Power Systems Engineering Research Center

PSERC Background Paper

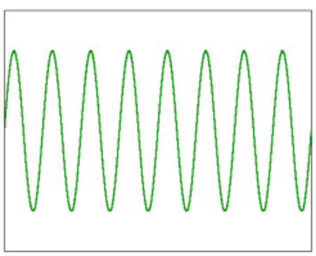
What is Reactive Power?

Peter W. Sauer
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

September 16, 2003

Engineering talk

Reactive power is a quantity that is normally only defined for alternating current (AC) electrical systems. Our U.S. interconnected grid is almost entirely an AC system where the voltages and currents alternate up and down 60 times per second (not necessarily at the same time). In that sense, these are pulsating quantities. Because of this, the power being transmitted down a single line also “pulsates” - although it goes up and down 120 times per second rather than 60. This power goes up and down around some “average” value - this average value is called the “real” power and over time you pay for this in kilowatt-hours of energy. If this average value is zero, then all of the power being transmitted is called “reactive” power. You would not normally be charged for using reactive power because you are consuming some energy half the time, and giving it all back the other half of the time - for a net use of zero. To distinguish reactive power from real power, we use the reactive power unit called “VAR” - which stands for Volt-Ampere-Reactive. Voltage in an electrical system is analogous to pressure in a water system. Current in an electrical system is analogous to the flow of water in a water system.



Let’s go back to this notion that voltage and current may not go up and down at the same time. When the voltage and current do go up and down at the same time, only real power is transmitted. When the voltage and current go up and down at different times, reactive power is being transmitted. How much reactive power and which direction it is flowing on a transmission line depends on how different these two times are.

Two extreme examples of the time relationship between voltage and current are found in inductors and capacitors. An inductor is a coil of wire that is used to make motors. A capacitor is made of parallel conductive plates separated by an insulating material. The electrical properties of these two devices are such that if they are both connected to the same AC voltage source, the inductor absorbs energy during the same “half cycle” that the capacitor is giving energy. And similarly, the inductor produces energy during the same “half cycle” that the capacitor absorbs energy. Neither of them absorbs any real power over one complete cycle. Thus, when a motor needs reactive power, it is not necessary to go all the way back to electric power generators on the transmission grid to get it. You can simply put a capacitor at the location of the motor and it will provide the VARs needed by the motor. This relieves the generator and all the lines between the generator and the motor of having to transmit those VARs. They are provided “locally” by the capacitor. This means that with the capacitors installed, the current in the lines will be smaller than when the capacitors are not installed. This is a good thing because current in the lines causes heat and every line can only handle a limited amount of current. Since the line current is smaller when the capacitors are installed, the voltage drop along all the lines is also less, making it more likely that the motor will have a voltage closer to the desired value. When there are not enough VARs flowing locally to the loads, the generators must supply them remotely, causing unnecessarily large currents and a resulting drop in voltage everywhere along the path.

A physical analogy for reactive power

While there are numerous physical analogies for this quantity called reactive power, one that is reasonably accurate is the process of filling a water tower tank with water - one bucket at a time. Suppose you want to fill a water tower tank with water, and the only way that you can do that is by climbing up a ladder carrying a bucket of water and then dumping the water into the tank. You then have to go back down the ladder to get more water. Strictly speaking, if you simply go up a ladder (not carrying anything) and come back down (not carrying anything), you have not done any work in the process. But, since it did take work to go up the ladder, you must have gotten all that energy back when you came down. While you may not feel that coming down the ladder completely restores you to the condition you were in before you went up, ideally, from an energy conversion viewpoint, you should! If you don’t agree, get out your physics book and check out the official definition of doing work.

OK, if you still don’t agree that walking up a ladder and coming back down does not require any net work, then think of it this way. Would you pay anyone to walk up a ladder and back down without doing anything at the top? Probably not. But, if they dumped a bucket of water in the tank while they were at the top, then that would be something worth paying for.

When you carry a bucket of water up the ladder you do a certain amount of work. If you dump the water at the top and carry an empty bucket down, then you have not gotten all your energy back (because your total weight coming down is less than going up), and you have done work during that process. The energy that it takes to go up and down a ladder carrying nothing either way requires reactive power, but no real power. The energy that it takes to go up a ladder carrying something and come down without carrying anything requires both real power and reactive power.

A reminder here is that power is the time rate of energy consumption, so consuming 500 Watts of real power for 30 minutes uses 250 Watt-hours of energy (or 0.25 kilowatt-hours which costs about 2.5 cents to generate in the U.S.). The analogy is that voltage in an AC electrical system is like the person going up and down the ladder. The movement of the water up the ladder and then down into the tank is like the current in an AC electrical system.

