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2005 December 15

Mr. Mark Cox
Distribution Policy
Office of Gas and Electricity Markets
London
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Electricity Distribution Use of System Charging Modification Proposals:
Central Networks and United Utilities – Reactive Power Charges

Dear Sir:

In regard to the consultation on reactive power charges, I provide a copy of "Constructing a Competitive Distribution Market in Reactive Power: Comments of Mark B. Lively to the Office of Gas and Electricity Markets." A competitive market in reactive power would require:

- Distinguishing between leading and lagging reactive power
- Time varying prices
- Voltage responsive prices

My paper discusses these topics and presents a mechanism for setting a market price that responds to the concurrent conditions on the distribution grid. The paper also discusses the appropriateness of forwards contracts where participants commit to provide or absorb reactive power.

The paper refers to two documents that appear on my web page www.LivelyUtility.com.

- "Wide Open Load Following: Mark Lively's Approach to Pricing Reactive Power," *Carnegie Mellon University Electric Industry Center Luncheon Seminar*, 2004 December 2. This PowerPoint presentation is an expansion of "Wide Open Load Following: Mark Lively's Approach to Pricing Reactive Power," *IEEE-USA Energy Policy Committee Presentation to FERC Task Force on Reactive Power*, 2004 October 25, which is also on the web page for download.
- "Comments Of Mark Lively, Utility Economic Engineers, Including Answers And Comments To Questions In Staff Report Of 2005 February 4," filed in *Principles for Efficient and Reliable Reactive Power Supply and Consumption*, FERC Docket No. AD05-1-000, 2005 April 4.

If you have any questions about my approach, please contact me electronically, either by phone (301-428-3618) or by e-mail (MLively@LivelyUtility.com).

Yours truly,

Mark B. Lively

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Utility Economic Engineer

# CONSTRUCTING A COMPETITIVE DISTRIBUTION MARKET IN REACTIVE POWER: COMMENTS OF MARK B. LIVELY TO THE OFFICE OF GAS AND ELECTRICITY MARKETS

On 2005 December 1, the Office of Gas and Electricity Markets (OFGEM) issued a Consultation on Electricity Distribution Use of System Charging Modification Proposals: Central Networks and United Utilities – Reactive Power Charges. Central Networks and United Utilities had recently proposed changes in their Use of System (UoS) charges in regard to Reactive Power Charges. OFGEM took advantage of the close proximity of the two filings to issue the consultation.

A stated objective of UoS charging methodologies is that they facilitate competition, as stated in paragraph (b) of footnote 2 to the 2005 December 1 Consultation letter from Martin Crouch, Director, Distribution, OFGEM. Despite this objective to facilitate competition, the UoS rate structure stifles competition for the generation reactive power.

The UoS rate structure prevents others from competing with the Distribution Network Operators (DNOs) for the supply or the absorption of reactive power. The UoS rate structure obstructs the competitive market by preventing consumers and other market participants from selling reactive power to the network.

The assumption of the UoS rate structure is that reactive power always creates a cost to the system. In some instances, reactive power can provide a benefit to the DNO. The UoS rate structure does not recognize the benefit that reactive power from customers can provide to the system, thus stifling competition.

Reactive power can be leading or lagging. The UoS does not distinguish between leading and lagging reactive power. This inadequacy prevents participants from being paid to help the system during periods of stress on the network.

- In some situations, leading reactive power can help the DNO raise a low local distribution voltage. In those cases, leading reactive power should be considered to be good and the UoS should reward providers. It does not.

- Sometimes the local distribution voltage is already high enough. In those cases, leading reactive power should be considered to be bad and the UoS should charge providers. UoS does not distinguish between helpful and harmful leading reactive power.

- Conversely, lagging reactive power is generally considered to be bad, in that it lowers the local distribution voltage below the desired voltage. The UoS should provide charges for lagging reactive power in those instances.

- However, sometimes the local distribution voltage is too high. In those cases lagging reactive power keeps the voltage from going even higher, should be considered to be good, and should be rewarded by the UoS. The UoS provides no reward.

