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ELECTRIC UTILITY ENERGY STORAGE SYSTEMS FOR PEAK SHAVING

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ABSTRACT

The state of the art of energy storage systems used by the electric utilities for peak shaving is discussed. The underlying concepts for the operation of the most important available schemes have been described. Whenever applicable the economics of the energy storage schemes as well as the cost expressed in § / Kw of electric capacity have been provided. In addition, the procedure used in modeling an energy storage system for planning purposes has been explained. The paper concludes with a prediction of the trend expected in future expansions of electric power plants.

1. INTRODUCTION

The demand for electricity in a utility system is characterized by hourly, daily, and seasonal variations. Unless peak shaving facilities can be provided at costs competitive with conventional peak load generation, the electric power system will have to be designed for peak load operation at high capital cost.

There are several courses of action, each with its own contribution to system reliability and to the utility industry.

1) Power peaking by interconnecting existing power networks;
2) Construction of new power plants for base generation and the use of older and less efficient steam turbines for peak power generation;
3) Addition of gas turbine peaking units; and
4) Construction of energy storage systems.

The last of the techniques mentioned above, which has become a very successful method of energy management, is the subject matter of this paper.

The basic concept of an energy storage system is to locate at the various substations devices that are able to accept energy from base load generators when the load demand falls below the baseload generating capability, store this energy, and release it to the power system when peak load conditions require it. In this manner the electric network is designed for less than peak loads and in accordance with the peak shaving capacity installed. A net consequence of this arrangement effectively increases the generating capability of the system as well as its reliability.

One of the oldest energy storage schemes used by the utilities is the pumped hydro storage. In this system water is pumped to an elevated reservoir for storage. Recovering the potential of this stored water during the peak periods allows minimum use of fossil-fired turbines with their high operating costs.The reliability of pumped hydro storage systems unfortunately is offset by some of their drawbacks. Pumped storages lack site flexibility, require transmission interconnections, and have a dynamic response which is not always optimum.

To counteract the increasing cost of operation of power plants and to minimize the environmental impact of the pumped hydro storage plants, utilities have increased the size of the plants and located these plants at distances remote from the population centers. It is quite clear that all these steps have led to an increase in the capital outlay. There is a need,therefore, for energy storage systems which have the reliability of the pumped hydro storage systems without their drawbacks.

Fernandes (1) has introduced a very convenient method of classification of energy storage systems which has been followed here. Two broad categories of energy storage system are indentified :

(1) The single input shaving system, and
(2) The dual input peak shaving system.

The single input shaving system is charged with off-peak electricity energy. The dual system generates electric power from a charge cycle obtained with off-peak electricity or, if necessary, from a primary or secondary fuel supply. The dual system could be operated as an electric generation plant.

Some of the single input systems presently used or under development are : a) Pumped hydro storage. b) Compressed air storage. c) Electrical batteries. d) Hydrogen storage. e) Fuel cells. f) Flywheels. g) Superconducting megnetic energy storage. h) Thermal storage.

Some characteristics common to all categories of energy storage systems are closely related to the nature of the baseload of the power system.

Indeed, higher forced outage rates could require an increase in reserve capcity margin. Experience indicates that when peak shaving systems are needed to maintain an 18 to 20 % reserve capacity margin a dual type system should be used to implement a single system capacity. The reasoning behind this procedure goes this way. If a forced outage prevents a charging of the storage dual system then the unit could be operating on a primary or secondary fuel under emergency. The dual system, therefore, displays a flexibility in bridging the mismatch that always exists between generation capacity and load growth.

Additional studies have also shown that a typical load profile for a utility would require 10 megawatt hours of storage for each magawatt of capacity. The storage devices, furthermore , would be expected to operate for 2,500 hours per year.

Aside from the utility-owned systems it may be more cost-effective to utilize consumer energy storage. The use of these distributed systems is believed to be more effective in improving the load factor than either power pooling or utility storage. Since the technology of energy storage is storngly influenced by scale, the importance of unit size should be considered.