Now, this pulsating power is not good in an electrical system because it causes pulsations on the shafts of motors and generators which can fatigue them. So, the answer to this pulsation problem is to have three ladders going up to the water tower and have three people climb up in sequence (the first person on the first ladder, then the second person on the second ladder, then the third person on the third ladder) such that there is always a steady stream of water going into the tank. While the power required from each person is pulsating, the total result of all three working together in perfect balanced, symmetrical sequence results in a constant flow of water into the tank – this is why we use “3-phase” electrical systems where voltages go up and down in “sequence” – (first A phase, then B phase, and finally C phase).

In AC electrical systems, this sequential up/down pulsation of power in each line is the heart of the transmission of electrical energy. As in the water tower analogy, having plenty of water at ground level will not help you if you cannot get it up into the tower. While you may certainly be strong enough to carry the bucket, you cannot get it there without the ladder. In contrast, there may be a ladder, but you may not be strong enough to carry the water. However, the people do take up room around the water tower and limit how much water can go up and down over a period of time - just as reactive power flow in an electrical system requires a larger current which limits how much real power can be transmitted.[1]

To make the system more reliable, we might put two sets of three ladders leading up to the tank on the tower. Then, if one set fails (maybe the water plus the person get too heavy and the ladder breaks), the other set picks up the slack (that is, has to carry more water). But, this could eventually overload the second set so that it too fails. This is a cascading outage due to the overloading of ladders.

How is reactive power related to the problem of voltage collapse?

In terms of this water-carrying analogy, the frequency of going up and down the ladder should be nearly constant (that, is like our 60 cycles per second electrical frequency). So, when more water is needed, the amount that each person carries up the ladder must get bigger (since they are not allowed to go faster or slower). Well, if this water gets too heavy, either the ladder might break, or the person might get too tired to carry it. We could argue that if the ladder breaks, that is like the outage of a transmission line that either sags or breaks under the stress of too much current. There are devices called relays in an electrical system that are supposed to sense when the load is too much and send a signal to a “circuit breaker” to remove the line from service (like removing the set of three ladders). If the person gets too tired, we could again stretch this analogy to say that this is like not having enough reactive power (resulting in low

---

[1] Another analogy that says that reactive power is the “foam on the beer” is fairly good here because the space in the glass is taken up by the useless foam - leaving less room for the “real” beer.

voltage). In the extreme case, the person might “collapse” under the weight of the water that the person is being asked to carry. If it happens to one person, it will probably happen to many of them. In the electrical system this could be considered a “voltage collapse”. While there are “undervoltage relays,” ***there are no relays in the system to directly sense the problem that the voltage is about to collapse***.

Remember, the people going up and down the ladders do not absorb or produce energy over a complete cycle and are therefore analogous to reactive power. It is the water going up the ladder to fill the tank that absorbs real power that must be paid for. But, the real power cannot be delivered without the reactive power. And, if there is not enough reactive power (like with people going up and down the ladders), the real power delivery will eventually fail.

In summary, ***a voltage collapse occurs when the system is trying to serve more load than the voltage can support***. A simulation has been prepared to illustrate voltage collapse by simply using a system with an Eastern generator and customer load, a Western generator and customer load, and East to West transmission lines. In the simulation, the Eastern generator has a constrained supply of reactive power and progressive line outages for unspecified reasons lead to a voltage collapse even when reactive power supply is ample at the Western generator. The results of the simulation are available in Power Point slides. (If you are connected to the Internet, click here to view the slides.)

In contrast to all of this, you could route a hose up the side of the water tower and simply turn on the water and let the water flow in the hose to fill up the tank. The water pressure is like voltage, and the water flow is like current. This type of system would be a direct current (DC) system and would not involve reactive power at all. However, the concept of voltage collapse is not unique to AC systems. A simple DC system consisting of a battery serving light bulbs can be used to illustrate how too much load on a system can lead to a condition where voltages drop to a critical point where “adding more load” results in less power transmission - a form of voltage collapse. (If you are connected to the Internet, click here to view Power Point slides illustrating DC voltage collapse.)

Contact Information

Peter W. Sauer
PSERC Site Director
Grainger Chair Professor
Department of Electrical & Computer Engineering
University of Illinois at Urbana-Champaign
1406 W. Green St.
Urbana, IL 61801
Phone: 217-333-0394
E-mail: sauer@ece.uiuc.edu

Power Systems Engineering Research Center
428 Phillips Hall
Cornell University
Ithaca, NY 14853-5401
Phone: 607-255-5601