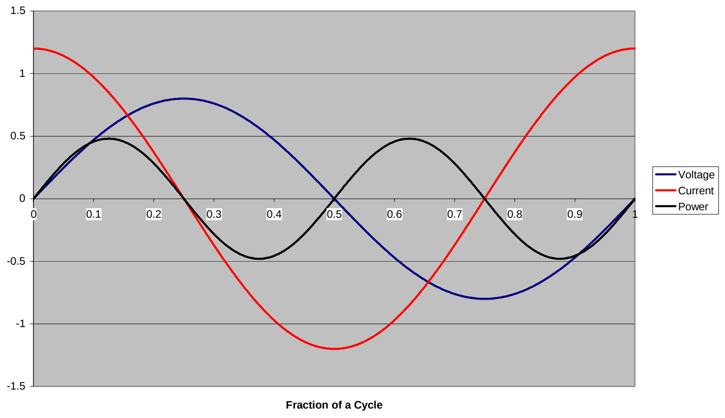
This paper discusses reactive power and how a dynamic pricing formula could provide a robust market for reactive power on the DNO distribution system.

Dynamic pricing will allow reactive power providers to influence the price they receive for reactive power. Profitability concerns can cause larger providers to withhold reactive power in an attempt to maximize their profits. Accordingly, this paper also discusses forward contracts that DNOs can offer a reactive power provider so that the operational concerns of the DNO mesh with the profitability concerns of the reactive power provider.

## REACTIVE AND ACTIVE POWER

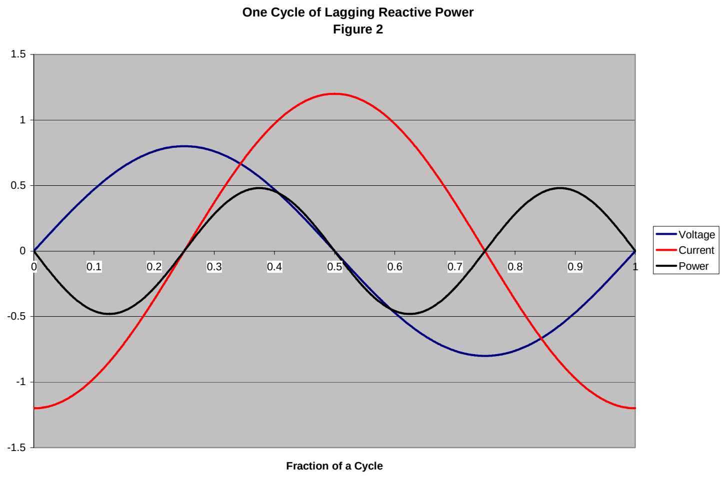
Reactive power effectively creates the voltage and the electro-magnetic fields that are necessary for the electric system to operate. In an alternating current (AC) system, reactive power flows into and out of the device twice each cycle. Figure 1 shows one cycle of leading reactive power. It is called leading reactive power because the current is out of phase with the voltage and is a quarter cycle ahead of the voltage. In other words, the current has a maximum slightly before when the voltage has a maximum. Also, as is more obvious from the graph, the current has its minimum slightly before the voltage has its minimum.

One Cycle of Leading Reactive Power
Figure 1



During the first quarter of the cycle, both the current and the voltage are positive. Power, the product of voltage and current, is thus positive, indicating that power is flowing into the device. In this example, energy is being accumulated in the device. During the second quarter of the cycle, the voltage is still positive, though declining, while the current is negative. Power, the product of voltage and current, is thus negative. Negative power indicates that power is flowing out of the device. Energy flow out of a device means that energy is being drained from the device.