In the first part of this paper an inventory of various storage schemes presently used or under investigation is covered. The ability of these schemes to improve the load factor on the distribution facility will be examined. Other features discussed are the capability of the system to improve the system reliability, to allow system expanison, and to reduce short circuit duties imposed by generation.

The second part of the paper is devoted to the concept of storage systems modeling. Finally, in the last part of the paper a speculative prediction is advanced on the trend in the design of futre power plants as affected by the economics and the technology of storage systems.

2. ENERGY STORAGE SYSTEMS

Beside the improved system load factor and power generation economics, energy storage capacities actually allow an increase of system peak capacity without new generation. This could solve, or at least, postpone, capacity expanison problems facing some electric utilities. Deferring the need for new generation and network facilities results in the added advantage of reduced air, noise, aesthetic pollution. Another consideration is that energy storage systems must meet utility-type standards for operating life, reliability, safety and environmental compatibility of generating equipment. The technical developments of several energy storage systems are summarized below.

2.1 Underground pumped hydro (2), (3), pumped storage has found wide applications for large scale energy storage. The conventional pumped storage takes advantage of the natural topography to develop the head and both upper and lower reservoirs. Constraints facing this approach are shortage of sites with the right combination of location within the power system and physical features, and also enviornmental considerations. In underground pumped storage, however, the lower reservoir and power plant are located in deep mined-out caverns and the upper reservoir is normally at ground level and may comprise either a natural water body (lake or river) or an artificially constructed pond. The reduced environmental impact makes pumped hydro with underground storage an attractive alternative. It is to be noted that since the elevation difference between upper and lower reservoirs is a design parameter, the major restrictions for this type of storage are equipment capability and rock conditions.In pumped hydro, substanital transmission facilities are required less sites can be developed within or near large urban load centers. Equipment needed for underground pumped hydro is commercially available and in wide spread use for conventional hydroelectric and pumped storage facilities. Also, underground construction and mining technologies are available and can be adapted for this system. Fig. (1).

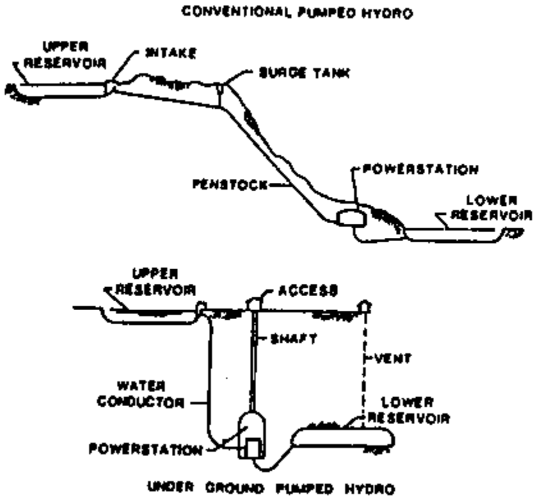


Figure 1 : Idealized drawings for two schemes of pumped storage.

2.2 <u>Compressed air storage</u>(3),(4),(5) comprises the use of off-peak power generation to compress air for peak period use in turbine-generators. During off-peakload periods, the turbine is disengaged and the compressor is driven by the generator used as a motor).

The compressed air may be stored in natural or man-made caverns, or depleted gas or oil fields. During periods of peak demand, the turbine would be connected (turbine - generator arrangement) with the compressor detached. The compressed air would then be used with an appropriate fuel to fire the turbine and the entire turbine output is used to drive the generator. Air storage may be accomplished either at a constant or variable pressure. The constant pressure system would require cooling of the air after the compression to bring its temperature down to about 50°C, and the heat energy removed from the compressed air must be considered as a system loss. The required development work relates mainly to adopting and modifying existing equipment for use with air storage systems. Although the availability of potential sites for compressed air storage systems is not apperent problem, this concept is not currently commercial. As stated earlier, it is necessary, during generation, to consume forms of fuel suitable for gas turbines (light or heavy distillate) and this appear to be an important factor in the future of air storage as fuelprices escalate. The first large compressed airstorage system has been completed in Germany by mid 1977. Fig. 2.3.

