactive power and thereby lower voltages. Most transmission-system equipment (e.g., capacitors, inductors, and tap-changing transformers) is static but can be switched to respond to changes in voltage-support requirements

Resource Control and Market Structures

System operation has three objectives when managing reactive power and voltages. First, it must maintain adequate voltages throughout the transmission and distribution system for both current and contingency conditions. Second, it seeks to minimize congestion of real-power flows. Third, it seeks to minimize real-power losses. These were the system-control objectives before restructuring, and they will continue to be the objectives after restructuring of the U.S. electricity industry. However, the mechanisms that system operators use to acquire and deploy reactive-power resources are changing (North American Electric Reliability Council 1996). These mechanisms must be fair to all parties as well as effective. Further, they must be demonstrably fair. Historically, system operations, generators, transmission devices, and the transmission system itself were all owned and operated by the same entity. In the future, the entities that own and operate generation may differ from those that own transmission, and both may differ from the system operator (which likely will control the transmission system). These changes will require the creation of new market structures, including rules and requirements for connection to the transmission system and the operation of certain equipment. In spite of these rule changes, the system operator must have the authority to deploy resources to meet the system's voltage-control objectives at minimum cost. Not surprisingly, more progress has been made in addressing the technical objectives of managing voltages than in developing market structures to perform this function in a restructured industry. The operating policies of the North American Electric Reliability Council (NERC 1996) focus on the concept of control-area responsibility for controlling voltage and reactive resources, allowing control areas to develop appropriate rules. Control areas are to maintain sufficient reactive resources to support voltages under first-contingency conditions. Each control area should take care of its own needs and avoid placing a burden on other control areas. NERC policies offer little guidance on what resources should be available or how the system operator should acquire and deploy them, leaving these decisions to the regional reliability councils and the individual control areas.

3. Sources & Differences

There are other sources of generating reactive power which includes capacitor banks, synchronous condensers (an idling, overexcited, synchronous motor) power electronics control devices such as a Static VAR Compensator (SVC, FACTS, STATCOM) etc (Kessinger 1997). A switching converter inside DER. Apart from synchronous generators, FACTS controllers are other devices that provide reactive power and dynamic voltage control. These methods are briefly explained below.

Voltage-Control Equipment

The power-system designer and operator have several devices available that can be used to control voltages by injecting, absorbing, or forcing the flow of reactive power. These devices differ in several important characteristics: response speed, continuity of control, response to system voltage changes, and capital and operating costs (Table 1).

Table 1. Characteristics of voltage-control equipment (“ORNL/CON-453 1997”)

Equipment type voltage	Speed of response	Ability to support	Costs		
			Capital (per kVAR)	Operating	Opportunity
Generator	Fast	Excellent, additional short-term capacity	Difficult to separate	High	No
Synchronous condenser	Fast	Excellent, additional	\$30-35	High	No
Capacitor	Slow, stepped	Poor, drops with V^2	\$8-10	Very low	No
Static VAR compensator	Fast	Poor, drops with V^2	\$45-50	Moderate	No
STATCOM	Fast	Fair, drops with V	\$50-55	Moderate	No
Distribut generation	Fast	Fair, drops With V	Difficult to Separate	High	Yes

Summary of FACTS cost estimates[**] ("HVDC Power Transmission Technology Assessment") ORNL/Sub-7662/1 Page.69, 1997

Shunt Capacitors	\$ 8/kVAr
Conventional series capacitors	\$ 20/kVAr
Conventional PAR transformer	\$ 20/kVA

Static VAr Compensator	$ 40/kVAr controlled portions
TCSC	$ 40/kVAr controlled portions
STATCOM	$ 50/kVAr
UPFC Series portion	$ 50/kW through power
UPFC Shunt portion	$ 50/kVAr controlled