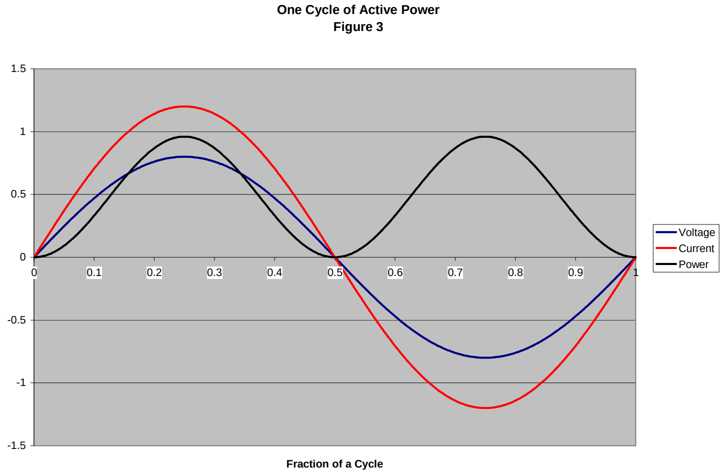
Figure 2 demonstrates lagging reactive power. Lagging reactive power refers to the current lagging behind the voltage. Thus the current reaches its maximum value after the voltage reaches its maximum value. Similarly the current reaches its minimum value after the voltage reaches it minimum value.



In the case of lagging reactive power, during the first quarter of the cycle, energy is drawn from the device because the power flow is defined to be negative. Power flows into the device during the second quarter of the cycle and then again during the fourth quarter of the cycle.

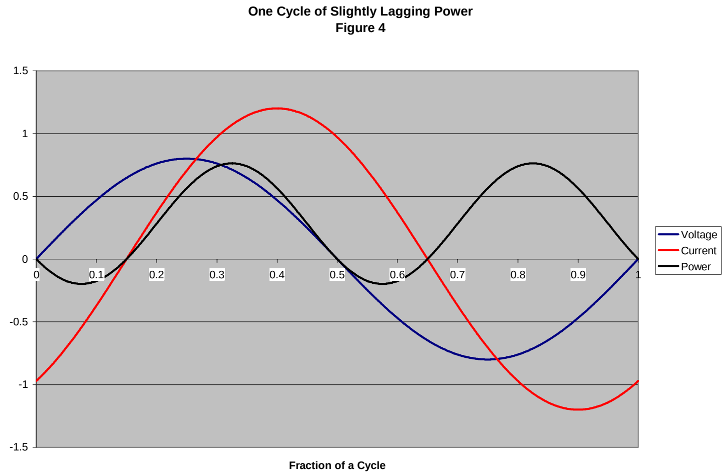
Figures 1 and 2 demonstrate the concept of pure reactive power, that is, there is no active power flowing to the customer or the customer's device. Because Figures 1 and 2 demonstrate the concept of pure reactive power, the current and voltage are out of phase with each other by one quarter of a cycle. Further, the amount of power flowing into the device during one part of the cycle is exactly balanced by the amount of power flowing out of the device during other parts of the cycle. That is, the area above the axis and below the power curve is equal to the area below the axis and above the power curve.

Figure 3 demonstrates the concept of pure active power. The voltage and current curves are in phase with each other. The voltage and current curves hit their respective maximums at the same time, they cross zero at the same time, and they hit their respective minimums at the same time. Whenever the voltage is positive the current is positive. Whenever the voltage is negative the current is negative. As a result, power is always positive, showing that energy is being delivered into the customer and its equipment throughout the cycle, with no power going back to the utility.



The graphs in Figures 1 through 3 show purely reactive or active loads. A more common load occurrence has a slightly lagging power factor, as is demonstrated in Figure 4. The current in Figure 4 reaches it maximum 0.15 of a cycle behind when the voltage hits its maximum. This is similarly true for the minimums for voltage and current, and for the zero crossings.

The graph of power in Figure 4 shows that most of the time power is positive, meaning that power is flowing into the customer or the customer device. There are short parts of the cycle when power is negative, which indicates that the power is flowing out of the customer premise and to the system. The energy returned to the system during these parts of the cycle is much smaller than the energy delivered to the customer during those parts of the cycle when power is positive and above the axis.



The concept of reactive power has often been called a mathematically construct, a way to put numbers around the various phenomena associated with AC power. Reactive power has been demonstrated here as the successive movement of power into and out of a customer or of a customer device. This movement of power into the device results in energy stored in the device as electromagnetic energy. The electromagnetic energy might be in the magnetic field associated with the electromagnet used to make a motor work. The electromagnetic energy might be the electric field associated with a capacitor. The subsequent movement of power out of the device represents the quenching or extinguishment of the field, a reduction in the amount of energy stored as electromagnetic energy.

