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HOMEOSTATIC UTILITY CONTROL

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Abstract - Distribution Automation and Control (DAC) systems have potentially major effects on costs, social impacts, and even on the nature of the power system itself, especially as dispersed storage, generation, and customer interaction become more prevalent. However, at the present time, it is not clear which particular modes of control will best exploit the capabilities of DAC. Homeostatic Utility Control is an overall concept which tries to maintain an internal equilibrium between supply and demand. Equilibrating forces are obtained over longer time scales (5 minutes and up) by economic principles through an Energy Marketplace using time-varying spot prices. Faster supply-demand balancing is obtained by employing "governor-type" action on certain types of loads using a Frequency Adaptive Power Energy Rescheduler (FAPER) to assist or even replace conventional turbine-governed systems and spinning reserve. Conventional metering is replaced by a Marketing Interface to Customer (MIC) which, in addition to measuring power usage, multiplies that usage by posted price and records total cost. Customers retain the freedom to select their consumption patterns. Homeostatic control is a new, untried concept. It is discussed in this paper because its great potential makes it a vehicle for interesting discussions of where the future may actually evolve.

INTRODUCTION

Rationale

Today's regulated electric utility system was built and is operated under a "supply follows demand" philosophy. The customer has the right to demand any amount of energy, and pays a constant, prespecified, infrequently updated, price. The philosophy of "supply follows demand" may be criticized for a variety of reasons:

- The need for rapid load following and large spinning reserve margins causes inefficient use of fuel;
- The large ratio between peak and average load implies that extra utility system capacity and distribution systems must exist to supply peak demand;
- The fixed nature of electricity prices discourages some forms of energy conservation and customer generation;
- The isolation of customers from the problems of the supply system makes it vulnerable to both short-term (New York City-type blackouts) and long-term (coal strike or oil embargo) emergencies;
- Finally, government regulation plays a mixed role; customers are isolated from changes in real cost while utilities are isolated from the effects of competition.

This paper introduces a basic philosophy in which the supply (generation) and demand (load) respond to each other in a cooperative fashion and are in a state of continuous equilibrium. Homeostasis is a biological term referring to the "existence of a state of equilibrium...between the interdependent elements of an organism." It is appropriate to apply this concept to an electric power system in which the supply systems and demand systems work together to provide a natural state of continuous equilibrium to the benefit of both the utilities and their customers. A set of interrelated physical and economic forces maintains the balance between electric supply and customer load.

Energy costs, including costs for electric power, have risen sharply in the recent past and may be expected to continue to rise in the future. This increase in costs makes conservation of energy more important and makes it increasingly important that the allocation of energy costs fall precisely on the user of that energy.

Variation of load levels on electric utility systems impose real costs. For equity and economic efficiency, the price of electric energy should reflect the variation in costs brought about by fluctuations in system load. The price should, therefore, be relatively higher when system load is high, and relatively lower when system load is low. Time-of-day rates attempt to adjust price to load level, based on the fact that, historically, load has been higher at some times of the day and year than at others. Such rates cannot, however, account for actual operating conditions or for load as it may be affected by, for instance, weather variability.

A second approach to reductions of the costs of uneven demand has been the use of direct utility-consumer communications to implement a "load follows supply" concept. Under such a system, carried to the extreme, the customer's demand would be controlled through interruption of power to specific uses. This has the advantage that it would allow the utility to run at constant output. Capital could be used to the optimum extent, and the system's vulnerability to equipment failures, oil embargoes, coal strikes, and weather would be reduced to a minimum. Any contingency of supply would be matched by a reduction of load. While such a system might be efficient and produce electric power at minimum cost, it is unlikely that it would be politically or socially acceptable.

The concept of Homeostatic Utility Control utilizes the economic response to price on the part of suppliers and consumers combined with the revolutionary developments occurring in the fields of communication and computation to develop an efficient, internally-correcting control scheme. The basic communication systems for such a scheme are being designed or are undergoing testing today. These open new possibilities in the control and operation of electric power systems, which are further enhanced by advancement in computation hardware. Large-scale integration is making

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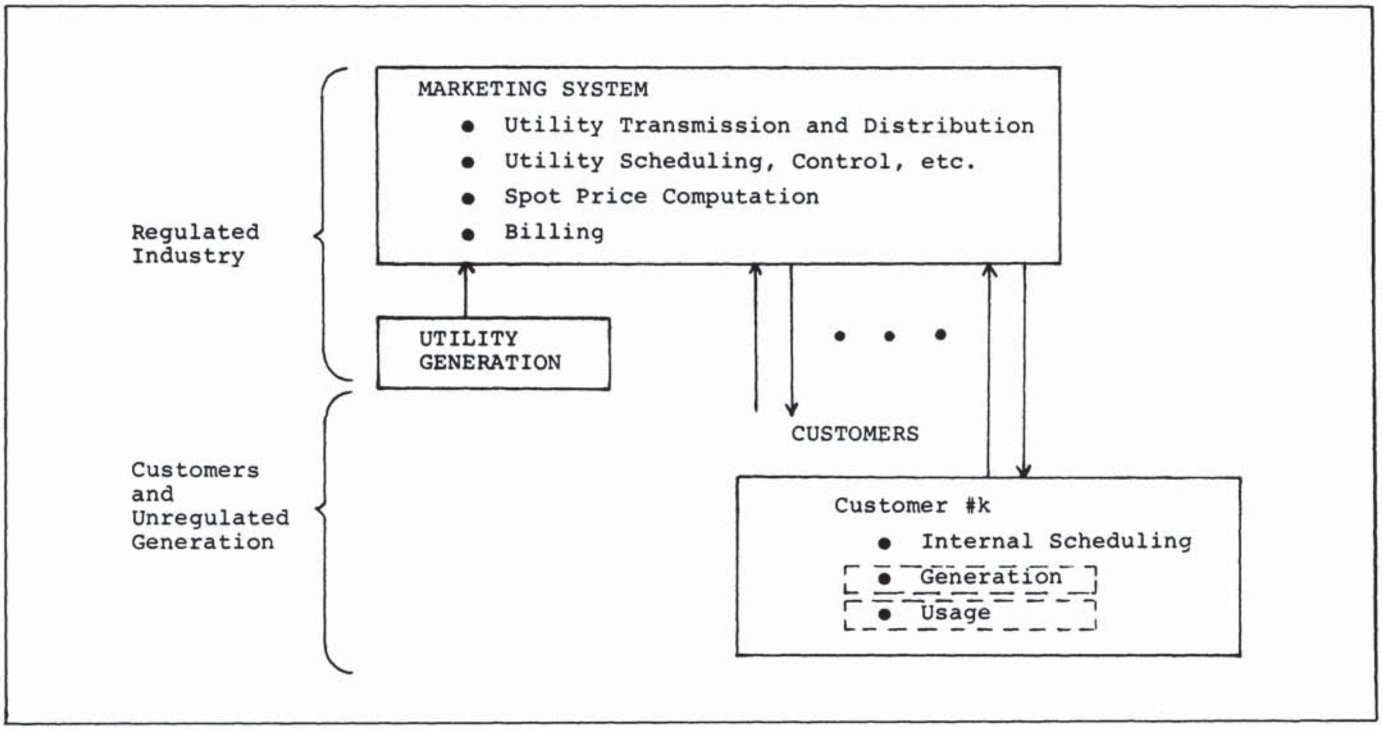

FIGURE 1: The Energy Marketplace

sophisticated computational ability available in small, economical packages. These developments will make it possible to communicate between customer and supplier and to control electric power systems in highly sophisticated ways.

The philosophy of Homeostatic Utility Control can offer a set of advantages of both "supply follows demand" and "demand follows supply" while avoiding the majority of their major pitfalls. It offers a continuous accommodation of the utility and customer to achieve stability and to minimize costs through a price-guided process involving independent choices by all parties.