4. GENERATION

An electric-power generator's primary function is to convert fuel (or other energy resource) into electric power. Almost all generators* also have considerable control over their terminal voltage and reactive-power output. Payment for the use of this resource is the specific focus of FERC's voltage control from generation service. The ability of a generator to provide reactive support depends on its real-power production (Rustebakke 1983). Like most electric equipment, generators are limited by their current-carrying capability. Near rated voltage, this capability becomes an MVA limit for the armature of the generator rather than a MW limitation. Production of reactive power involves increasing the magnetic field to raise the generator's terminal voltage. Increasing the magnetic field requires increasing the current in the rotating field winding. Absorption of reactive power is limited by the magnetic-flux pattern in the stator, which results in excessive heating of the stator-end iron, the core-end heating limit. The synchronizing torque is also reduced when absorbing large amounts of reactive power, which can also limit generator capability to reduce the chance of losing synchronism with the system. The generator prime mover (e.g., the steam turbine) is usually designed with less capacity than the electric generator, resulting in the prime-mover limit. The designers recognize that the generator will be producing reactive power and supporting system voltage most of the time. Providing a prime mover capable of delivering all the mechanical power the generator can convert to electricity when it is neither producing nor absorbing reactive power would result in underutilization of the prime mover.

To produce or absorb additional VARs beyond these limits would require a reduction in the real-power output of the unit. Control over the reactive output and the terminal voltage of the generator is provided by adjusting the DC current in the generator's rotating field (Hauth,and Tatro 1997). Control can be automatic, continuous, and fast. The inherent characteristics of the generator help maintain system voltage. At any given field setting, the generator has a specific terminal voltage it is attempting to hold. If the system voltage declines, the generator will inject reactive power into the power system, tending to raise system voltage. If the system voltage rises, the

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reactive output of the generator will drop, and ultimately reactive power will flow into the generator, tending to lower system voltage.

The voltage regulator will accentuate this behavior by driving the field current in the appropriate direction to obtain the desired system voltage.

5. SYNCHRONOUS CONDENSERS

Every synchronous machine (motor or generator) with a controllable field has the reactive-power capabilities discussed above. Synchronous motors are occasionally used to provide dynamic voltage support to the power system as they provide mechanical power to their load. Some combustion turbines and hydro units are designed to allow the generator to operate without its mechanical power source simply to provide the reactive-power capability to the power system when the real-power generation is unavailable or not needed. Synchronous machines that are designed exclusively to provide reactive support are called synchronous condensers. Synchronous condensers have all of the response speed and controllability advantages of generators without the need to construct the rest of the power plant (e.g., fuel-handling equipment and boilers). Because they are rotating machines with moving parts and auxiliary systems, they may require significantly more maintenance than static alternatives. They also consume real power equal to about 3% of the machine's reactive-power rating.

6. CAPACITORS AND INDUCTORS

Capacitors and inductors (which are sometimes called reactors) are passive devices that generate or absorb reactive power. They accomplish this without significant real-power losses or operating expense. The output of capacitors and inductors is proportional to the square of the voltage. Thus, a capacitor bank (or inductor) rated at 100 MVAR will produce (or absorb) only 90 MVAR when the voltage dips to 0.95 pu but it will produce (or absorb) 110 MVAR when the voltage rises to 1.05 pu. This relationship is helpful when inductors are employed to hold voltages down. The inductor absorbs more when voltages are highest and the device is needed most. The relationship is unfortunate for the more common case where capacitors are employed to support voltages. In the extreme case, voltages fall, and capacitors contribute less, resulting in a further degradation in voltage and even less support from the capacitors; ultimately, voltage collapses and outages occur.

Inductors are discrete devices designed to absorb a specific amount of reactive power at a specific voltage. They can be switched on or off but offer no variable control. Capacitor banks are composed of individual capacitor cans, typically 200 kVAR or less each. The cans are connected in series and parallel to obtain the desired capacitor-bank voltage and capacity rating. Like inductors, capacitor banks are discrete devices but they are often configured with several steps to provide a limited amount of variable control which makes it a disadvantage compared to synchronous motor or FACTS controllers.

