Reactive Power and Importance to Bulk Power System

OAK RIDGE NATIONAL LABORATORY
ENGINEERING SCIENCE & TECHNOLOGY DIVISION

Outline

- **What is Reactive Power and where does it come from?**
- **Why is it important?**
- **Reactive Power and Blackouts**
- **Reactive Power Delivery Limitations**
- **How Reactive Power Dispatch Has Changed**
- **Advantages and Disadvantages of Various Devices**

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Where Does Reactive Power Come From?

- **"Power" refers to the energy-related quantities flowing in the T&D network**
- **Instantaneously, Power is the product of voltage and current**
- **When voltage and current are not in phase or in synch, there are two components**
  - **Real or active power is measured in Watts**
  - **Reactive (sometimes referred to as imaginary) power is measured in Vars**
  - **The combination (vector product) is Complex Power or Apparent Power**
- **The term "Power" normally refers to active power**

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Why Do We Need Reactive Power

("Signatures of the Blackout of 2003",
Roger C. Dugan et. al.)

"*Reactive power (vars) is required to maintain the voltage to deliver active power (watts) through transmission lines. Motor loads and other loads require reactive power to convert the flow of electrons into useful work. When there is not enough reactive power, the voltage sags down and it is not possible to push the power demanded by loads through the lines.*"

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Importance of Reactive Power

- **Refers to the circulating power in the grid that does no useful work**
- **Results from energy storage elements in the power grid (mainly inductors and capacitors)**
- **Has a strong effect on system voltages**
- **It must balance in the grid to prevent voltage problems**
- **Reactive power levels have an effect on voltage collapse**

Reactive Power is a Byproduct of Alternating Current (AC) Systems

- **Transformers, transmission lines, and motors require reactive power**
- **Transformers and transmission lines introduce inductance as well as resistance**
  - **Both oppose the flow of current**
- **Must raise the voltage higher to push the power through the inductance of the lines**
  - **Unless capacitance is introduced to offset inductance**
- **The farther the transmission of power, the higher the voltage needs to be raised**
- **Electric motors need reactive power to produce magnetic fields for their operation**

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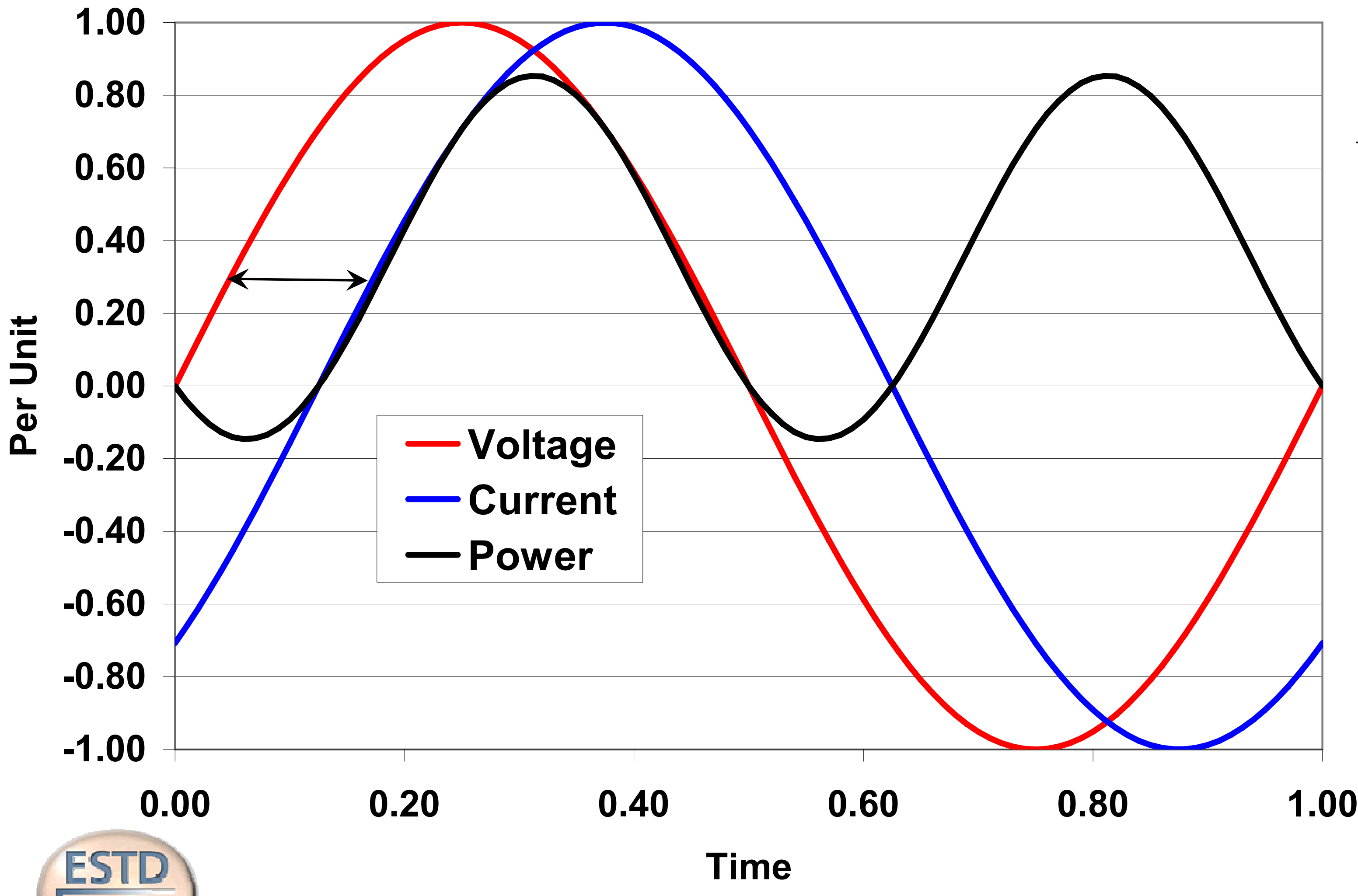
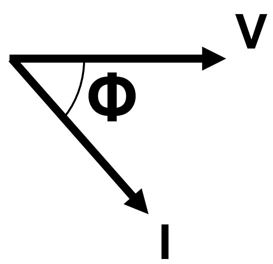
Reactive Power and Power Factor