Basic Structure

Homeostatic Utility Control requires three distinct functional developments or adaptations for its successful implementation. The first is a short-term mechanism which can operate to balance the supply and demand in a time frame less than five to ten minutes. Within current Utility Generation systems this function is generally fulfilled by governor and AGC action in central power plants which cause supply to follow demand. An alternative, lower-cost approach which causes demand to follow supply is based on a Frequency Adaptive Power Energy Rescheduler (FAPER). A FAPER is a frequency-responsive switching device which will control significant energy (as opposed to power) consuming loads. An example of such a load would be an electric melt pot in a processing plant or, at a residential scale, an electric heating or hot water system. The basic principle of the FAPER is rescheduling uses of electricity in which the demand is for an average rather than an instantaneous condition. The FAPER will turn the device off and back on as a function of the utility's ability to provide energy.

The second concept required for Homeostatic Utility Control is that of a mechanism by which consumers can pay a price for electricity which reflects, over time, the true current cost of the energy which they are receiving. This Energy Marketplace, in Figure 1, contains three classes of actors: first, the Customer who purchases power from the Marketplace or sells excess generation to it, second, the Utility Generation which is a supplier of electricity to the Marketplace, and, third, the utility Marketing System which acts as a broker for the electricity. The Marketing System is responsible for transmission and distribution and billing and metering transactions required both to distribute the electrical energy and to record the time and quantity of energy supplied and consumed; it is also a repository for information concerning the cost of generation and the willingness of the consumer to buy electricity at a given price. As will be discussed in greater detail in the sections which follow, the Marketplace operates under a set of "spot prices" for the energy which reflect both the capital and operating costs during any given period of time. The spot price becomes, therefore, the currency which both establishes the level of demand on the part of the sum of the customers and guarantees the supplier a fair return on the energy generated during the time period.

The third concept in Homeostatic Utility Control is the requirement for a device or set of devices which can provide the communication and recording functions critical to the operation of a system with high variability in the critical variables such as cost and price. The Marketing Interface to Customer (MIC) capable of maintaining and billing against variable spot prices as well as acting to credit a consumer with significant "storage" through FAPERs installed in his system. A MIC varies in complexity as a function of application and expected energy usage from large systems for industry to relatively simpler systems which could be installed in an individual residence.

It is important to conclude this general discussion of Homeostatic Utility Control with one negative caveat. The system has never been tried, and detailed analysis is just getting started. As of the time of writing, plans are to carry on beyond discussing concepts with utilities and with academic colleagues to the construction of FAPERs and MICs and to the completion of some detailed engineering and economic analyses.

THE FREQUENCY ADAPTIVE POWER ENERGY RESCHEDULER

A FAPER is activated by changes in the frequency of the electric powery system above and below the standard 60 Hz. The FAPER provides a new type of low-cost, short-term, lossless storage adaptable to the power system. FAPERs operate on loads which require energy rather than power.* FAPERs have no long-term impact upon the amount of energy used, but they do shift the actual period of consumption to times of relative availability on the part of the utility.

As an example consider the operation of an industrial melt pot with a FAPER. If the melt temperature lies outside of the maximum and minimum allowable range, the heating system is turned on and off accordingly, independent of frequency. However, if the temperature is within the allowable range, the heating system operation is influenced by the measured frequency. If the frequency is below 60 Hz, the heating system operation tends to be turned off; if frequency is above 60 Hz, the heating system tends to be turned on. When supply (mechanical power out of turbines) is less than demand (electric power to customers), system frequency decreases and vice versa. Thus, decreasing demand when frequency is low is a stabilizing action.

The power frequency response characteristic, discussed in detail by Appendix A, can be adjusted to perform different functions such as:

- Governor Function: Demand is responsive to small frequency changes associated with random load variations (less than one minute).
- Spinning Reserve Function: Demand is responsive to large frequency changes associated with loss of generation, tie lines, etc. (1 to 10 minutes)

A FAPER uses only locally available measurements, i.e. frequency and in the example of heating systems, temperature, so the basic FAPER concept does not intrinsically require any utility-consumer communication. However, such communication systems make it conceptually possible to adjust the power frequency response characteristics, $g[\Delta f(t)]$ and frequency reference, to changing system conditions. The advantages of this extra level of sophistication are unexplored at the present time.

FAPERs contain:

- frequency measurement;
- temperature or other process measurement;
- control logic;
- output actuation, and
- power supply.

Consider a customer (industrial, commercial or residential) with various, independent energy usage-type devices to be placed under FAPER control. Three possible approaches are:

- Stand Alone: Each FAPER is located at an individual device with its own sensors, logics, actuators, and power supply;
- Common Supply: One power supply and frequency meter serve all the individual logics located at the devices;
- Common Logic: One computer makes the decisions for all the devices at a site.

The capital cost per device is dependent on which approach is used. Installation costs for retrofitting FAPERs on existing devices would probably be prohibitive, except for large devices, such as those found in industry, and possibly electric home heating. However, FAPER installation costs on new devices should be minimal after the technology is established.

Installation of FAPERs can be viewed as giving the power system short-term energy storage which can be used to provide "governor action" and "spinning reserve." This energy storage can be assumed to be lossless compared, for example, to pumped hydro. Its speed of response is determined by the FAPER's electronics. The only costs are those of building and installing the FAPERs.

A rough feel for some of the factors involved can be obtained as follows:

· Define:

x: Capacity of device under FAPER control, i.e., power used when device is on (kW).

T: Length of time device is on during normal cycle.

Then

xT: Maximum stored energy (kWh).

On the average, only some percentage of this "stored energy" can be considered to be available at any instant for control because of the device's normal cycle and the probability the device itself is in a turned-off mode (e.g., home heating in the summer).

Define:

p: Probability device is in active mode (e.g., it is winter for a home heating device) $0 \le p \le 1$

Then, taking into account the randonmess of the cycling, a crude approximation yields

$$\frac{xTp}{2} : \text{Amount of stored energy available for control on the average at any instant of time (kWh)} \quad (1)$$

Define:

c: Capital, installation cost of FAPER ($)

Then

$$K = \frac{2c}{xTp} : \text{capital cost of controllable storage (kWh)} \quad (2)$$

Many possible sets of reasonable guesses for numerical values are available depending on the device. For electric home heating, one set of numbers is:

x = 50 kW
T = 0.2 hour (12 minutes)
p = 0.25 (3-month heating season)
c = $10

which yields

K = $8/kWh.

If enough FAPERs were in operation, it would be possible (conceptually at least) to remove the existing central power station governors and the central dispatch AGC system. A slower (5-minute) central-dispatch control signal would be sent to the power plants based on economics and the need to remove time and energy errors. With such a system, tie-line interchange would be maintained and balanced on a longer time scale based on estimated/computed flows as well as direct measurements. This "smoothing out" of the central power station behavior has economic value in terms of improved heat rates and less "wear and tear" on the plants.

The value of a FAPER's ability to provide spinning reserve can be determined by evaluating the costs of conventional spinning reserve for the utility of concern.

FAPERs provide a distributed type of control action. Intuitively, it is better to control a large, complex, distributed system using many small, distributed control actions on them than to apply large control forces at a few points (like power plants). Thus, FAPERs have the potential of improving the overall power system's dynamic characteristics and hence influencing the transient stability, dynamic stability, and long-term (slow-speed) dynamic control problems.

ENERGY MARKETPLACE

While the primary purpose of the FAPER is to smooth out short-term supply-demand inequalities, the Energy Marketplace concept strives to improve the economic operation of the system. The key to the Energy Maketplace approach is the setting of electric energy "spot prices," which vary as frequently as every five minutes, depending on overall system demand, plant outages, solar generation, wind generation, fuel costs, and other factors.* They can also

*It is possible to define "energy-type usage devices" as being characterized by (1) a need for a certain amount of energy over a period of time in order to fulfill their functions and (2) indifference as to the exact time at which the energy is furnished. Examples include space conditioning, water heating, refrigeration, pumping, ovens, melting, and grinding. Similar "power-type usage devices" are characterized by needing power at a specific time. Examples include lights, computers, TV, and many motors used in industrial processes.