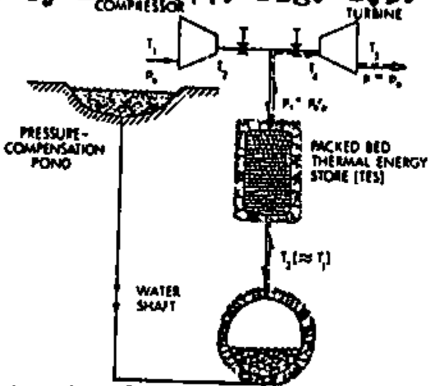


Figure 2 : Single-stage heat-of-compression storage adiabatic compressed-air system.

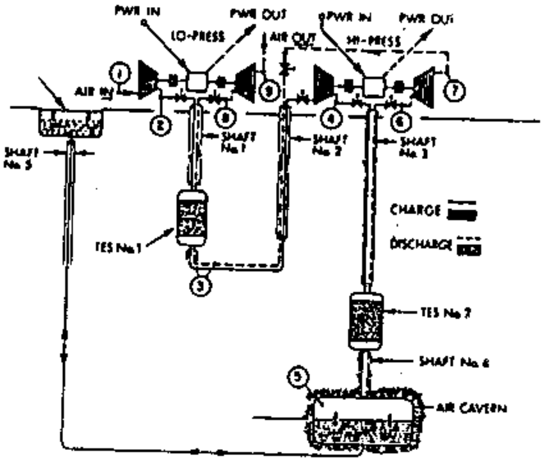


Figure 3: Adiabatic compressed air storage system with two stages of thermal storage.

2.3 <u>Electric Storage Batteries</u> are considered a special case of chemical storage where initial conversion, storage and reconversion are combined in a single device. Greater attention is now being focused on the possible use of batteries for bulk energy storage in utility systems and for electric cars. Leadacid batteries might become an important example of this approach if an advanced technology capable of long cycle life can be developed around cell designs that minimize lead requirements and can be produced inexpensively in volume,. Technically and economically feasible lead batteries for utility applications could conceivably become commercially available in about 4 - 5 years.Research and development (6) are progressing not only in lead-acid batteries but also in zinc-chlorine, sodium sulfur (7), lithium-iron sulfide batteries. An assessment of the potential of each battery type for utility storage is required. Emphasis is focused also on completing a feasibility study of a battery storage test (BEST) facility.

In general, there are three possible duty cycles that can be used for the operation of rechargeable storage batteries (8):

The daily cycle --- the storage system is charged at night and during the early morning hours and discharged during the peak load period. This cycle requires the minimum enorgy storage capacity; however, it dose not utilize all the available off-peak energy.

The weekly cycle --- the storage system is charged on the weekend and also during the off-peakperiods of the weekdays and discharged during the peak load periods to the weekdays. The weekly cycle requires more than twice the energy storage capacity needed for the daily cycle, but it would utilize most of the available off-peak energy.

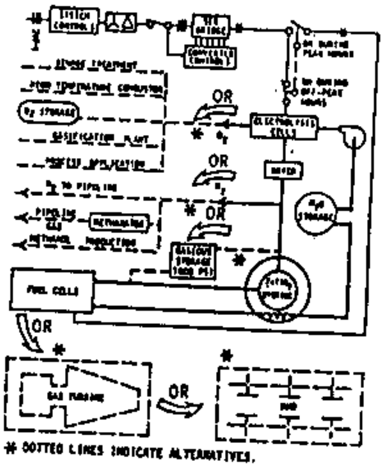
The seasonal cycle --- the storage system is charged during weekends and weekdays all year and only discharged when system peak loads occur. This is usually during the summer (but possibly the winter) season. This cycle is capable of utilizing all the available off-peak energy, although it requires a prohibitive amount of storage capacity.

