Power Factors and the Efficient Pricing and Production of Reactive Power

by Sanford V. Berg*

with the assistance of
Jim Adams
and Bob Niekum**

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*Associate Professor of Economics and Executive Director, Public Utility Research Center, University of Florida.

**Research Associates, PURC. Departments of Nuclear Engineering and Electrical Engineering, respectively.

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ABSTRACT

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Most electricity price schedules penalize large industrial customers for low power factors. Not to be confused with the load factor (relating average to peak KW demand), the power factor reflects the impact of reactive power (measured in kilovolt-amperes-reactive) on electrical systems: two loads with the same pattern of KW demand and KWH energy consumption can have different implications for electrical current requirements. This note identifies the relevant cost-of-service issues for power factor adjustments, describes how industrial customers are charged for reactive power, and suggests that present pricing practices be re-examined since industry norms have evolved outside a cost-benefit framework.

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Our understanding of the efficient pricing of electricity has improved in recent years as utilities and regulators examined the implications of price signals for customers. One neglected area is the so-called "power factor adjustment" for large industrial customers found in most electricity price schedules. This note identifies the relevant cost-of-service issues, describes how electric utilities tend to charge customers for costs incurred in dealing with the power factor problem, and suggests the need for changes in present pricing practices.

Reactive Power

One reason so little attention has been given to reactive power is the inherent difficulty in understanding the concept. A technical discussion of the phenomenon of reactive power involves reference to resistive and inductive loads, capacitors and inductors, and kilovolt amperes. The economist's eyes glaze over and he (or she) turns to other, more pressing, problems. The complexity of an electrical system goes beyond the knowledge (and interest) of most economists. So rate designers are left alone to deal with the fact that two loads placed on the system involving the same kilowatt (KW) demand and kilowatt hour(KWH) energy consumption can have different implications for the electrical current requirements. We are familiar with the KWH energy charge, and understand that industrial customers are also billed for the maximum instantaneous KW demand, but the presence of another charge for a low power factor (affecting electrical current requirements) is not widely known.

The impact of different types of electrical loads can be illustrated by noting that a <u>resistive</u> load (such as a light bulb or an electric heat strip) does not affect the relationship between the electrical current and the voltage in an alternating current (AC) power system. The current remains in phase with the voltage. However, if the voltage were applied to a purely <u>inductive</u> load (such as an unloaded transformer), the output current would lag or follow the output voltage. Such a circuit would "consume" only reactive power (measured in kilovolt ampere reactive--KVAR). The physical relationships in an electrical system imply that as more reactive power is consumed, less real power (measured in KW) can be produced by the unit generating the electricity.

The relationship between real power (KW) and reactive power (KVAR) can be depicted in terms of a production possibilities frontier relating the two. Figure 1 shows the technical trade-off between KWs and KVARs. The name plate capacity of a generating unit is in kilovolt amperes (KVA), which would be numerically equivalent to KW if no reactive power were produced. However, as more reactive power is produced to