*The terms "Energy Marketplace" and "spot price are taken from reference [1] .

change with respect to geographic location in the service area because of differences in spatial conditions such as T&D losses, line loading, and localized weather patterns. The spot prices provide an economic stabilizing mechanism that tends to keep the overall supply-demand system in equilibrium: as consumption goes up, so does price, which tends to reduce consumption while increasing production. This smooths out the unanticipated demand variations over time.

The spot price for a customer to buy power from the system would ordinarily be different from the spot price paid by the system buying back power from a customer. The difference in the buying and buying-back spot prices reflect transmission capital costs and losses and billing and metering costs. Allocation of utility generation capital costs presents difficulties. To facilitate a discussion of the issues and potential approaches for updating the spot prices, this presentation decomposes the utility system into three component "actors," as was first shown in Figure 1:

- The Utility Marketing System which is the part of the electric utility responsible for the transmission and distribution of power, control of Utility Generation, computation and communication of the spot prices to the consumers, and billing.
- The Utility Generation, which supplies power to the Marketing System from the individual utility-owned generation and storage plants to the Marketing System.
- The Customers, who can individually buy power from the Maketing System or sell excess self-generated power to it. Each customer is responsible for the scheduling of his own usage and generation at the set spot prices; this can be accomplished through any means ranging from intuition to the employment of a computer-based scheduler that takes account of current and anticipated spot prices.

The separation of the utility into separate Utility Generation and Marketing System components is made solely as a vehicle for the exposition of the Energy Marketplace concept.

The establishment of an Energy Marketplace and the selection of a procedure for calculating the spot prices is a significant change from the current process where every price modification must be approved by the regulatory process. It is a generalization of the approach taken for fuel adjustment clauses: the adjustments are not a subject to review, but the procedure for calculating them is reviewed.

The two important issues in the determination of a procedure for setting the spot prices are, first, the allocation of costs and profits among the actors and, second, how the customers can react to the pricing system by modifying their usage and generation patterns. The following subsection discusses potential approaches for selecting the spot-pricing formulae. The second subsection describes methods for the consumer to react to the spot-pricing information.

Spot-Pricing Formulae

There are many possible approaches to the setting of spot prices. At one extreme, prices could be set so that load and generation just balance without regard to the profits or losses received by any party. At the other extreme, the utility and the customers alike could be monitored and controlled so that no party receives what would be considered an unfair return. Politically and economically acceptable approaches, however, must mix these two extremes — with necessarily more complicated pricing procedures.

The selected formulae for determining spot prices must reflect the typical range of often conflicting goals involved with utility pricing and system dispatching. The specification of the goals themselves can be as controversial as the personal philosophies of "social good" or "fairness." Several potential goals that have arisen in discussions are:

- The Marketing System should minimize operating costs.
- To prevent monopolistic pricing and guarantee a fair rate of return on capital, regulation may be necessary.
- The present and future reliability and availability of power should be ensured.
- Demand levels and patterns should be influenced to take on desirable characteristics.

Appendix B elaborates on these points and outlines some of the spot-pricing formulae that could be implemented.

In practice, it is expected that no single set of spot-pricing formulae will be universally agreed upon as being best. Fortunately, the Homeostatic Utility Control concept is such that the choice of spot-pricing formulae can be adapted to fit the particular needs and philosophy of the area being served by the utility.

Utility and Customer Scheduling of Generation and Usage

The utility and the customers independently determine their patterns for generation and usage of electricity subject to the spot prices. Spot prices are not predetermined since they depend on random events such as demand fluctuations, weather conditions, plant outages, and numerous other factors. Usually it will be possible, however, to predict future spot prices with sufficient accuracy so that both the customers and the utility are able to schedule their generation and usage in an orderly fashion.

The Marketing System, the branch of the utility responsible for systems management, uses sophisticated, general-purpose, digital computers with extensive operator interaction for economic dispatch, unit commitment, maintenance scheduling, and fuel management for the Utility Generation. The Marketing System also forecasts customer purchases and sales since these affect the control of the Utility Generation; this modeling is done probabilistically because the customers are independently selecting their strategies according to their anticipations concerning future spot prices.

Customers are completely free to choose independently how and when they intend to buy, use, generate, or sell power. Each customer scheduler has available the current values of the spot prices as communicated from the Marketing System. A customer scheduler could also have models of the customer's needs for power, both real and perceived, as well as forecasts of future spot prices and weather.

The simplest type of customer scheduler would exist at the small commercial establishment or residential level. These would be simply spot-price readouts with the actual scheduling being done by human judgment. Usually such human decision making would ignore five-minute variations in spot price. However, a warning device could alert customers to unexpected events that have occurred or when spot prices have risen above some prespecified level.

The next level of complexity of customer schedulers are "special-purpose energy computers." These are small, essentially preprogrammed microor minicomputers which accept a certain class of inputs specifying the customer's choice of life-style and priorities. The computer reschedules, as appropriate, various devices and provides the customer with various types of information and suggestions.

The most sophisticated customer scheduler is the general-purpose computer which is programmed specifically for the explicit needs of the customer. They would be installed in many of the larger commercial installations and almost all industrial installations. They would allow extensive automatic control features as well as sophisticated input-output devices for human interaction.

Usually spot prices will be quite predictable; however, fluctuations and uncertainties in price may be unacceptable to some customers. Such customers could obtain long-term contracts from the Marketing System in which the rate is prespecified; for example, they could be set for one year in advance, as in today's rates. These long-term contracts would include prespecified time-of-day or seasonal variations. Such long-term contracts with prespecified rates are viewed as "insurance policies," and the customer would expect to pay more on the average for the insurance associated with a long-term contract. These long-term contracts would have limits on the amount of energy and demand covered by the insurance. These are similar to the options and futures contracts offered in commodity markets -- except they would probably be bundled in monthly or annual packages.

THE MARKETPLACE INTERFACE TO THE CUSTOMER (MIC)

A critical hardware element required to complete the Homeostatic Utility Control is the subsystem which is situated at the interface between the Marketing System and the Customer. The MIC serves several purposes. It is a usage-recording monitor, replacing the watthour meter. It also serves as an information transfer point, passing the posted spot price on to the customer, while relaying usage back to the Marketing System. The MIC may serve other functions, such as detecting changes in system frequency and passing information on differential frequency to the customer. It also detects responsiveness of load to changes in frequency.

The MIC is at the end of the Marketing System's information path, and represents the point beyond which the utility has neither direct control nor access to information.

In the simplest manifestation the MIC would have two functions. One would be to relay the spot price to the customer. The other would be to integrate cost, the product of price received from the Marketing System, and load, measured by a part of the MIC. Then the result would be:

$$b(t_1) = \int_0^{t_1} r(t)\, x(t)\, dt \qquad (3)$$

where $b(t_1)$ is the cost to the customer incurred over the time interval $0 \leq t \leq t_1$; $r(t)$ is the spot price at time t; and $x(t)$ is the load at time t.

The spot price $r(t)$ will have one of two values. If load $x(t)$ is positive, $r(t)$ will be the customer's buying price. On the other hand, if $x(t)$ is negative, the customer is generating power and $r(t)$ will be the system's buying-back price.

Communication once every five minutes from the Marketing System to every MIC is necessary to post the spot price. There seems to be little problem in establishing such communication with any of a variety of systems presently available or under test. However, security of communication and metering are areas of concern. Issues such as the possibility of communications error or tampering suggest the desirability of having a reverse communication capability from the MIC to the Marketing System to, for example, confirm the posted spot price.

FAPERs are designed so as not to interfere with the prime functions of the energy-type usage devices they control. However, customers still need some reason to install them, since they will cost something. It is possible that the utility could pay for them or their installation could be mandated by law. It is doubtful that such coercive methods would be very effective, however. A more appealing concept would be to reward frequency-dependent load behavior so that customers with FAPERs automatically get a financial benefit.

One way to provide a benefit to FAPER installations is to change the cost algorithm to:

$$b(t_1) = \int_0^{t_1} \left[r(t) + h[\Delta f(t)] \right] x(t)\, dt \qquad (4)$$

where $h[\Delta f(t)]$ is a price differential that is a decreasing function of frequency, roughly of the form shown in Figure 2. The $\Delta f(t)$ is the frequency deviation from nominal. On the long-term average, this logic would yield financial benefits for customers with FAPERs.