In considering the installation of rechargeable storage battery capacity, energy capacity (KWh) as well as power capacity (KW) must be considered. For example, any given amount of available off-peak energy could be utilized with a number of different KWH/KW capacity combinations. The optimum amount of installed battery capacity on any electric power system is a function of the load shape, the amount, distribution, and cost of available off-peak energy,and the desired mode of operation or duty cycle.

The cost of battery capacity is an important element in this study and is usually represented in terms of dollars per killowatt hour of storage capacity. Capital costs of present day battery systems are in the order of approximately § 50/KWH. Projected capital costs of advanced design battery systems currently under development have projected to be in the order of 20 § /KWH. It is interesting to compare the cost in $/KW for a battery storage system with the installed capital costs for gas turbines and pumped hydro storage,from § 100 to § 150/KW and § 200 to § 300/KW respectively. The estimated base installed cost for an advanced technology lead-acid battery system is § 300/KW; this figure is based on a ten hour battery system (9). Studies show that the larger storage capacity requirments of the weekly cycle could economically limit the application of storage batteries in electric power systems to the daily operation.

Among the primary advantages of battary storage systems are the following: short lead time, improved utility load factor, remote operation, low maintenance cost, rapid dispatch and transmission saving. The main disadvantages, however, are : short life, limited storage capacity and inverter cost.

2.4 Hydrogen is the best known example of advanced chemical energy storage. Several technical approaches exist or have been proposed for hydrogen generation, storage and reconversion to electric, thermal or mechanical energy (10), (11), (12). The economics of a hydrogen storage peaking power plant has been examined in (13). Production of hydrogen will be from water using energy sources such as nuclear reactors. Reactors used to generate electricity may be employed in the electrolysis of water. Alternatively, nuclear energy may be used to support a series of reaction at tempuratures below 1000 °K which is referred to as " thermo-chemical " manufacture of hydrogen. The current electorlyzer technology is handicapped by modest efficiency and high capital cost. In any case, hydrogen generated by using off-peak energy will be stored and then used during peaking hours in a fuel cell, gas turbine or boiler to generate electricity. Hydrogen storage may be under high pressure in underground steelined tunnels, preferably located in sound rock to minimize cost, at cryogenic temperatutes, as a liquid or as a metal hydride. These hydrides can absorb large quantities of hydrogen at slightly elevated pressures. During peak-hours, by reducing the pressure below a certain level and increasing the temperature of the metal hydride, the hydrogen previously absorbed will be removed from the hydride and used to power a fuel cell. Fig. (4).



* DOTTED LINES INDICATE ALTERNATIVES.

Figure 4 : Schematic of a hydrogen cycle peak shaving system.

Current research interests focus on development of improved material capable of long life under high operating temperatures. Also under development is the power generating subsystem which may consist-of modified gas turbines or advanced fuel cells.

2.5 Fuel cells (14) are a form of electrochemical energy storage where two gases are liberated by water electrolysis and stored remotely from the electrodes. The cell is both the means by which the chemicals reacting to liberate energy are brought into contact and the means of drawing off the energy released as electric current at the cell voltage. At zero current the voltage generated has a characteristic value for every pair of chemicals.On large scale, power drawn from the system during off-peak hours is converted to dc and supplied to a tank of pressurized fuel cells acting as electrolyzers. Hydrogen and oxygen produced at cathode and anode, respectively, are stored under high pressure. Necessary water for the electrolysis is fed to the cells from a water storage. Between the cells and storage the gases pass through heat exchangers, rejecting heat to cooling water at about 200°C. During the peaking period, hydrogen and oxygen drawn back from underground storage are fed to the cells and water is regenerated and returned to the water storage. The dc power produced by the cells is converted to ac and fed to the power system. Cost involved in this technique includes the cells and the ac-dc converter installation. Large scale electrochemical storage could be economically attractive compared to other alternatives if efficiency can be substantially improved.