## REACTIVE AND ACTIVE DEMAND

Reactive power by itself does not seem to use any energy. Rather, reactive power is the way energy is stored and then released by a customer. Reactive power is important to the utility for at least three reasons.

- Reactive power affects the voltage on the network, pushing voltage up or pushing voltage down.
- Most reactive power increases the electrical losses on the network, though some can offset the effects other reactive power.

- Most reactive power uses up the capacity of the network, though again some reactive power can offset the effects of other reactive power.

These are important concepts in setting the price for reactive power. The effect on electrical losses will be demonstrated as part of using up the capacity of the network.

The demand for electricity is demonstrated in Figure 5. This paper will use the convention that active power is a vertical line and that reactive power is a horizontal line. As is illustrated in Figure 5, lagging reactive power will be drawn as an arrow pointing to the right of the diagram. Though not shown in Figure 5, leading reactive power will be drawn as an arrow pointing to the left of the diagram.

**The Demand For Power**
**Figure 5**

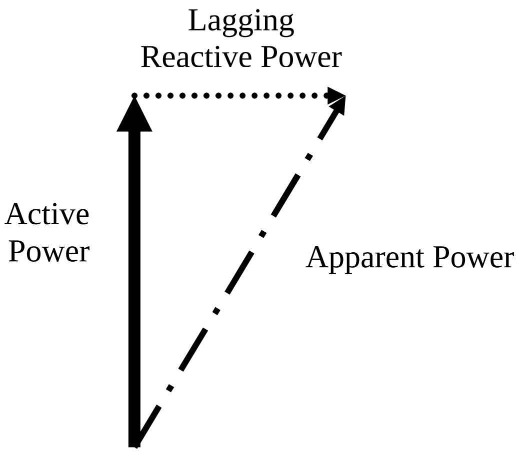


Figure 5 also demonstrates the concept of apparent power, the mathematical sum of active power and reactive power. Apparent power is equivalent to the hypotenuse of the right triangle formed with active power and reactive power as the two legs.

Apparent power can be calculated from the magnitude of the voltage and the magnitude of the current. Apparent power is the simple product of these two numbers. Thus apparent power is measured in Volt-Amps or thousands of Volt-Amps or KVA. From Figure 5, active power is apparent power times the cosine of the phase angle between the voltage and the current. Similarly, reactive power is the apparent power times the sine of the phase angle between the voltage and the current.

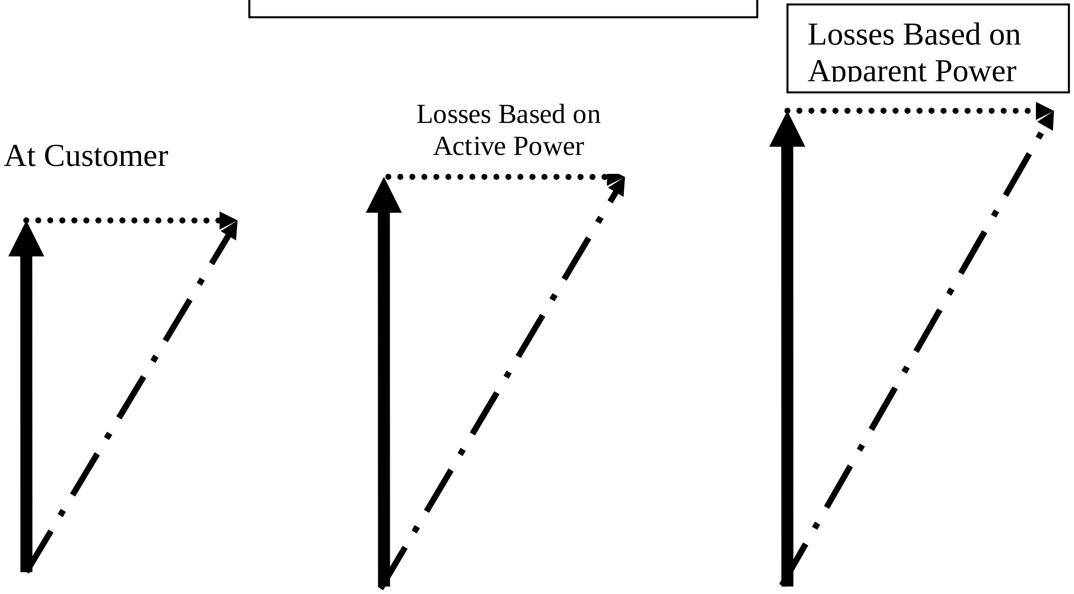
In Figure 4, the phase angle was the stated 0.15 fraction of a cycle or 54 degrees. Active power was thus cosine (54˚) or about 58% of the apparent power. Reactive power was thus sine (54˚) or about 81% of the apparent power.