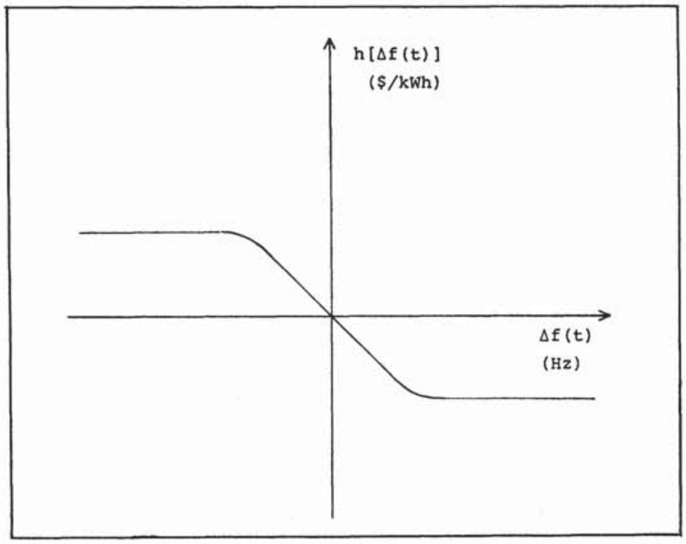

FIGURE 2: FAPER Price Differential

A potential disadvantage of this approach is that customers receive financial benefits from FAPERs only when the FAPERs actually affect demand. FAPERs can provide a spinning-reserve function even when it is not used. Therefore, an alternative approach is to have MIC estimate what portion of a customer's demand is under FAPER control, on the average. This would be done by observing load changes coincident with frequency changes. This percentage would be used as the basis for a billing credit.

Further discussion of the MIC subsystem and associated customer subsystems is the topic of a companion paper [2].

CONCLUSION AND DIRECTIONS FOR FUTURE RESEARCH

Homeostatic Utility Control is a concept which looks forward to the utility systems at the turn of the coming century. The basic premise is that technological and economic conditions will change over the next 20 years to create a system whose control mechanisms will need to be fundamentally different from those of today's utilities. These differences will come from the revolution in solid-state control devices which will provide the availability of metering systems that can interface the customer with the utility. Such systems will permit the utility to charge a rate for electric power which equals, or more nearly equals, the current costs of generating the power. At the same time it will be possible for customer generation to be introduced smoothly into the full utility system and paid for accordingly.

This paper has introduced three concepts which will be required for the utility control systems of the decades ahead. Each concept has been matched with a device or a scheme of implementation: a Frequency Adaptive Power Energy Rescheduler, an Energy Marketplace, and a Marketplace Interface to the Customer. These devices and control schemes are not the only approaches available but are intended to initiate the discussion. Given the limited research work which has been completed to date, Homeostatic Utility Control shows potential to:

- Generate a healthier climate in the relationship between the utilities and customers as customers see and appreciate the time-varying cost of electric power.
- Reduce the capital requirements needed for generation and transmission expansion by reducing the time variation in load.
- Reduce the need to carry certain types of spinning reserve which results in fuel and capital savings.
- Reduce the small, rapid governor actions of the large, central-station generators, resulting in fuel savings as well as less equipment wear and tear.

- Allow the system to accept more readily a stochastically fluctuating energy source, such as wind or solar generation.
- Simplify the expansion of cogeneration.
- Improve the dynamic behavior of the power system.
- Allow customers to retain complete independence of choice in pattern of demand as they respond only to price.
- Simplify control, operation, and planning of electric power systems because the Energy Marketplace and FAPERs introduce stabilizing forces which tend to keep the overall system in a natural equilibrium.

The above list represents the authors' efforts to stimulate discussion of what "might be" in terms of the development and control of electric utilities at the turn of the century. This list is not necessarily all-inclusive nor can its elements be substantiated at present. What lies ahead is the detailed developmental and analytic work required to prove both the physical and economic concepts. The purpose in preparing this paper has been to introduce a new set of concepts to the field and to bring to the fore the notion that utility control and operating procedures of the next century may look very little like those of today. Fundamentally different control mechanisms, whose constituent parts are in today's technology, will be required.

ACKNOWLEDGMENT

The ideas in this paper came from diverse sources. Their integration into the overall Homeostatic Utility Control concept started to take place in the Fall of 1978 during an internal workshop/seminar/discussion group of MIT faculty, staff, and students whose purpose was to take a "fresh look" at the future of power system control, operation, and planning. The authors of this paper wholeheartedly acknowledge the help and support of the many others who participated in the earlier discussions.

APPENDIX A

FAPER CONTROL LOGIC

The following FAPER control logic appears to have many advantages, but analysis of its overall system effect has not yet been carried out. Other types of specific logics are also under consideration.

In order to make the discussion explicit, the case of an industrial melting pot is used as an example.

Define:

t: time

$T(t)$: melting pot temperature

T_{min}: minimum allowable temperature

T_0: nominal set point temperature

T_{max}: maximum allowable temperature

$\Delta f(t) = (f(t) - 60)$: frequency deviation from 60 Hz

$u(t)$: $\begin{cases} 1 & \text{heater on} \\ 0 & \text{heater off} \end{cases}$

$t+$: time t plus a small increment

The present thermostat control logic is:

$$u(t+) = \begin{cases} u(t) & T_{min} < T(t) < T_{max} \\ 1 & T(t) \leq T_{min} \\ 0 & T(t) \geq T_{max} \end{cases} \quad \text{(A.1)}$$

The FAPER Control Logic involves changing this equation to:

$$u(t+) = \begin{cases} u(t) & T_\ell < T(t) < T_u \\ 1 & T(t) \leq T_\ell \\ 0 & T(t) \geq T_u \end{cases} \quad \text{(A.2)}$$

where

	$\Delta f(t) < 0$	$\Delta f(t) > 0$
$T_u(t)$	$T_{max} + g[\Delta f(t)]$	T_{max}
$T_\ell(t)$	T_{min}	$T_{min} + g[\Delta f(t)]$

and $g[\Delta f(t)]$ has roughly the shape of Figure A.1.

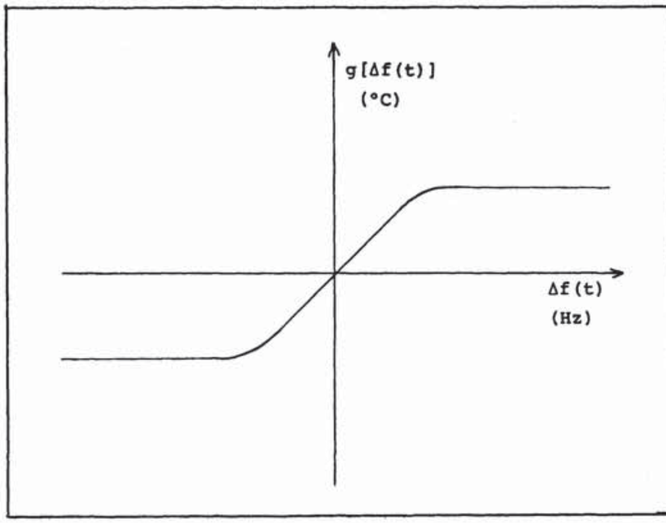

FIGURE A.1: FAPER Power Frequency Response Characteristic

APPENDIX B

SPOT PRICING METHODS

In the development of this paper, the most heatedly discussed aspects have been alternative schemes for the setting of spot prices. This appendix summarizes some of the issues and outlines various types of spot-pricing formulae. No single formula or philosophy is being advocated here since Homeostatic Utility Control is not tied to any particular spot-pricing method.

Define:

$e(t)$: time rate of expenditure ($/hour)

$r(t)$: current spot price for electric energy ($/kWh)

$x(t)$: power flow at time t (kW)

$g(t)$: generating capacity (kW)

where the following subscripts and superscripts may be used to identify specific applications of the above variables.