2.6 Flywheels are widely used outside utility systems to smooth pulsed power or conversely to generate large power pulses. However, their storage capacity is quite limited and very expensive compared with that of other methods proposed for energy storage in utilities. In principle, flywheels of any desired capacity could be built, if it were not for the limits implied by the finite strength of the flywheel material. Most flywheels have been made of steel, but because of the fear of a failed flywheel, they have been limited to low speeds of operation: thus their usefulness has been limited. Flywheels made of fibre composites may be the answer and the densities of such materials are quite low compared with that of steel. The strength of many fibre composites is extremely high and for the same geometry and dimensions of flywheel the maximum kinetic energy which can be stored is proportional to the strength. In other words, the basic criterion in the design of large-capacity flywheels is that the strength-to-density ratio of the material must be as high as possible.

Unlike previous flywheels, which have been solid disks, the likely configuration of the superflywheel would be either the fanned circular brush configuration (15) or a multirim configuration in which the fibres are arranged in consecutive hoops of successively larger radii. Superflywheels would be housed in sealed enclosures and coupled directly to variable speed motorgenerators. Units would be arranged in groups and possibly placed underground for aesthetic and safety reasons. It is expected that in addition to the cost of the units themselves , additional expense will be incurred in structures, miscellaneous electrical and mechanical equipment, and electrical switching and control systems. Development of systems to control power-input and output over a wide range of speed is a major consideration, and to achieve the deisred measure of control it is necessary to be able to vary speed and acceleration/deccaleration over a wide range and with good stability. Another important consideration of a flywheel system is its reliability; when a steel flywheel fails, it tends to break into three pieces of approximately equal size. Therefore, flywheel systems can never be viable in utility applications unless acceptable reliability and lifetime can be answered.

2.7 Superconducting magnetic storage technique consists of a large magnet shaped, perhaps, in a solenoidal or toroidal configuration, and cooled to an appropriate temperature (16), (17). The absence of electrical resistance in the superconducting material of the magnet would allow the establishment of a persistent current and resulting magnetic fleid. Using off-peak energy, the superconducting magnet is charged, and during peak periods, energy is fed back to the system through an inverter which is used as a rectifier during charging,. Losses encountered in this technique are due to cooling and to the inverter-converter system, and the overall efficiency of this inductive energy storage is in the range of 80-90%. In (16) it has been shown that such magnetic energy storage systems exhibit competitive economics for utilities power generation only in extremely large capacities. Superconducting magnets have been fabricated in various sizes and shapes since early sixties, but the storage capacity of even the largest is far too small for use in power systems. Development is underway to optimize the configuration and to accomplish maximum operating field conditions at minimum cost. Development of materials having superconductive transition temperatures near 28 °K, thereby allowing the use of liquid hydrogen as a coolant and be able to be fabricated into large magnets, would be a fundemental breakthrough.

2.8 Thermal Energy Storage has three areas of application to electric utilities; first, storage on the customer's side of the meter for space conditioning and water heating, second, intermediate temperature storage at the generating plant for feedwater and third, high temperature storage at the generating station as steam (3), (10),. In (18) several practical forms of application using thermal storage in residential (space heating, air conditioning and water heating), commercial and industrial sectors are discussed. Off-peak water heating and space heating may represent a significant load and thus improve the load factor for some electric utilities (19). In some applications, demand change savings alone justify off-peak thermal energy storage, but one major consideration is the degree of acceptance by the customer and the establishment of appropriate rate structures.