Apparent power is important because it is proportional to the current being carried on equipment, such as wires, transformers, and motors. The current going through equipment determines how much electrical power is lost within the equipment. The electrical losses in the equipment show up as heat and an increase in temperature. Thus, the capacity of most electrical equipment is related to apparent power, which depends on both active power and reactive power. Reactive power thus uses up some of the capacity of the network.

Reactive power has often been compared to the carbonation in some beverages, such as soda, beer, or sparkling wine. When carbonation fizzes out of solution as foam, the carbonation (or more accurately the foam) takes up some of the capacity of the glass in which the beverage is served. Without the carbonation (foam), the beverage would be tasteless and flat, but more of the beverage could be served in a glass. With the carbonation (foam), the beverage is appetizing but a glass can hold less of the beverage. The same can be said for reactive power. Without reactive power, electrical devices can handle more active power. But the active power has less value without the reactive power being included with the active power.

Electrical losses increase with the square of the current, the “I Squared R” concept. Thus, electrical losses vary with the square of the apparent power. Reactive power, by increasing apparent power, will generally increase electrical losses on the network. The increased electrical loss also increases the fuel requirement for the system. Thus, though reactive power delivered to a customer does not result in the net delivery of energy to a customer, reactive power does result in the network having to use fuel to meet the related electrical losses.

**Electrical Losses**
**Figure 6**



The effect of reactive power on active power requirements is shown in Figure 6, a modification of Figure 5. The actual load at the customer premise is shown on the left side of Figure 6. The distribution and transmission systems will incur electrical losses moving electricity from the generator to the customer.

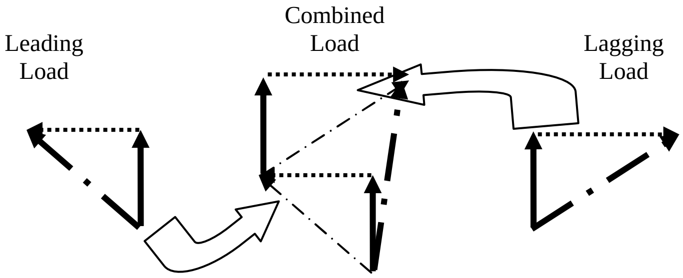
The center portion of Figure 6 demonstrates the amount of electricity that must be provided by the generator to meet the electrical losses **if the electrical losses were determined merely by the active power requirements of the customer.** For discussion purposes, we can assume that the losses based on active power flows are 10%. Thus, each of the arrows in the middle section of Figure 6 is 10% longer than each of the arrows on the left side of Figure 6.

The actual losses are determined by the apparent power requirements of the customer. Further, electrical losses are the result of the I Squared R rule. For discussion purposes, we can assume that apparent power is 120% of the active power. This is equivalent to a power factor of 83%. If electrical losses would have been 10% for the active power in Figure 5, the losses based on the apparent power would be 14.4%. Thus, each of the arrows on the right section of Figure 6 is 14.4% longer than each of the arrows on the left side of Figure 6.

## SUPPLYING REACTIVE DEMANDS COMPETITIVELY

Though reactive power generally increases electrical losses on the transmission and distribution system, leading reactive power can cancel some of the effects of lagging reactive power, as illustrated in Figure 7. Two customers are shown with similar active power loads, but with significantly different reactive power loadings, one leading and one lagging. Adding the two loads together, the active power loading is the sum of the two individual active power loads. The reactive power loading is the net of the two reactive loads. As a result the resulting apparent power loading is less than the sum of the two apparent powers for the individual loads.