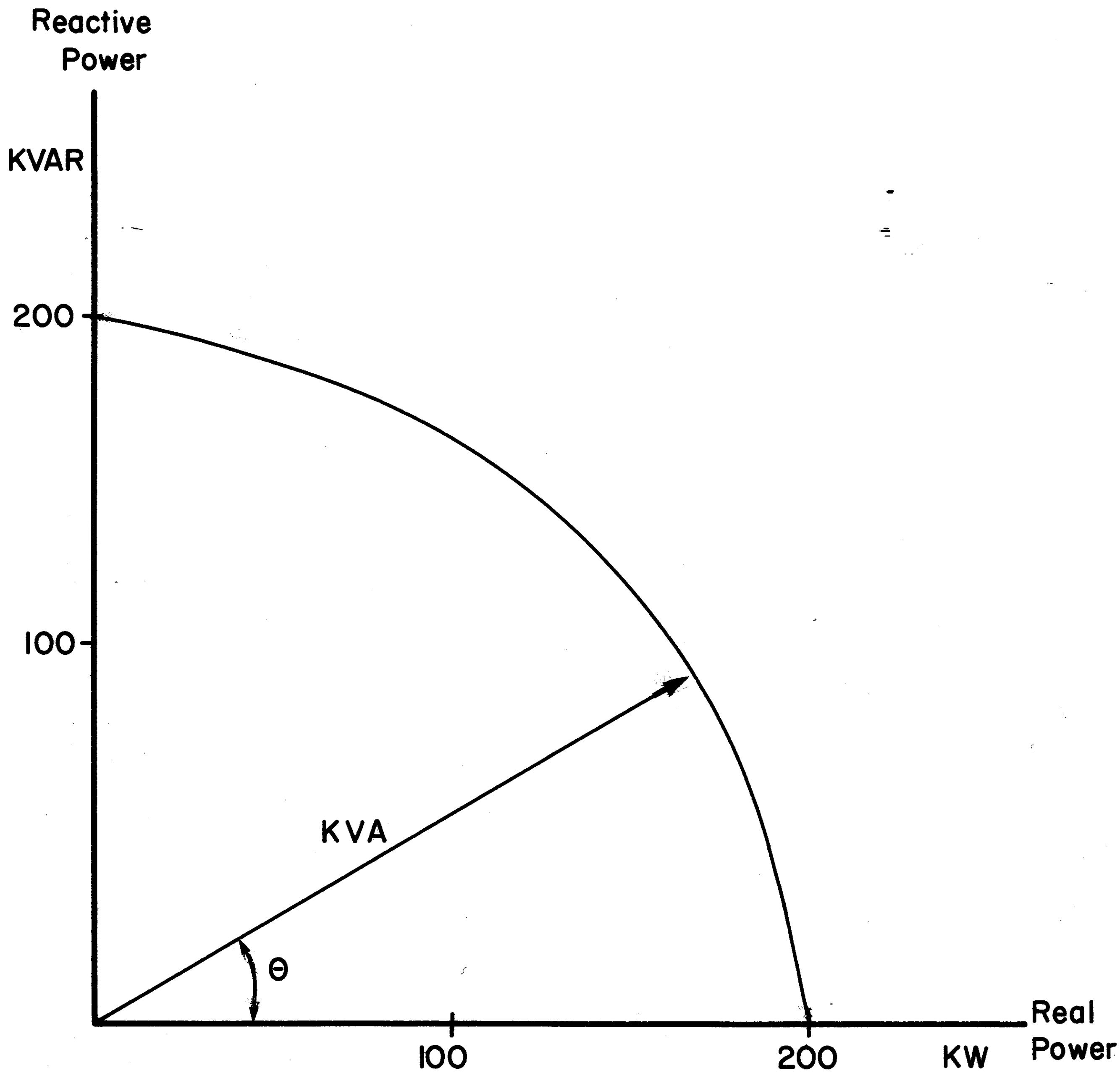

Figure 1
The Power Factor (Cos Θ) and Reactive Power

serve inductive loads, less real power (KW) can be produced by the generator with a given KVA rating. The production possibilities frontier is a circle, where the quantity cosine Θ is called the power factor of the load.[1] The resistive load from light bulbs is such that Θ is zero, so the power factor is unity. On the other hand, if the load were purely inductive, the power factor would be zero. Thus, if the utility metered the average value of instantaneous power (KW), this number would be zero. Similarly, zero KWH would be measured for a purely inductive load.

Systems planners and designers of electrical systems can control for the excess current caused by inductive elements by adding devices called capacitors along the cable run. Capacitors essentially produce KVARs, so they can compensate for the reduction in KW capacity available to serve other customers which would otherwise occur when inductive loads dominate the system. Thus, there are at least two ways to maintain real capacity as customers demand more reactive power (causing an increase in Θ). One way is to add capacitors and another is to add capacity.[2] Ignoring for now other benefits from such additions (improved

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[1]If C = capacity, then real power = $C(\cos \Theta)$ and reactive power = $C(\sin \Theta)$. The production possibilities circle has the form real power squared plus reactive power squared is equal to the square of the capacity.