Subscripts:

k: customer identifier (k = 1, ...)

n: utility generator identifier (n = 1, ...)

f: fuel component

op: operation component

m: maintenance component

cap: capital component

cb: customer buying from Marketing System

bb: Marketing System buying-back from customer .

Superscripts:

ug: utility generation

ms: marketing system

hence, for example,

$r_{cb,k}(t)$ = selling price paid by kth customer to buy from the utility

$r_{bb,k}(t)$ = buy-back price paid to kth customer for selling to the utility

$x_{cb}(t)$ = summed net power flow to all customers

$e_f^{ug}(t)$ = cost of fuel being consumed by the Utility Generation

$x^{ug}(t)$ = total utility generation

Pricing Philosophy

The basic concept of spot pricing is to establish a reasonable customer buying price ($r_{cb,k}(t)$ \$/kWh) that reflects the time-varying cost of energy production and delivery to that customer's terminals. A customer buy-back price, $r_{bb,k}(t)$, must also be established for reverse energy flow. It may be derived from the above or computed independently.In either case, $r_{bb,k}(t)$ must be less than $r_{cb,k}(t)$.

One clear issue is that customers should not contribute to the costs of the supply system "downstream" of their specific location. Capital and loss costs of the distribution network will be shared among the customers supplied by that specific part of the system. This would enable decisions on future changes to a local section of the distribution to be made, at least in part, by the affected customers--who would clearly carry the costs.

Philosophical questions in establishing the customer buying price $r_{cb,k}$ include:

- Should the price be computed on the basis of historical costs, on the basis of expected future expansion costs, or should it contain elements of both?
- Should operating costs at a given point in time be based on average costs, incremental costs, or a mixture of both?
- Should capital costs be based on total system capacity, on the average capital cost of units presently connected, or on the capital cost of the last unit connected?
- What value should be assigned to voltage quality, reliability, and availability of supply?

The customer buying price will normally be dominated by fuel and capital costs and many methods have been suggested for the calculation of these cost components, some of which may have far-reaching consequences for system planning and operation.

For example, peaking units, such as gas turbines, will appear much more expensive if capital costs are recovered only during their actual hours of operation rather than over the physically useful lifetime of the unit. This cost difference would be reflected in a significant difference in the rate of rise of the spot price near the generation capacity limit; generation expansion policy would probably also be affected.

Similarly, capital charges would tend to be much higher if based on future replacement costs rather than on historical construction costs.

Specific Examples: $r_{cb}(t)$

Some specifc example of price calculation for the customer buying spot price $r_{cb}(t)$ follow. Distribution system costs are neglected for simplicity because of their variation with customer location and voltage level.

1. "Average cost"

$$r_{cb}(t) = [e^{ms}_{op,f,m}(t) + e^{ug}_{cap}(t)]/x_{cb}(t) \tag{B.1}$$

where

$x_{cb}(t)$ is the power flow to customers,

$e^{ms}_{op,f,m}(t)$ is the total marketing system operating expenditure,

given by

$$e^{ms}_{op,f,m}(t) = e^{ug}_{op}(t) + e^{ug}_{f}(t) + e^{ug}_{m}(t) + $$

$$+ e^{ms}_{op}(t) + r_{bb}x_{bb}(t) \tag{B.2}$$

and

$e^{ug}_{cap}(t)$ is the capital expenditure.

The capital term, $e^{ug}_{cap}(t)$, can be derived from either total plant capital or only that for the units connected. It may be calculated on either

- a historical basis,
- estimated future replacement cost, or
- some combination of these.

2. "Incremental Cost"

In this case the expenditure is computed as for case 1, but $r_{cb}(t)$ is taken as the local gradient at the given operating point:

$$r_{cb}(t) = \partial[e^{ms}_{op,f,m}(t) + e^{ug}_{cap}(t)]/\partial x_{cb}(t) \tag{B.3}$$

3. "Average Cost Plus Quality of Supply"

In this scheme $r_{cb}(t)$ has the components: (i) an economic cost component derived as in case 1, (ii) a "short-term quality of supply" component based on the probability of loss of supply at the present operating point. This component is designed to signal the customer of the changing quality of supply owing to problems such as line overload or stability limits, in order that those who can provide equivalent quality supply more cheaply by internal means will do so. There would normally be local as well as system-wide contributions to this price component. Revenue obtained from this price component could be directed towards rectifying the course of the quality degradation. (iii) A "long-term quality of supply" component based on system expansion needs, computed by long-term expansion studies based on predicted system growth. This component would be spread evenly over all energy sold, and adjusted only on a yearly basis. It is designed to forewarn customers of the most likely long-term future trend in pice. Revenue could be allocated to forward financing of new major plant.

4. "Marginal Cost"

This approach differs from the other three in that it is based entirely on the incremental change in future predicted costs produced by a step change in power flow at the present time. It would be computed by means of long-term system expansion studies.

Specific Examples: $r_{bb}(t)$

Some specific examples of the customer spot buy-back price, $r_{bb}(t)$, follow. The customer buy-back price may be derived from r_{cb} (t), derived by an independent method, or left to float according to demand. There would normally be the constraint $r_{cb} \geq r_{bb}$.

1. "System Lambda"

The value of r_{bb} would be set equal to the incremental fuel cost of the most expensive utility generation. This would tend to minimize overall fuel costs. If utility generation was already at full available capacity, both r_{bb} and r_{cb} would rise to the natural supply/demand level. In the notation of this appendix

$$r_{bb} = \frac{\partial\, [e_f^{ug}(t)]}{\partial\, x^{ug}(t)} = \lambda^{ug} \tag{B.4}$$

2. "System Lambda Plus Quality Constraint"

A quality constraint is added to the incremental cost of case 1. This would tend to give forewarning of operating problems and give a transition between "normal" and "emergency" conditions.

3. "Free Market"

This is the ideal free market case where price is always allowed to find its own level from supply/demand forces. In this case r_{bb} and r_{cb} move together with an allowance for marketing system operation.

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Frederick H. Pickel (S'74) was born in Seattle, Wash., on June 12, 1952. He received the B.S. degree in engineering and economics from Harvey Mudd College, Claremont, Calif., in 1974, and the M.S. degree in operations research and the M.S. degree in civil engineering both from Massachusetts Institute of Technology, Cambridge, in 1978. He is currently a doctoral candidate at M.I.T. in engineering-economic systems analysis for energy planning.

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Alan J. Cox was born in Ottawa, Ontario on September 10, 1952. He received a B.Sc. in Environmental Science from York University in Toronto in 1976 and a M.A. degree in Economics from the University of British Columbia in 1978.

During 1978 he was a Research Associate at U.B.C.'s Program in Natural Resource Economics studying the economics of utilizing wood waste for heat and electricity production in British Columbia's pulp and paper industry. He is currently a Visiting Economist at M.I.T.'s Energy Laboratory, Cambridge, Mass., where he is primarily associated with photovoltaics projects. His chief interests are the evaluation of alternative energy sources for industrial use.

Mr. Cox is a member of the Canadian Economic Association.

Discussion

Charles J. Frank (Electric Power Research Institute, Palo Alto, CA): *General Comments* The published paper contains one negative caveat: "The system has never been tried, and detailed analysis is just getting started." It is unfortunate that this paper has been published in its present form when a number of economic and technical hurdles need to be resolved before homeostatic control can realistically be considered. In the remainder of the discussion, I will list a number of problems I had with this paper. But before I do, I would like to comment on the mechanism which gave birth to this idea.

The acknowledgement refers to "an internal workshop/seminar/discussion group of MIT faculty, staff, and students" – in other words, a brainstorming session. I will agree that brainstorming sessions in the past have resulted in valuable contributions to our society. But such sessions have been successful because the participants had reasonable familiarity with the subject being discussed and their collective backgrounds and experience spanned the topic. Of the six authors of this paper, I see no one with experience in power system operations, load management, or distribution of power. Lack of such experience has caused the paper to be deficient in the areas I will now delineate.