Offsetting Leading and Lagging Loads
Figure 7



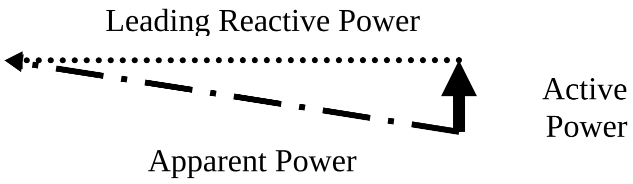
There are several ways to meet the reactive needs of an electrical system. Historically, the two most common are the installation of distribution capacitors and the operation of generators at less than unity power factor. More recently, power electronics have become available to assist with this process, sometimes using flywheels or superconducting magnets.

- Distribution capacitors cheaply provide almost pure reactive power near the source of the demand for such reactive power. However, distribution capacitors have only one function, providing reactive power. Further, distribution capacitors have limited operational range, they are on or off. In addition, the switching of capacitors on and off often causes temporary voltage problems during the switching operation.
- Generators are very flexible in their operation. In addition to meeting lagging reactive power requirements, generators can meet leading reactive power requirements. Generators can be smoothly transitioned over their entire range from leading to lagging with nominal, if any, voltage transients. However, generators are better used to provide active power instead of reactive power.
- Power electronics can be very flexible in their operation. Generally they have been used to condition the power flow between the customers and the utility to eliminate various harmonics, including reactive power.

On a cost basis, many utilities decide to install distribution capacitors. Some have been able to justify the decision on the basis reduced electrical losses alone.

Using the symbols introduced in Figure 5, distribution capacitors can be modeled as an arrow pointing to the left that consumes a minor, almost insignificant amount of real power. The real power consumption is the result of electrical I Squared R losses on wires and other parts of the equipment. Indeed, Figure 8 is almost misleading by showing any active power requirement for capacitors. The length of the active power arrow may actually be shorter than the width of the reactive power arrow. The electrical losses on capacitors are often much less that 5%.

**Power Model of Distribution Capacitors**
**Figure 8**



The value of distribution capacitors to the utility was effective illustrated previously in Figure 7. Figure 7 showed how a leading power factor load of one customer could be used to offset some of the lagging power factor load of another customer. This concept is how capacitors help offset lagging loads.

Consider the load on the left in Figure 7, the load with leading reactive power. That leading reactive load could be the load shown in Figure 8, a pure capacitor, especially if the active load in Figure 7 is reduced to only a few percent of the magnitude shown in Figure 7.

## REACTIVE POWER AND VOLTAGE

An important part of the reactive power phenomenon is the effect on local voltage. Leading reactive power has the effect of increasing the voltage in an area. Conversely, lagging reactive power has the effect of decreasing the voltage in an area.

Some DNOs have tariffs that include charges for reactive power. Some reactive power charges are in the form of using apparent power (KVA) as the billing determinant for demand. Some DNOs charge for reactive power (KVAR) in excess of some fraction of real power (KW).

The reactive power provisions in some DNO tariffs encourage customers to install capacitors to offset the reactive power imposed by motors. By offsetting the lagging reactive power of motors, customers can lower their reactive power charge. Occasionally customers shut off their motors without shutting off the capacitors. This has generally been a problem for DNOs during nights and weekends. The DNOs experience high voltage conditions on the related distribution and transmission lines serving these customers.

The transmission and distribution lines moving electricity from the generators to the customer loads contribute to the reactive power phenomenon. The transmission and distribution systems are themselves electromagnetic devices. As such, the transmission and distribution systems produce or consume reactive power. Typically lightly loaded lines have a capacity effect, providing reactive power and raising the local voltage. In contrast, heavily loaded lines have an inductive effect, consuming reactive power and lowering local voltage.

## CREATING A MARKET FOR REACTIVE POWER

Most markets for the use of the distribution grid have yet to develop the concept of a fungible commodity. *The American Heritage Dictionary, Second College Edition*, 1985, defines "fungible" as "being of such a nature or kind that one unit or part may be exchanged or substituted for another unit or equal part to discharge an obligation." The standard approach to the distribution grid market relies on the DNO's planning program. The capital costs of the distribution grid are converted into a demand charge. Under this standard approach, any user of the distribution grid would be viewed as causing the DNO to incur a cost, collected as a demand charge.