- **Reactive power is present when the voltage and current are not in phase**
  - **One waveform leads the other**
  - **Phase angle not equal to 0°**
  - **Power factor less than unity**
- **Measured in volt-ampere reactive (VAR)**
- **Produced when the current waveform leads voltage waveform (Leading power factor)**
- **Vice versa, consumed when the current waveform lags voltage (lagging power factor)**

AC Voltage and Current Phase Shift Due to Inductance Current Lags Voltage



$$v = L\frac{di}{dt}$$

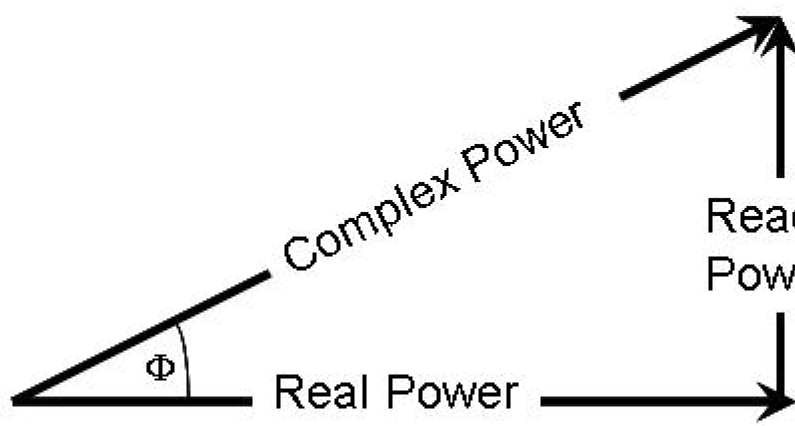


Power Triangle

$$\text{Complex Power} = \sqrt{(\text{Real Power})^2 + (\text{Reactive Power})^2}$$

$$\text{Real Power} = \text{Complex Power} \times \text{Cos}(\Phi)$$

$$\text{Power Factor} = \text{Cos}(\Phi) = \frac{\text{Real Power}}{\text{Complex Power}}$$



Reactive Power and Past Events

- **Voltage drops related to reactive power contributed to blackouts in the West (1996) and in France (1978)**
- **PJM itself came close to a blackout due to reactive power problems in 1999**
  - **PJM is unusual, they have rigorous regional monitoring of reactive power and rules for its operation and compensation**
- **Significant voltage swings due to reactive power in the Midwest and Northeast in 2003**

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Reactive Power in the News
(New York Times, Sept. 26, 2003)

"Experts now think that on Aug. 14, northern Ohio had a severe shortage of reactive power, which ultimately caused the power plant and transmission line failures that set the blackout in motion. Demand for reactive power was unusually high because of a large volume of long-distance transmissions streaming through Ohio to areas, including Canada, than needed to import power to meet local demand. But the supply of reactive power was low because some plants were out of service and, possibly, because other plants were not producing enough of it."