STATIC VAR COMPENSATORS (SVCs)

An SVC combines conventional capacitors and inductors with fast switching capability. Switching takes place in the subcycle timeframe (i.e., in less than 1/60 of a second), providing a continuous range of control. The range can be designed to span from absorbing to generating reactive power. Consequently, the controls can be designed to provide very fast and effective reactive support and voltage control. Because SVCs use capacitors, they suffer from the same degradation in reactive capability as voltage drops. They also do not have the short-term overload capability of generators and synchronous condensers. SVC applications usually require harmonic filters to reduce the amount of harmonics injected into the power system.

7. STATIC SYNCHRONOUS COMPENSATORS (STATCOMs)

The STATCOM is a solid-state shunt device that generates or absorbs reactive power and is one member of a family of devices known as flexible AC transmission system (FACTS) devices (Kessinger 1997). The STATCOM is similar to the SVC in response speed, control capabilities, and the use of power electronics. Rather than using conventional capacitors and inductors combined with fast switches, however, the STATCOM uses power electronics to synthesize the reactive power output. Consequently, output capability is generally symmetric, providing as much capability for production as absorption (El-Keib 1997). The solid-state nature of the STATCOM means that, similar to the SVC, the controls can be designed to provide very fast and effective voltage control (Purucker 1997). While not having the short-term overload capability of generators and synchronous condensers, STATCOM capacity does not suffer as seriously as SVCs and capacitors do from degraded voltage. STATCOMs are current limited so their MVAR capability responds linearly to voltage as opposed to the voltage-squared relationship of SVCs and capacitors. This attribute greatly increases the usefulness of STATCOMs in preventing voltage collapse.

DIFFERENCES AMONG EQUIPMENT TYPES

Generators, synchronous condensers, SVCs, and STATCOMs all provide fast, continuously controllable reactive support and voltage control. Capacitors and inductors are not variable and offer control only in large steps (El-Keib 1997).

An unfortunate characteristic of capacitors and capacitor-based SVCs is that output drops dramatically when voltage is low and support is needed most. The output of a capacitor, and the capacity of an SVC, is proportional to the square of the terminal voltage. STATCOMs provide more support under low-voltage conditions than do capacitors or SVCs because they are current-limited devices and their output drops linearly with voltage. The output of rotating machinery (i.e., generators and synchronous condensers) rises with dropping voltage unless the field current is actively reduced. Generators and synchronous condensers generally have additional emergency capacity that can be used for a limited time. Voltage-control characteristics favor the use of generators and synchronous condensers. Costs, on the other hand, favor capacitors. Generators have extremely high capital costs because they are designed to produce real power, not reactive power. Even the incremental cost of obtaining reactive support from generators is high, although it is difficult to unambiguously separate reactive-power costs from real-power costs. Operating costs for generators are high as well because they involve real-power losses (Chapman 2003 and Dandachi 1996).

Finally, because generators exist primarily to provide real power, they experience lost opportunity costs when called upon to simultaneously provide high levels of both reactive and real power. Synchronous condensers have the same costs as generators; but, because they are built solely to provide reactive support, their capital costs do not include the prime mover or the balance of plant and they incur no opportunity costs. SVCs and STATCOMs are high-cost devices, as well, although their operating costs are lower than those for synchronous condensers and generators.

8. DISTRIBUTED GENERATION

Distributing generation resources throughout the power system can have a beneficial effect if the generation has the ability to supply reactive power. Without this ability to control reactive-power output, performance of the transmission and distribution system can be degraded. Induction generators were an attractive choice for small, grid-connected generation,

primarily because they are relatively inexpensive. They do not require synchronizing and have mechanical characteristics that are appealing for some applications (wind, for example). They also absorb reactive power rather than generate it, and are not controllable. If the output from the generator fluctuates (as wind does), the reactive demand of the generator fluctuates as well, compounding voltage-control problems for the transmission system. Induction generators can be compensated with static capacitors, but this strategy does not address the fluctuation problem or provide controlled voltage support. Many distributed generation resources are now being coupled to the grid through solid-state power electronics to allow the prime mover's speed to vary independently of the power-system frequency. For wind, this use of solid-state electronics can improve the energy capture (Kessinger 1997 and Hingorani 2000).