[2]A promising new device which can produce or consume reactive power is the static var compensator. The availability of new technologies further complicates the choices facing utilities.

system stability, the counteraction of voltage problems, and increased system reliability), cost-minimizing systems planners will add devices or capacity, depending on which is more economical.

Figure 2 illustrates how a drop in the power factor due to increased consumption of reactive power (KVARs) can be compensated for by an expansion in generating capacity. Initially, there is KW_0' in capacity, with KW_0 of real power being delivered, given a power factor of cos Θ_0. Now, if a change in the mix of electrical loads caused a drop in the power factor to cos Θ_1, the real power that could be delivered with the existing generating system drops to KW_B, as the system moves from A to B. If the real power demanded remains at KW_0 (and reliability is to be held constant), then the installation of capacity (shifting out the production possibility frontier) equivalent to $KW_1' - KW_0'$ permits point C to be attained.

Rate designers who wish efficient price signals and equitable sharing of cost burdens will include some penalty for those who impose added costs onto the system. The power factor adjustment is just such a signal to large industrial customers. The question that arises is the severity of the penalty, which (from the standpoint of economic efficiency) ought to reflect the costs of coping with this aspect of electricity delivery systems. Too great a penalty could result in customers purchasing expensive machinery and modifying production techniques unnecessarily. Too low a charge would cause underinvestment by customers, and overinvestment by the electric utility for dealing with the problem. If one considers the potential resource