In practice, any user of the grid can meet some of the reactive power requirements of another user. This concept of one user meeting the reactive power needs of another customer is the concept shown above in Figure 7. The planning approach to pricing reactive power is rarely fungible. Indeed, under most DNO tariffs, each customer would still be charged for the apparent power it places on the system, with no netting against the apparent power of other users.

Electricity has been treated at retail as the ultimate fungible commodity, at least on a sales basis. For most customer classes, the same tariff price is charged to all consumers for all the energy taken during a month. This constant price occurs despite wholesale prices that vary throughout the day, sometimes throughout an hour, and that vary by location. The value of reactive power to the consumer of the distribution system obviously varies throughout the day in a similar manner. But it is often difficult to devise a method to show that the cost of reactive power varies throughout the day, let alone operate a market for a fungible commodity related to reactive power.

## MARGINAL COST OF REACTIVE POWER

A competitive market looks at the cost of making an additional sale. In the markets regulated by OFGEM, these costs are evaluated on a half hour basis, or more frequently. The cost of reactive power on a half hour basis is related to the electrical losses incurred by the DNO. The electrical losses are driven by the amount of apparent power on the system. Users who reduce the apparent power on the system, even though they increase their own apparent power, should receive a credit under the DNO tariff. This marginal cost approach is appropriate for the excess demand on the system, the portion of the demand not covered by traditional rate making assumptions.

Marginal cost is an alternative approach to rate setting that builds on the incremental costs identified above. During most days of the year, the marginal cost of using the distribution grid is limited to the electrical losses on the distribution lines and transformers. Such electrical losses are often considered to be trivial relative to the full cost of owning the distribution grid.

One exception is during periods of extremely high prices for electricity delivered to the distribution grid. These periods are also often during periods of high electrical losses on the distribution grid. Another exception is during extremely high loading, perhaps even dangerously high, on the distribution grid. These high loadings are often attributed to high active power levels, but can be aggravated by high reactive power levels.

One approach to creating a fungible market for reactive power is to use a formula for the reactive power price. The independent variables in the price would be (1) the network cost of active power and (2) local voltage. The price for reactive power would be positive or negative depending on whether the local voltage is above or below some nominal value and whether the reactive power was leading or lagging.

When the voltage was at its nominal value the price for reactive power would be zero. When the voltage is above its nominal value, there would be a charge for leading reactive power and credit for lagging reactive power. Such charges and credits reflect the electrical losses imposed or reduced by the leading or lagging reactive power. Conversely, when the voltage is below its nominal value, there would be a charge for lagging reactive power and credit for leading reactive power. Such charges and credits reflect the electrical losses imposed or reduced by the lagging or leading reactive power.

A formula for reactive power is based on the concept of using the quality of a public good, such as voltage, to set the price of a commodity, such as reactive power. Some of this is explained in “Wide Open Load Following: Mark Lively’s Approach to Pricing Reactive Power,” *Carnegie Mellon University Electric Industry Center Luncheon Seminar*, 2004 December 2. This PowerPoint presentation is available for free download from www.LivelyUtility.com and is an expansion of “Wide Open Load Following: Mark Lively’s Approach to Pricing Reactive Power,” *IEEE-USA Energy Policy Committee Presentation to FERC Task Force on Reactive Power*, 2004 October 25. The latter is also on the web page for free download. The concept is also presented in “Comments Of Mark Lively, Utility Economic Engineers, Including Answers And Comments To Questions In Staff Report Of 2005 February 4,” filed in *Principles for Efficient and Reliable Reactive Power Supply and Consumption*, FERC Docket No. AD05-1-000, 2005 April 4.

## FUTURES CONTRACTS

DNO tariffs are to facilitate competition in the generation and supply of electricity, which presumably includes the generation and supply of reactive power. As mentioned above, some DNOs install capacitors on their distribution system to supply reactive power. If there is competition in the generation and supply of reactive power, the DNO should indeed be buying some reactive power from private organizations. A formula for reactive power would allow private organizations to own the capacitors or power electronics that achieve the desired effect of controlling voltage better.