For gas-fired microturbines, power electronics equipment allows them to operate at very high speeds. Photovoltaics generate direct current and require inverters to couple them to the power system. Energy-storage devices (e.g., batteries, flywheels, and superconducting magnetic-energy storage devices) are often distributed as well and require solid-state inverters to interface with the grid. This increased use of a solid-state interface between the devices and the power system has the added benefit of providing full reactive-power control, similar to that of a STATCOM.

In fact, most devices do not have to be providing active power for the full range of reactive control to be available. The generation prime mover, e.g. turbine, can be out of service while the reactive component is fully functional. This technological development (solid-state power electronics) has turned a potential problem into a benefit, allowing distributed resources to contribute to voltage control.

Synchronous motor dynamic characteristics

Based on preliminary investigation and computation of synchronous motor dynamic characteristics, with a 250hp synchronous machine, it has been found that it can reliably provide a much more efficient and relatively cheap VAR

At unity power factor the current reduces, so is the I^2R losses, because losses are proportional to the I^2R and increase in losses also increases winding temperature and hence resistance, the effect of generating reactive power is to increase loses in a non-linear manner.

The curve in figure 1 shows the preliminary test results curve from the test analysis carried out on 250hp synchronous motor. Varying the excitation field current at certain set values of supply voltage the characteristics curve shown in the figure conform to the characteristic and takes the shape of a V- curve similar to that found in text book. It will be seen from figure 1 shown that by varying the excitation current at set value of supply voltage in steps the voltage initially goes down and later increases to 500V at about 9.5A excitation current, which clearly illustrated synchronous motor performance. The curve in figure 1 and 2 shows the line voltage versus real power and real power versus the excitation current.

For each curve, the minimum armature current occurs at unity power factor, when only real power is being supplied. At the other point on the curve, some reactive power is being supplied to or by the motor as well. Thus for field currents less than the value giving minimum armature current (I_A) is lagging, consuming reactive power Q. For field currents greater than the value giving the minimum I_A, the armature current is leading, supplying reactive power Q to the power system as a capacitor would. Therefore, by controlling the field current of a synchronous motor, the reactive power supplied to or consumed by the power system can be controlled which explains the dynamic of synchronous motor to control voltage variation compared to capacitor bank.

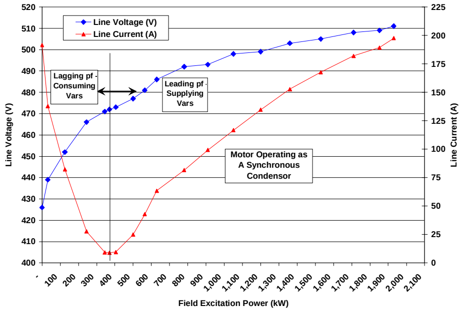

Figure 1. Synchronous motor: utility's a-phase supply voltage & current vs motor's dc field excitation power.

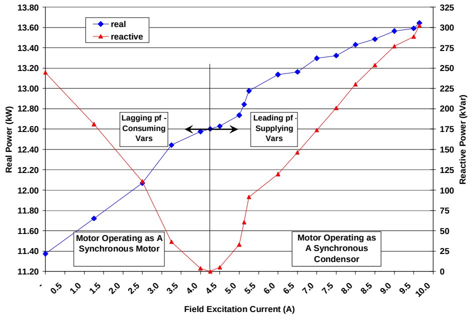

Figure 2. Load supply of reactive power.

9. CONCLUSIONS

The assessment methodology and guidelines for assessing the impact of DER on electric distribution systems are only starting to be developed. Over the next decade, as distributed generation moves into the mass market, distribution utility engineers will require these standardized assessment tools and guidelines to successfully implement and control these DER technologies in an open and competitive electricity market (Kueck 2004). The result of this study can help lead the way to developing these processes and help foster the successful implementation of distributed resources in electric utility distribution systems.