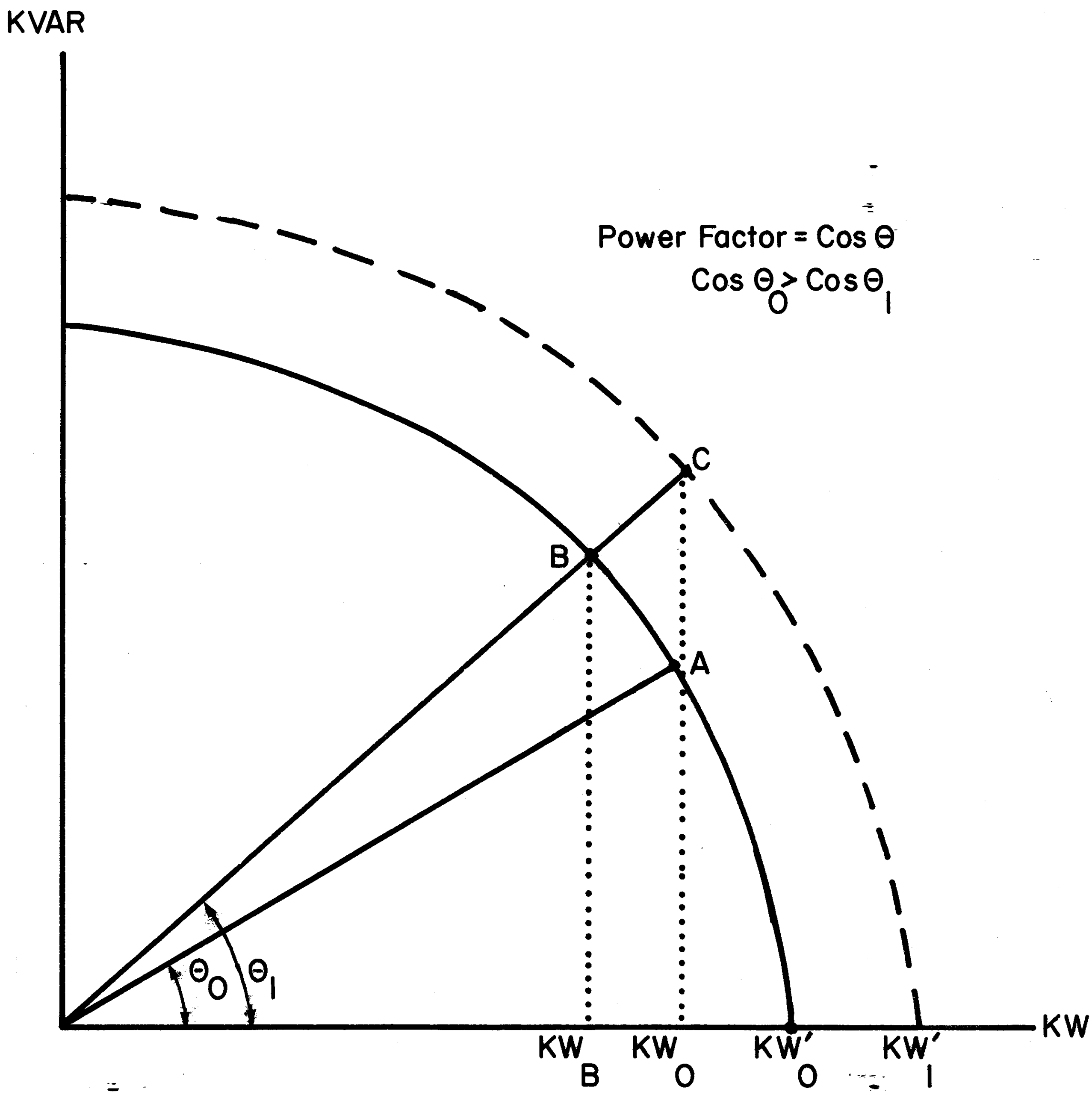

Figure 2

Capacity Expansion in Response to a Reduction in the Power Factor misallocations from the standpoint of the nation as a whole, then careful analysis of proper signals warrants much more attention than it has received in the past.[3]

Illustrative Pricing Policies

Actual rate schedules from four utilities will be used to illustrate different ways utilities deal with the power factor problem. One would hope to find some consistency in the way regulators allow the costs imposed by low power factors to be reflected in penalties. However, two of the utilities from North Carolina are allowed completely different ways of determining the power factor penalty. A Florida utility is used to illustrate how gradations can be achieved in dealing with relatively low power factors, while a California company serves as an example of how tolerances for low power factors differ across jurisdictions.

Of course, what is on the "books" as the rate schedule and what penalties are actually imposed are two different items altogether. These adjustments in the rate schedule tend to leave much to the discretion of the company. A typical clause from Florida Power Corporation states:

> *Where the customer is found to have a power factor of less than 85%, the Company may, at its option, measure the monthly demand in KVA, in which case the KW demand for billing purposes shall be 85% of the measured KVA.* [Emphasis added.]

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[3]As Sullivan (1982) notes in his review of the issues, "[Induction motors] are used in most appliances as well as in a variety of large mining activities. Problems like poor power factor, voltage flicker, [and] high inrush currents, can usually be traced to the starting and stopping of large induction machines" (p. 11).

Note that the operative clause leaves the initiative up to the electric utility to find customers with low power factors and install measurement devices. It may well be that such clauses in the rate schedule (which amounts to a contract) merely give some leverage for dealing with potential problems--as negotiations with large customers iron out difficulties. An investigation of penalties actually imposed would provide important information about power factor penalties in practice. Furthermore, utility-initiated discussions with large power consumers would have to be identified in any such study of the implementation of this component of the rate schedule.

The two opposing costing philosophies are illustrated by Carolina Power & Light and Duke Power. The former uses 85% as the trigger for penalties, but the reactive power factor adjustment is based on the costs of providing capacitors to bring the power factor to 85% or greater. Thus, the customer has the option of installing his own capacitors, adjusting his equipment to reduce reactive power consumption, or paying a penalty. Figure 3 illustrates how capacitors affect the production possibility frontier relating KVARs and KWs. As an alternative to adding 23.8 KVA (141.4 - 117.6) of capacity to meet the reduction in the power factor from 0.85 to 0.717, capacitors could be installed, so the reactive power demand of 100 KVAR (up from 62 KVAR) can be met without reducing KW output. The additional 38 KVAR of reactive power capabilities can be characterized as an outward shift in the production possibility frontier.