Reactive power and the August 14th Blackout

- **Several hours before, First Energy noticed low voltage**
  - **A sign of insufficient reactive power**
  - **Subsequently, increased VAR production at nine of its plants**
  - **Low voltage shut down the Eastlake plant**
- **About two hours before, brush fire in southwest Ohio knocked out a power line**
  - **Redirected power on the system**
  - **Changed need for reactive power on other lines**
- **About one hour before, power lines between Cleveland and southern Ohio tripped**
- **Few minutes before blackout, all links between northern Ohio and southern Ohio shut down**
  - **Known for some time as reactive power weak spot**

Reactive Power Limitations

- **Reactive power does not travel very far**
- **Usually necessary to produce it close to the location where it is needed**
- **A supplier/source close to the location of the need is in a much better position to provide reactive power**
  - **versus one that is located far from the location of the need**
- **Reactive power supplies are closely tied to the ability to deliver real or active power**

How Reactive Power Control Implemented

- **Regulate to control voltage to a desired nominal value**
- **Often, reactive power injections regulate voltage at the location of the injection**
- **Control effects tend to be localized**
- **Some reactive power supply mechanisms:**
  - **Shunt capacitors (fixed and switchable)**
  - **Synchronous condensers**
  - **Synchronous generators**
  - **Static VAR compensators**

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How Management of Reactive Power Has Changed

- **Under regulated environment, most utilities owned/controlled G&T&D in its own control area**
  - **Provided reactive power just as it had to provide sufficient generation and voltage**
- **Restructuring has changed this and is causing problems dealing with reactive power**
  - **Merchant (non-utility) generation and related financial incentives**
  - **Transmitting power over longer distances with multiple transactions**

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What has Lead to Problems

- **Regulated, electric rates based on kWh and kVA giving incentive for pf correction**
- **Restructuring, separation of G&T&D businesses**
  - **Generation: More likely kW based from non-regulated generation removing incentive for pf correction**
  - **Distribution: may not have significant incentive and strict budget for installation of capacitors**
  - **Transmission: who will own and operate and thus no incentive for improvement**
- **Electricity is transmitted between control areas**
  - **Has to be communication to properly operate the system, including adjustments to reactive power.**
  - **ISOs (i.e., MISO) has not yet defined any system rules concerning reactive power**

What PJM Has Done

- **Adopted MW limits for flows in the system without local generation being present to produce VARs**
- **Generators now receive “lost opportunity” revenue payments when they must provide additional reactive power**
- **Included specific VAR obligations and penalties for non-compliance in each new interconnection service agreement with generators**

Reactive Power Compensation Devices *Advantages and Disadvantages*

- **Synchronous Condensors - synchronous machines designed exclusively to provide reactive power support**
  - **At the receiving end of long transmission lines**
  - **In important substations**
  - **In conjunction with HVDC converter stations.**
  - **Reactive power output is continuously controllable**
- **Static VAR compensators – combine capacitors and inductors with fast switching (sub cycle, such as <1/50 sec) timeframe capability**
  - **Voltage is regulated according to a slope (droop) characteristic**

Reactive Power Compensation Devices (cont.)

- **SVC (cont.)**
  - **Range from absorbing to generating reactive power**
  - **Advantages: fast & precise regulation of voltage and unrestricted, largely transient-free, capacitor bank switching**
  - **Disadvantage: same degradation in reactive capability as voltage drops as capacitors**
- **Static synchronous compensator (STATCOM) - solid-state shunt device that generates or absorbs reactive power**
  - **member of FACTS device family**
  - **similar to the SVC in response speed, control capabilities, and the use of power electronics**

Reactive Power Compensation Devices (cont.)

- **STATCOM (cont.)**
  - **member of FACTS device family**
  - **similar to the SVC in response speed, control capabilities, and the use of power electronics**
  - **Disadvantage: Doesn’t have the short-term overload capability of generators and synchronous condensors**
  - **Advantage: does not suffer as seriously as SVCs and capacitors do from degraded voltage**
- **Series Compensation –application of series capacitors and reactors for long transmission lines and transient stability improvement**
  - **reduces net transmission line inductive reactance**

Reactive Power Compensation Devices (cont.)

- **Series Compensation (cont.)**
  - **Advantage: series capacitor reactive generation increases with the current squared (generating reactive power when it is most needed)**
  - **Disadvantage: At light loads series capacitors have little effect**
- **Shunt capacitors - mechanically switched or fixed shunt capacitor banks installed at substations or near loads**
  - **Keeping voltage within required limit**
  - **Advantage: much lower cost compared to SVCs**
  - **Switching speeds can be quite fast with current limiting reactors to minimize switching transients.**

Reactive Power Compensation Devices (cont.)

- **Shunt capacitors (cont.) - Disadvantages**
  - **Reactive power output drops with the voltage squared**
  - **For transient voltage instability the switching may not be fast enough to prevent induction motor stalling**
  - **Precise and rapid control of voltage is not possible (capacitor banks are discrete devices, but they are often configured with several steps to provide a limited amount of variable control)**
  - **If voltage collapse results in a system, the stable parts of the system may experience damaging overvoltages immediately following separation.**

Reactive Power Compensation Devices (cont.)

- **Shunt reactors - mainly used to keep the voltage down**
  - **absorb reactive power in the case of light load and load rejection**
  - **compensate the capacitive load of transmission lines**
- **Other Mechanisms**
  - **Unified Power Flow Controllers (UPFC) and other advanced FACTS**
  - **Tap staggering of transformers connected in parallel**
  - **Disconnection of transmission lines**
  - **Load shedding**
- **Oversize DER (DG) to produce reactive power locally**