The ability of power electronics to control the voltage implies that the power electronics will also have the ability to control the price that it receives for the reactive power provided to the DNO. The power electronics owner can control the price by withholding capacity from the system. By controlling the price that it receives for reactive power, the power electronics owner can artificially inflate its profitability. DNOs can limit this manipulation by contracting with the potential suppliers of reactive power.

Table 1 illustrates the potential for a power electronics provider to manipulate the market by withholding reactive power capacity. The first column shows the amount of leading power that the power electronics device injects into the network. The second column shows the shortage of reactive power with the specified injection. Without any injection, the shortage is presumed to be 8.0 MVAR. The third column shows the price for reactive power using the formula

$$\text{Price (\$/KVARH)} = 10^{\text{(MVAR/4)}}$$

In the formula, MVAR refers to the shortage of reactive power in the location. The power electronics provider has the incentive to withhold the production of reactive power to maximize its net income. In the example summarized in Table 1, the power electronics provider would want to produce about 1.7 MVAR of leading reactive power. This leaves the DNO 6.3 MVAR short.

## CONCLUSIONS

The current DNO tariffs for reactive power stifle competition for the generation and supply of reactive power. These tariffs prevent users from reaping any of the economic benefits to the system associated with meeting the reactive power needs of other users. Pricing surplus reactive power using a formula driven by the cost of energy and local voltage conditions can help the DNO recover the cost of electrical losses on the distribution grid and facilitate competition. However, futures contracts should be considered along with such a pricing formula. The futures contracts could be similar to traditional purchased power contracts.

## Power Electronics Revenue Optimization
## Table 1

| Power Electronics Production (MVAR) | Distribution Overload (MVAR) | Price ($/KVARH) | DER Revenue ($/HR) |
|---|---|---|---|
| 0.0 | 8.0 | $100.00 | $ - |
| 0.1 | 7.9 | $94.41 | $ 9,441 |
| 0.2 | 7.8 | $89.13 | $ 17,825 |
| 0.3 | 7.7 | $84.14 | $ 25,242 |
| 0.4 | 7.6 | $79.43 | $ 31,773 |
| 0.5 | 7.5 | $74.99 | $ 37,495 |
| 0.6 | 7.4 | $70.79 | $ 42,477 |
| 0.7 | 7.3 | $66.83 | $ 46,784 |
| 0.8 | 7.2 | $63.10 | $ 50,477 |
| 0.9 | 7.1 | $59.57 | $ 53,610 |
| 1.0 | 7.0 | $56.23 | $ 56,234 |
| 1.1 | 6.9 | $53.09 | $ 58,397 |
| 1.2 | 6.8 | $50.12 | $ 60,142 |
| 1.3 | 6.7 | $47.32 | $ 61,510 |
| 1.4 | 6.6 | $44.67 | $ 62,536 |
| 1.5 | 6.5 | $42.17 | $ 63,254 |
| 1.6 | 6.4 | $39.81 | $ 63,697 |
| 1.7 | 6.3 | $37.58 | $ 63,892 |
| 1.8 | 6.2 | $35.48 | $ 63,866 |
| 1.9 | 6.1 | $33.50 | $ 63,643 |
| 2.0 | 6.0 | $31.62 | $ 63,246 |
| 2.1 | 5.9 | $29.85 | $ 62,693 |
| 2.2 | 5.8 | $28.18 | $ 62,004 |
| 2.3 | 5.7 | $26.61 | $ 61,197 |
| 2.4 | 5.6 | $25.12 | $ 60,285 |
| 2.5 | 5.5 | $23.71 | $ 59,284 |
| 2.6 | 5.4 | $22.39 | $ 58,207 |
| 2.7 | 5.3 | $21.13 | $ 57,064 |
| 2.8 | 5.2 | $19.95 | $ 55,867 |
| 2.9 | 5.1 | $18.84 | $ 54,626 |
| 3.0 | 5.0 | $17.78 | $ 53,348 |