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[4] One could argue that a particular demander's change in behavior (causing a drop in its power factor) is only partially responsible for the need for an additional 38 KVAR in capabilities; the continued instantaneous demand of 100 KW also requires KVAR capabilities. Thus, KW or KWH charges ought to reflect some cost responsibility.

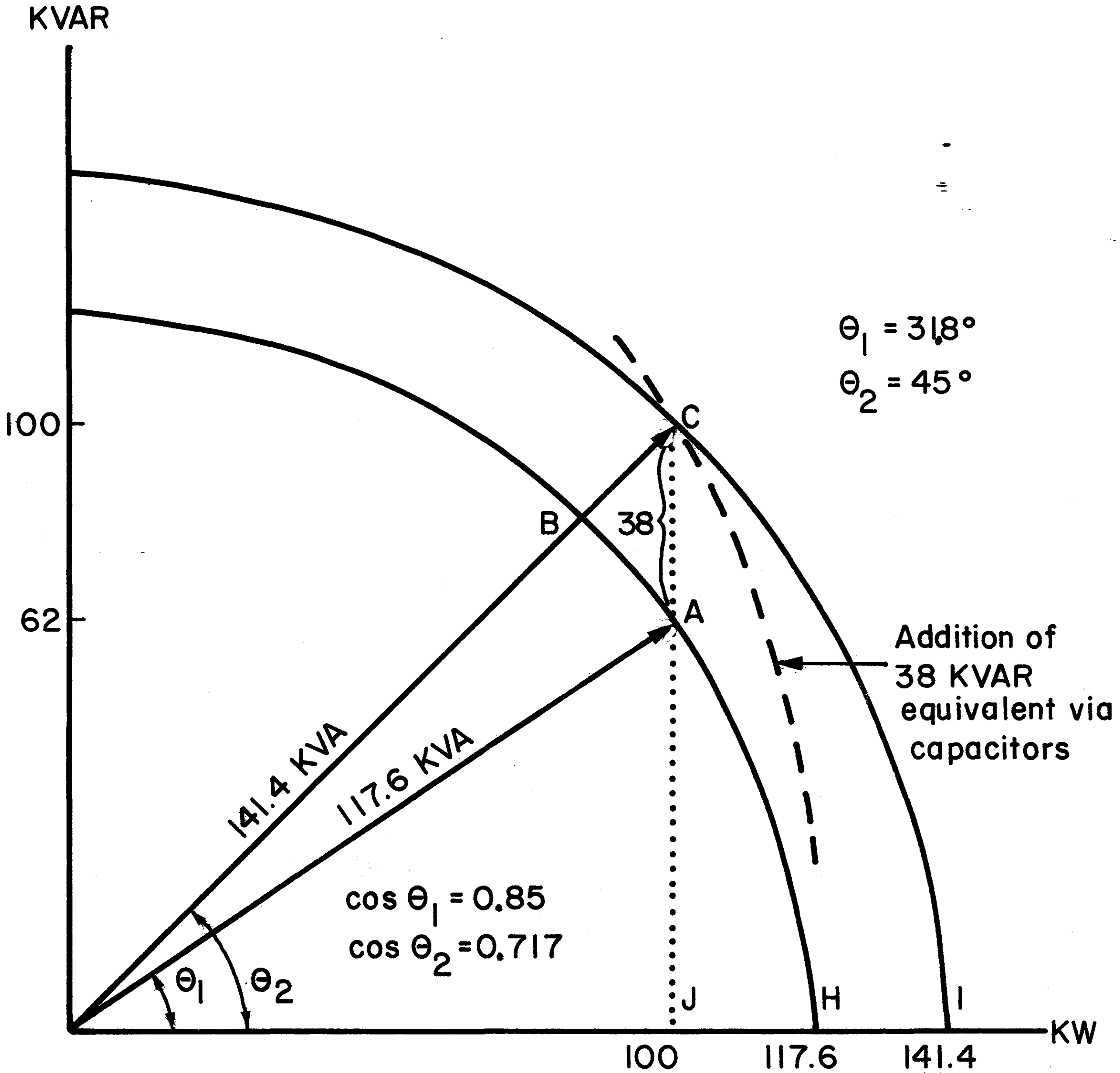

Figure 3
Addition of Capacitors in Response to a Drop in the Power Factor

The particular billing algorithm used by Carolina Power & Light takes customers with a power factor of less than 85% and calculates the adjustment by multiplying the difference between the maximum KVAR and 62% of the maximum KW demand registered in the current billing month by $0.25. A customer with an 85% power factor and a maximum demand of 100 KW would have a reactive power demand of 62 (at point A in Figure 3). A drop in the power factor to 71.7% would involve a maximum KVAR reading of 100 at point C. Multiplying 0.62 times the maximum KW reading of 100 and subtracting this from the maximum KVAR reading (100), yields 38. The additional reactive power requirements would result in an additional monthly cost to the customer of $9.50 ($0.25 x 38).

Duke Power has the same power factor trigger point of 85%, but the billing algorithm is quite different: "The total KWH for the month is multiplied by 85% and divided by the average power factor for that month for adjustment purpose."[4] In terms of Figure 3, a decrease in the power factor from 85% to 71.7%, with a constant real power demand of 100 KW will result in an increase in reactive power load from 62 KVAR to 100 KVAR. Total monthly KWH consumption is multiplied by 1.185 to obtain the power factor penalty. If the Duke Power customer had a load factor of one, it would consume 2400 KWH per day. At 5¢/KWH, the monthly bill would jump from $3600 to $4266: a

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[4]Duke Power Schedule 1 (NC), Industrial Service, December 1978.

penalty of $666--compared with $9.50 for Carolina Power & Light's customer. A 3¢/KWH rate would still yield a $400 penalty: forty times the CP&L penalty. Both companies are regulated by the same commission.