ECONOMIC AND TECHNICAL POINTS TO CONSIDER

1. *Cost of Homeostatic Control*

Under "Basic Structure", the authors refer to homeostatic control as "an alternate, lower cost approach" than conventional governors and Automatic Generation Control (AGC). I can find no data to support the claim to lower cost. Since this device might eventually be installed industrially, commercially and residentially, there are a number of costs not mentioned in the paper but must surely be anticipated. There are:

- Basic unit cost
- Installation
- Maintenance
- Inspection and repair
- Customer tampering

There is no data to suggest what a PAPER or MIC basic unit cost will be. These, of course will be installed by a licensed electrician, so this cost will not be negligible. Any device installed at a customer site will be subject to maintenance inspection, and repair costs. Since homeostatic control purports to replace the conventional watt-hour meter, the authors might be interested in contacting utility meter departments to see ingenuity displayed by customers in tampering with these devices. Since homeostatic control will require a micro-computer of some sort, the authors may wish to consider the frustration the banking industry has had with clever computer programmers.

In the paper, the authors refer to ability of homeostatic control to be adaptable to spot price formulae options. This implies some adjustments to FAPER and MIC devices to provide the adaptability. But, depending on how this adaptability is provided, mechanisms subject to tampering may inadvertently be made available to customers.

To overcome tampering on homeostatic control devices, exterme care will be needed to develop a foolproof system. This costs money.

In summary, since none of the costs of homeostatic control are discussed, it is too early to make any claims about this being a lower cost alternative. In addition, the homeostatic device accuracy and its impact on reliability of electric service when many devices are installed need to be examined before its widespread use can be considered.

2. *Accuracy of Frequency Measurement*

Both the FAPER and the MIC require frequency deviation measurements. This will probably be the most difficult technical and economic hurdle to overcome. To perform a frequency difference measurement, a frequency standard is required. Devices of this sort are already used by the power industry. These use the U.S. Bureau of Standards WWBB or a local crystal oscillator. One of these devices widely used costs about $60,000 and has an accuracy of about .001 Hz.

Some of my preliminary calculations indicate that FAPER and MIC devices might require 10 times more accuracy than the currently available $60,000 frequency deviation devices. But assuming I am wrong and that an accuracy of .001 is acceptable for homeostatic control, what mechanism do the authors propose to use to obtain a low cost frequency deviation device? Mass production may decrease the current cost somewhat, but the authors should be thinking in terms of well under $100 for the whole homeostatic apparatus for each installation. Obviously, the current frequency deviation devices will have to be re-designed to meet this cost criteria.

3. *Homeostatic Control versus Governors and AGC*

Several references are made in the paper to homeostatic control assisting or even replacing conventional turbine governors and AGC.

I would like to first comment on homeostatic control assisting conventional frequency control methods. When the penetration of homeostatic control devices is high enough in a control area, their impact will need to be coordinated with governor and AGC control actions. Ostensibly, homeostatic control will work in a manner to decrease the frequency error. But conventional governors provide primary frequency control and AGC provides a coordinated supplemental control. Initially, homeostatic control will be a tertiary effect. The biggest concern I have is if homeostatic devices would have simultaneous actions causing large blocks of power to be shed at given frequency deviations. From what I read in the paper, the authors visualize some adjustments by the customers of sensitivities to cost and discomfort when their devices are not operational. Depending on how this is implemented, some diversity in homeostatic actions would occur. Studies of the amount of this diversity might be of interest to assure that homeostatic control can, in fact, assist conventional frequency controls.

My biggest concerns are statements made in the paper that homeostatic controls might replace governors and AGC. If the governors and AGC are replaced, what mechanism do the authors perceive to maintain 60 Hz? Homeostatic devices as described in the paper could not do this. These devices will defer load as long as an operating constraint, like melt pot temperature is in a given range. But when temperature is below this range, homeostatic controls will be overridden to place power on the device to get it back in the normal range of operation.

So homeostatic divices will have some frequency regulation characteristics, but they cannot be depended on to maintain 60 Hz.

4. *Homeostatic Control versus Spinning Reserve*

Throughout the paper, the authors have misused the term "spinning reserve." To rectify that error, I will quote definitions of operating reserve, spinning reserve, non-spinning reserve, and intenuptible loads from the most recent North American Power System Interconnection Committee (NAPSIC) Operating Manual:

> *Operating Reserve* is that reserve above firm system load required to provide for: Regulation within the hour to cover minute-to-minute variations, load forecasting error, loss of equipment, and local area protection. It consists of Spinning and/or Non-Spinning Reserve.
>
> *Spinning Reserve* is that Operating Reserve connected to the bus and ready to take load.
>
> *Non-Spinning Reserve* is that Operating Reserve capable of being connected to the bus and loaded within a specified time.
>
> *Interruptible Loads* are those loads which can be interrupted by circumstances defined by contract.

At best, homeostatic control has created a new form of interruptible load. I feel that no utility would be willing to consider homeostatically deferred load as a contribution to its operating, spinning, or non-spinning reserves. I say that because homeostatic controls provide an active controller to withdraw that portion of the deferred demand when the device operating constraint is exceeded. No utility could depend on temporarily unused energy to give it continued reliable operation.

Conclusions and Directions for Future Research

Much of what I have saie may have seemed negative. Let me close on a number of positive notes.

First, before much additional publicity and more unneeded papers on homeostatic control are published, the authors may wish to address the points I raised concerning technical feasibility at a price utilities would be willing to pay for homeostatic controls. Until these are overcome, homeostatic control will remain nothing but an idea.

Following a successful resolution of these issues, I would encourage the authors to study the distribution system impacts and the power system operation impacts. Since homeostatic control is a form of load management, it may be subject to the same weakness other load management schemes suffer from: undesirable distribution system impacts due to load pattern shifting.

Finally, since this paper was in a session on the distribution system in the year 2000, the authors may wish to consider another homeostatic type device, a VAPER, or voltage control device. This device, to automatically adjust voltage to the desired operating range, coupled with the FAPER and MIC might have attractive possibilities. However, I caution the authors to scrutinize feasibility, cost, and system impact of this new concept along with my recommendations on further homeostatic research.

Manuscript received August 6, 1979.

Robert W. Alford (Siemens-Allis, New Orleans, LA): The basic premise as stated by the authors is that certain technical and economical changes during the next 20 years will establish the basis for acceptance of a concept such as Homeostatic Utility Control by the turn of the century. The issues of whether it can be done and whether it can be done at a reasonable cost should be complemented with other equally important issues pertaining to whether or not such a concept should be implemented at all. In the short term, at least, social/political issues may predominate over the technical and economic ones.

The position is taken by the authors that direct control requiring utilities crossing the "meter-line" is not a very acceptable practice. However, it is a commonly held position throughout utility circles that *indirect load control* cannot in the short or mid term provide the the equilibrium of supply and demand that is required. The results of most studies considering customer acceptance of various load control strategies indicates that complicated pricing procedures are undesirable and require *too much* consumer participation to make them effective. That attitude may be responsible for the fact that although in general we assume that consumers do not want all that follows with direct load control, comments derived from consumers involved in the various projects indicate they are relieved that they themselves do not have to take the responsibility for controlling those individual loads. It may be entirely too speculative to think that during the next 20 years the basic underlying reasons for these attitudes will change significantly.

Confirmation of posted spot prices at each metering location will require extremely high data rates for bidirectional communication systems, particularly if confirmation is done often; it doesn't seem reasonable that confirmation can be made every five minutes along with the changing spot price.

The concept of Homeostatic Utility Control seems to encourage the necessity for complicated pricing procedures even more complex than are currently being considered for time of day rates. Yet at the same time, the proposal that industrial long term contracts might be negotiated with prespecified TOD or seasonal variations in rates violates the premise that these more complex real time pricing procedures are necessary. For example, if revenue to the utility will not change and if preferential treatment is given to certain customer classes or individual customers, then why not continue along the slightly modified path we now envision, rather than move to pricing policies and procedures which require extensive, expensive, probably unnecessary hardware and software implementation, and which can only serve to confuse an already difficult regulatory situation.