Voltage control is accomplished by managing reactive power on an alternating-current power system. Reactive power can be produced and absorbed by both generation and transmission equipment. Reactive-power devices differ substantially in the magnitude and speed of response and in their capital costs. System operators, transmission owners, generators, customers, power marketers, and government regulators need to pay close attention to voltage control as they restructure the U.S. electricity industry. Voltage control can affect reliability and commerce in three ways:

Voltages must be maintained within an acceptable range for both customer and power-system equipment to function properly.

The movement of reactive power consumes transmission resources, which limits the ability to move real power and worsens congestion. The movement of reactive power results in real-power losses.

When generators are required to supply excessive amounts of reactive power, their real-power production must be curtailed. Although this cost is low when compared with the cost of energy, it still aggregates to a significant amount of money. These changes in industry structure require new institutional rules and markets to plan for additional voltage-support capacity, to reserve that capacity for future use, and to deploy that capacity in real time to meet current and contingency conditions. These services can be obtained through engineering mandates or through markets.

The process of controlling voltages and managing reactive power on interconnected transmission systems is well understood from a technical perspective. Three objectives dominate reactive-power management. First, maintain adequate voltages throughout the transmission system under current and contingency conditions. Second, minimize congestion of real-power flows. Third, minimize real-power losses. This process must be performed centrally because it requires a comprehensive view of the power system to assure that control is coordinated. System operators and planners use sophisticated computer models to design and operate the power system reliably economically. Various devices can be deployed to control voltages with varying capital and operating costs, varying degrees of control, and varying performance characteristics. Far less effort has been directed at finding commercially efficient ways of providing the resources needed for voltage control. Central control by rule works well but may not be the most economically effective means. The economic impact of control actions can be quite different in a restructured industry than for vertically integrated utilities. While it may be sufficient to measure only the response of the system in aggregate for a vertically integrated utility, determining individual generator performance will be critical in a competitive environment. When an investor is considering construction of new generation, the amount of reactive capability that the generator can provide without curtailing real-power production should depend on system requirements and the economics of alternatives, not on a fixed rule. The introduction of advanced devices, such as STATCOMs and SVCs, further complicates the split between transmission- and generation-based voltage control. The fast response of these devices often allows them to substitute for generation-based voltage control.

But their high capital costs limit their use. If these devices could participate in a competitive voltage-control market, efficient investment would be encouraged. In areas with high concentrations of generation, sufficient interaction among generators is likely to allow operation of a competitive market. In other locations, introduction of a small amount of controllable reactive support on the transmission system might enable market provision of the bulk of the reactive support. In other locations, existing generation would be able to exercise market power and would continue to require economic regulation for this service. A determination of the extent of each type within each region would be a useful contribution to restructuring. NERC (1997) emphasized the importance of planning and operating systems to maintain voltages as the U.S. electricity industry is restructured:

System planners and operators need to work closely together during the design of new facilities and modification of existing facilities. Planners must design adequate reactive support into the system to provide satisfactory voltage profiles during normal and contingency operating conditions. Of particular importance is sufficient dynamic support, such as the reactive output of generators, which can supply additional reactive power during contingencies. System operators must have sufficient metering and analytical tools to be able to tell when and if the operational reactive resources are sufficient. Operators must remain cognizant of any equipment outages or problems that could reduce the system's static or dynamic reactive support below desirable levels. Ensuring that sufficient reactive resources are available to control voltages may be increasingly difficult because of the deintegration of the electricity industry. Traditional vertically integrated utilities contained, within the same entity, generator reactive resources, transmission reactive resources, and the control center that determined what resources were needed when. In the future, these resources and functions may be placed within three different entities. In addition, these entities will have different, perhaps conflicting, goals. In particular, the owners of generating resources will be driven, in competitive generation markets, to maximize the earnings from their resources. They will not be willing to sacrifice revenues from the sale of real power to produce reactive power unless appropriately compensated. Similarly, transmission owners will want to be sure that any costs they incur to expand the reactive capabilities on their system (e.g., additional capacitors) will be reflected fully in the transmission rates that they are allowed to charge. Thus, although reactive-power costs are only about $1.5 billion today (Kirby and Hirst 1996), failure to appropriately compensate those entities that provide voltage-control services could lead to serious reliability problems and severe constraints on commercial transactions.

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