Duke does not consider additional capacitors as the cost of moving from A to C, rather the utility seems to be charging for the extra generator capacity needed to move from B to C: allocated over KWH consumption. The distance $\overline{BC}$ is equal to $\overline{HI}$, and represents additional capacity costs (23.8 KVA). However, the Duke pricing algorithm is inconsistent with treating capacity additions as the response to drops in the power factor. Since the charge is applied on the basis of total KWH, only so long as the customer has a load factor (ratio of peak KW demand to average KW demand) of unity, does the adjustment to the bill reflect this approach in a consistent fashion. For example, if the customer has a load factor of, say 0.80, then its peak demand is 12½% greater than its average KW. Adjusting the bill on the basis of total KWH will understate the "capacity cost impact" of increased reactive power consumption--especially since the problem tends to be greatest during periods of peak demand.

Economic principles support a pricing approach that has price reflect marginal costs. A case can be made that the opportunity cost of producing reactive power is the cost of capacitor addition, rather than capacity addition. Not only is the comparable device less expensive, but line losses (due to higher current requirements for low power factors) are cut. Thus, the installation of capacitors becomes even more economical as the power factor decreases, since such an investment reduces the transmission losses in the electrical distribution system in question. Of course, voltage control, system stability and generator design options will also affect the appropriate investment.

The power factor adjustment can be used to provide an incentive for improving a customer's power factor. Florida Power Corporation's rate schedule for large general service demanders states that "When the power factor at the time of the highest measured 30-minute interval KW demand is greater than 85%, then for each 1% increase in the power factor above 85% the measured KW demand shall be reduced by 0.5%." In this case the reward for high power factors is based on avoided KW capacity costs (presumably at an embedded historical cost). The utility and the industrial customer split the calculated savings and the demand charge is reduced.

In contrast to the algorithms discussed so far, this scheme avoids the discontinuity of using some magic target point to penalize poor performance (in terms of reactive power consumption) without rewarding improvements. Such an incentive <u>structure</u> is good economics. Whether the incentive <u>level</u> is appropriate depends on whether capacitors or capacity represents the correct investment for KVAR production. If the former are appropriate, the FPC over-rewards high power factors. Also, the appropriate level should reflect marginal cost today, not some measure of undepreciated investment in devices or capacity.