The concept of Homeostatic Utility Control includes in it most, if not all of the concepts, devices, and directions which are already well into conceptualization and development. Field testing is under way in many cases. These are the first necessary steps to be taken in the long, gradual improvement of utility control. Future concepts and systems will be largely influenced by the success and failure observed during the next 5 - 10 years.

Manuscript received August 7, 1979.

Sarosh N. Talkudar (Carnegie-Mellon University, Pittsburgh, PA): The authors have put forward some very interesting ideas for operating utility networks as energy marketplaces or brokerages in which customers could buy and sell energy. We have been working in this area for some time (see, for instance [1]) and are in complete agreement with the authors on the benefits of such brokerages. However, we seem to have a slightly different view of the manner in which the strategies and control algorithms for the brokerages should be developed.

Energy management problems are inherently multiobjective in nature [2]-[4]. For instance, some typical utility objectives are to minimize their capital and operating costs and to maximize security. Typical customer objectives include minimizing their capital and operating costs as well as the impacts of service interruptions. Most of these objectives are conflicting – improvements in one of them must be paid for with degradations of one or more of the others. Such situations call for tradeoffs between the conflicting objectives. Resource scarcities and socio-economic pressures are making the selection of a particular tradeoff a problem that deserves very careful consideration.

Spot prices and "FAPER-like-storage" are only two of a large set of control means for manipulating power system behavior, i.e., for achieving objective tradeoffs (operating equilibria). Examples of other members of the set of control means are service interruptions, curtailments and the deployment of a wide variety of DSG (Distributed Storage and Generation) devices. All these control means have strongly coupled effects on system behavior.

A strategy developed by considering spot prices and FAPER-like-storage in isolation from the other available control means will result in inferior performance. To prevent this would seem to require a more global view [3],[4] – the inclusion of a wider range of control means and the explicit recognition of the multiobjective nature of the problem.

The authors have not explicitly precluded such a global approach though their paper seems to argue against it. Would they care to clarify this issue?

sector. The five minute value was chosen because a five minute up-date is often used in utility economic dispatch of generation. In practice, not all customers need to have the same up-date rate. The social and political issue of invasion of privacy could be more important than technical engineering-economic issues in determining the amount of information which can be transferred back from the customer.

Mr. Alford's comments on complexity vs. simplicity raise another key point. We wholeheartedly agree that simplicity is highly desirable. Our position is that relative to the rate making process itself, spot pricing is simpler than most present day, prespecified pricing schemes which involve combinations of block rates, time of day and seasonal variations, demand and energy charges, rachet clauses, incentives, and customer class prejudices. Present day prespecified rate making is complex because it is so difficult to relate prespecified rates directly to costs. Spot pricing simplifies the rate-making process by centering the arguments on the definition of "real costs" without bogging down in the allocation of costs to different customer classes, prespecified times of day, etc. Spot pricing can complicate an individual customer's life because the luxury of prespecified rates is lost. The customer has to worry that the price of electricity can vary with time in a fashion similar to food, gasoline, and other basic commodities of life. As energy costs continue to rise and have a greater impact on our lifestyle, we feel that customers will prefer to view electricity as a commodity whose price varies rather than living under complicated rate-making procedures which are subject to special interest pressures. The complications introduced into the customer life by homeostatic concepts are not large when the details of responding to homeostatic signals are done by the customer's computer.

There seems to be a lack of communication relative to the proposed role of long term contracts. As stated in the paper

> "Such long term contracts with prespecified rates are viewed as insurance policies and the customer would expect to pay more on the average for the insurance associated with the long term contract".

This is not preferential treatment given to certain customers. It is a concept introduced so that not all customers, such as some residential, have to be on time varying spot prices. It also provides a vehicle for gradually introducing spot pricing and could be used by customers who, as discussed in the paper, want to buy options or futures such as in a commodity market.

Relative to Mr. Alford's point about regulation, the discussion at the Boxborough Conference [2] explicitly indicated that homeostatic concepts probably will not "confuse an already difficult regulatory situation". State regulators who attended encouraged further development and testing.

We agree with Mr. Alford's concluding comments that many of the devices associated with homeostatic control are already well into development with field testing underway in many cases. This makes it possible to implement particular homeostatic control concepts in the near future if they indeed live up to their potential benefits.

In his "general comments", Mr. Frank insists that all issues be finally resolved before there is any open discussion. We strongly disagree with this notion. Honest and open discussion of ideas which have social and economic, as well as technical content, is necessary if for no other reason than to help clarify just what the issues are. We will resist the temptation to respond directly to Mr. Frank's *ad hominem* comments on our understanding of electric power systems.

Relative to Mr. Frank's "Cost of Homeostatic Control", the paper repeatedly emphasized that it was dealing with ideas of potential, not proven value. There is one line in the Introduction which read "an alternate lower cost approach which causes demand to follow supply is...". The word "potentially" should have been inserted between "alternate" and "lower". Although we did not attempt to provide cost estimates for the hardware, we did provide explicit discussions on most of the cost issues raised by Mr. Frank. Relative to installation costs, the paper states:

> "Installation costs for retrofitting FAPERs on existing devices would probably be prohibitive, except for large devices, such as those found in industry, and possibly electric home heating. However, FAPER installation costs on new devices should be minimal after the technology is established".

Relative to unit costs, three possible FAPER approaches were discussed (stand alone, common supply, and common logic) because the basic unit and installation cost depends on the choice of approach. From a practical point of view we feel the major unit cost for FAPERs will be in the power supply, output actuators and basic packaging, not in the logic or frequency measuring circuits. Discussions with meter manufacturers who are building "time of day meters" indicate that the major costs for MICs will also be in packaging, etc; not in the computer chips that do the sophisticated computations.

Relative to customer tampering or diversion, the paper states:

> "However security of communication and metering are areas of concern. Issues such as the possibility of communications error or tampering suggest the desirability of having a reverse communication capability..."

Admittedly we have no experience in the banking industry but we do have day to day contact with clever MIT electrical engineering computer science students and hence appreciate what can be done. Our past experiences while specifically working on the diversion/tampering problem leads us to believe that there will never be a "fool proof" system, independent of whether one is talking about today's system or homeostatic techniques. Our experiences indicate that one of the best counters to tampering/diversion is to have the detailed information exchange between the customer and the utility which could occur in homeostatic control. From a practical point of view, the ability to deal with tempering/diversion may not be limited by technical software and hardware issues but by the social and political issues of invasion of privacy. The tempering/diversion issue applies only to the MIC if the paper's proposal to give customers a financial benefit for favorable frequency behavior is followed. In such a case what, if anything, the customers do with FAPERs is entirely their decision.

Relative to "Accuracy of Frequency Measurements", Mr. Frank says his preliminary calculations indicate a need for 10 times more accuracy than .001 Hz. We find it difficult to respond because we have no idea why he feels such accuracy is required. It is not needed for the FAPER to perform governor or spinning reserve type functions. The block diagram of the one FAPER we have built and tested is given in reference [2]. The design is built around an INTEL 8748 single chip computer and involves counting pulses from a precision oscillator over one cycle. With a pure sinusoidal voltage waveform, it could provide a resolution of about .01 Hz. One of our practical concerns is the nature of the waveform which will be encountered at the distribution level. Fortunately, we can allow relatively long averaging times when dealing with governor and spinning reserve type functions. Long term drift of the local reference is an explicit technical problem, but does not seem particularly difficult to handle. One approach was discussed in the paper which states

> "However such communication systems make it conceptually possible to adjust the power frequency characteristics and frequency reference to changing conditions".

There are also circuit designs which can average past history to correct for local reference drift. As already indicated in remarks above, we feel that, in mass production, the cost of FAPERs and MICs will be dominated by packaging, power supply, and actuator costs.