The Florida Power Corporation (FPC) philosophy is similar to Duke Power, but instead of adjusting the bill in terms of total KWH, the KW demand for billing purposes is taken to be 85% of the measured KVA. Thus, if the customer initially had a power factor of 0.85, with a maximum instantaneous demand of 100 KW, and the power factor dropped to 0.717 (as in Figure 3), then the measured KVA would rise from 117.6 KVA to 141.4 KVA. The demand charge would be applied to 85% of 141.4 or 120.2 KW (instead of to 100 KW). The calculated increase in generating capacity to meet the reduction in power factor is 20.2 KVA for FPC compared with a 23.8 KVA increase implied by the reduction in power factor. When the load factor is less than one, the Duke adjustment approaches the FPC formula. Nevertheless, the two adjustment techniques illustrate how even similar principles can yield different signals, depending on the specific penalty algorithm and whether it is applied to KW or KWH.

Another example of how the power factor can come into play is with interruptible and curtailable service. For FPC, both these customer classes are penalized for power factors of less than 85%. In addition, for interruptible customers, the non-fuel portion of the energy and demand charge (per KWH) is to be reduced by 0.5% for each 1% increase in average power factor above 85%. Peak power factors might be a better target, since associated opportunity costs of KVAR production are relatively greater during peak periods. For curtailable customers (who reduce loads at the utility's request), the measured KW demand is reduced as the power factor increases above 85%. Note that since KVARs contribute to line losses, improvements in power factors yield a production benefit (due to fuel savings) as well as a capacity (or capacitor) credit.

A California utility has a different target point for the power factor: San Diego Gas and Electric states that if the KVAR demand exceeds 75% of the KW demand, the customer will receive a written notice to install compensating equipment. The associated power factor trigger point is less tight than the three noted so far because, as can be seen in Figure 3, the 85% power factor has associated with it a KVAR demand of 62 when KW is 100. Thus, for San Diego Gas and Electric, KVAR could exceed 62 for 100 KW, without the customer incurring a penalty.

The interesting economic issue is how to determine the trigger point. If all of San Diego's customers have relatively low power factors, the equity of tolerating low power factors may not be called into question. Yet the price signal for efficiency may be inappropriate if the other utilities are correct in their choice of 0.85. Our guess is that, like the industry standard of one day in ten year loss of load probability for system reliability evaluation, the choice of a 0.85 power factor reflects historical accident and a convenient focal point for engineers. The "standard" (developed over seventy years ago) involves compromises reflecting costs and material constraints at that time. However, given the high cost of additional investments by electric utilities today, regulators and utility managers ought to be deriving prices from economic principles that reflect today's technological constraints.

Conclusions

The detailed engineering realities of electric utility systems are beyond the understanding of most regulators and managers. However, the technological trade-off between producing real power (KW) and reactive power (KVAR) is not such a sophisticated notion that aspects of rate design can be left to industry norms that have evolved outside a cost-benefit framework. The four illustrative schedules revealed some commonalities, but they also have some very different approaches to penalizing customers with heavy inductive loads (and low power factors).

The reason for reactive power pricing is that large KVAR customers may have relatively low measured KW demand and KWH consumption. Present penalties reflect divergent costing philosophies. The utility industry is only beginning to recognize the importance of KVAR production and consumption--

by customers and by the utility itself. The latter stem from transmission losses and system characteristics. For example, how does electric utility X deal with a neighboring utility who is not compensating X for supplying KVARs? Interconnected systems raise complex pricing issues.

Furthermore, the KVAR problem reinforces the arguments for peak load pricing. During periods of heavy load, there tends to be inadequate VAR production, so voltage sags and capacitors must be switched in. When the load is light, voltage rises, capacitors are switched off and reactors may by switched in to consume VARs. The related problems of system design and customer incentives have not been explored by analysts. It is time for companies and regulators to focus much more carefully on principles of rate design in arriving at rate schedules which lead to equitable cost-sharing and efficient price signals.

References

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