Relative to "homeostatic control versus governors and AGC", the FAPER control law of Appendix A permits simultaneous action, causing large blocks of power to be shed at given frequency deviations. This law is based on customer diversity and the existence of many active FAPERs. It changes the upper and lower limits on the "dead band cycle" as a function of frequency and is designed to provide a smooth, diversified response to frequency deviations. Mr. Frank's biggest concern of how homeostatic control will maintain 60 Hz is answered in the paper which states

> "A slower (5 minute) central dispatch control signal would be sent to the power plants based on economics and the need to remove time and energy errors. With such a system, tie-line interchange would be maintained and balanced by a longer time scale based on estimated and computed flows as well as direct measurements".

The paper discussed time error control because we feel the integral of frequency deviations are of more real concern than frequency deviation *per se*. Energy deviations and the associated dollar costs are also an important issue.

Relative to "Homeostatic Control Versus Spinning Reserve", the definition Mr. Frank quotes *is* the definition we were using. Care was taken in the paper to use phrases such as FAPER's have potential "to fulfill spinning reserve functions" or "to replace the need for spinning reserve", in order to emphasize the role of the FAPER. There was no claim that FAPER action could contribute to a non-spinning reserve function. It was repeatedly stated that it is a method of short-term rescheduling or deferral of demand that has a specific, but by no means all-encompassing, role in power system operation. The longer term responses associated with such operating reserves can be addressed by economic responses to spot prices combined with the use of interruptable spot prices and micro-shedding.

Relative to "Conclusions and Directions of Future Research" the

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F. C. Schweppe, R. D. Tabors, J. L. Kirtley, Jr., H. Outhred, F. H. Pickel, and A. J. Cox: Since this paper was written to stimulate discussion, we welcome the discussors' comments. The discussors have responded to the ideas in quite different ways. However there are some similar underlying currents that repeatedly appear in their comments. Therefore our specific responses will be prefaced with some general remarks.

Our paper should have more strongly emphasized the difference between the:

- principles underlying homeostatic control
- technical concepts arising from those principles, and
- potential impacts of implementing the concepts.

The principles underlying homeostatic control are to exploit the advances occurring in communication and computation technology to achieve a cooperative equilibrium between the customers and the utility while seeking maximum independence of action for the individual customer. The particular technical concepts discussed in the paper that follow from these principles are buy and buy-back spot pricing, the FAPER, and the MIC. The potential impacts of implementation discussed in the paper ranged over a host of areas such as cost of operation, introduction of dispersed generators, system dynamics, and customer-utility relationships. Although each technical concept arose from the same underlying principles, most of the technical concepts stand alone if desired. The potential impacts of implementation for individual technical concepts overlap. In our responses to the discussors, we will try to differentiate between homeostatic principles, homeostatic concepts, individual potential impacts of a particular concept, and overall potential impacts of all concepts arising from homeostatic principles.

We also feel it will be helpful to point out the analogies between homeostatic control and present practices in power system operation and control. The spot pricing concept allows customer dispatch of loads, which is analogous to utility economic dispatch, unit commitment, etc. of generation. Spot prices are simply the most elemental form of an electricity rate. Depending on how it is computed, it is the instantaneous marginal or average revenue requirement associated with a kilowatt of load. Today's prespecified rates (block, time of use, etc.) are, in essence, a complicated mixture of option and future contracts based on guesses of how this elemental spot price might behave. The FAPER and related concepts are load-based devices analogous in effect to governor control of generation.

Homeostatic control concepts can be adapted little by little and in diverse ways that are matched to a specific utility's area. No sudden, irreversible commitment is needed. The discussors often seem to be addressing residential sector customers. We feel the implementation of homeostatic concepts can start almost immediately with large industrial and commercial customers. We would be surprised by widespread implementation of anything like spot pricing in the residential sector before the turn of the century.

We will now address the specific issues raised by the discussors.

We agree with Mr. Talukdar that energy management is a multiobjective problem requiring tradeoffs between conflicting interests and desires. A homeostatic principle is to give the participants (utility and customers) as much individual independence as possible to reach their own local optimum. Spot pricing is a concept which provides a mechanism for communication between the various participants. The nature of the resulting global behavior is determined by the particular pricing formula that is adopted. Homeostatic concepts provide a "natural" approach which does not put the utility in the undesirable position of having to exercise direct control over specific customer actions.

We also agree with Mr. Talukdar that spot pricing and FAPERs are only examples of explicit concepts that result from the principles underlying homeostatic control. In order to illustrate this point further, micro-shedding and interruptable spot pricing are other homeostatic concepts even though they were not discussed in the present paper (they were discussed in the companion paper presented at the same session) [1]. In micro-shedding the utility sends the customer a direct command to shed a percentage of the customer's load while the customer makes the final decision on which specific loads to drop. Interruptable spot pricing enables the customer and utility to renegotiate their interruptable power purchase agreements on a time varying basis, just like the buy and buy back spot prices.

We do not view homeostatic concepts as replacements for the deployment of distributed storage energy devices. As stated in the paper,

> "Homeostatic control shows potential to: ... allow the system to accept more readily a stochastically fluctuating energy source, such as wind or solar generation ... (and) simplifies the expansion of cogeneration".

Implementation of homeostatic concepts could provide the difference that makes a particular distributed storage or generation concept viable.

Mr. Alford's discussion raises several fundamental points. We agree with him that social and political issues may dominate technical and economic issues both in the short term and very likely in the long term. This is one of the main reasons we held a conference on homeostatic control in Boxborough, Mass. [2] at which we sought to involve state regulators, legislators and customer representatives as well as engineers and economists.

The homeostatic principle of not crossing the meter line (i.e. customer independence) arose from concern over social and political issues. However Mr. Alford is not alone in his disagreement with this principle. The issue of whether the utility wants, needs to, or should cross the meter line is a basic question the electric power industry has to face both now and in the future. It cannot be resolved here. However our arguments in favor of the homeostatic principle of the utility not crossing the meter line can be summarized as follows. Working with industrial and commercial customers on their abilities and desires to adjust their use of electricity to various types of price signals provided one of the motivations behind homeostatic control [3,4]. This work showed many, although not all, of these customers could and would respond to homeostatic concepts, provided of course that they saved money. Many of the energy monitoring and control systems being sold and installed today in the industrial and commercial sector could respond directly to spot prices with relatively small programming changes and could provide FAPER action with presently available hardware. With such a system industrial and commercial customers retain the responsibility of telling their computers what priorities should be used in controlling individual loads but are relieved by their own computers, of managing their actual response to time-varying homeostatic signals. Microelectronic technology will eventually make it equally possible for residential customers to have computer systems which enable them to handle spot prices, interruptable rates, micro-shedding signals, etc. in a similar fashion. The homeostatic principle of exploiting computer communication technology enables utility computers to deal directly with customer computers so the customer is directly involved without being burdened with the details. Psychological research indicates that customer response is greatly improved when the customers feel directly involved.

The relationship between homeostatic control and reliance on time-of-use pricing and conventional load management technologies can be summarized as follows. Under homeostatic control, the customer, not the utility, is given the primary opportunity to discover options for modifying the load – and the customer is free to exercise independently these controls as they fit his/her needs. The customer is then penalized or rewarded for consuming or controlling according to actual system conditions, not on the basis of conditions projected for rate-making but not actually realized. Under utility controlled load management schemes, the utility must identify opportunities for load control, often in areas where it has little understanding of the customer's technology or requirements.

We agree with Mr. Alford that confirmation of spot prices every five minutes implies a high data rate if it is done for all residential customers. However we feel that it is quite reasonable at the industrial and commercial level while not obviously unreasonable for the residential

VAPER concept was suggested by an attendee of the Boxborough Conference [2]. It is an interesting idea that requires further consideration.

In summary to all three discussors, it is clear that the homeostatic principles, the resulting concepts, and the subsequent potential impacts lead to many open issues ranging from the basic philosophy of power system management to cost and circuit designs. There are other open issues not covered by the discussors but we do not feel it is appropriate to go into them here. A lot more work is required before these open issues are resolved. However we have become convinced that homeostatic concepts should be actively considered for both the near term and distant future. We hope others will see where homeostatic type principles lead them and will engage in the specific analysis of the various concepts that result. Our industry is facing difficult challenges and it is essential that we consider the potentials of new and alternative ways of dealing with them.

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