In thermal plants, consideration has been given to store heat during low power demand periods and return it to the cycle to augment the capacity of the station. Heat may be stored underground in the form of pressurized hot water and will be subsequently returned to the station as preheated feedwater. As estimate of 25 per cent increase in net plant output above normal ratings can be achieved through this technique of thermal storage. To avoid the risk of ground water contamination by accidental releases of feed water carrying radioactive corrosion products or radioactivity due to steam generator leaks, it has been suggested that storage may take place in steel lined tunnels with concrete encasement.

3. Modeling Of Energy Storage Systems :

Generally speaking models of energy storage systems are needed for planning and production costing studies. The models are also required for meaningful comparative studies.

An appropriate model for the energy storage system is the one which reflects the role played by the device. A formulation that meets with these requirements is best explained in fig.(5).

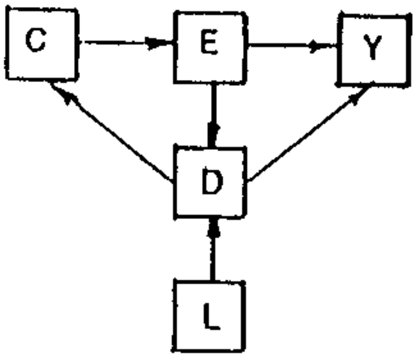


Figure 5 : Basic steps in the formulation of model

The temporal behavior of the load curve is divided into a number of intervals. During the j-th off-peak period, the system operator or decision-maker, D, will decide how to charge the individual storage device, E. This is done by specifying the duration δ of the charging time interval i_j and the power input π i during this interval.

A similar situation holds for the j-th off-peak period. The decision model depends on the prevailing load L. It also depends on the state of E,i.e., how much energy is available, and on other characteristics of E, such as, rate of charge and discharge, and permissible rate of change.

One introduces the generation strategy G defined as follows. Let the generating capacity of the power network be g. The capacity deficiency $L-g_s$ defines the generation strategy G which must be realized by the energy storage system E. In a complex situation G could be realized by a collection of storage devices G_1, G_2 - G_n so that $G = \sum G_i$. G is actually described by a sequence of time intervals i_j and the output power $\pi_{o,j}$ during intervals. Fig. (6).

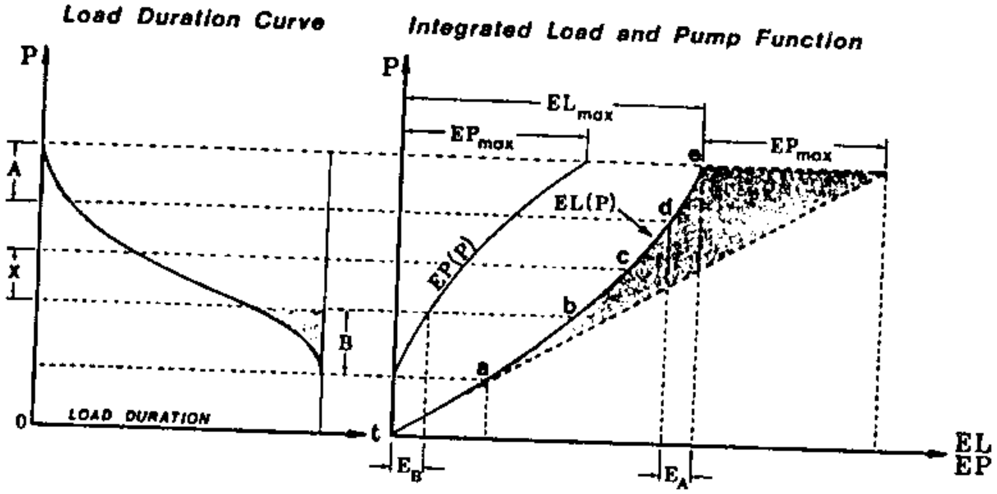


Figure 6: Representative load of a pumped hydro system. EP (P) - Integrated pump function; El (P)- Integrated load function; A, E_A -- Generating capacity/Energy; B,E_B -- Pumping capacity/Energy.

In parallel to the generating strategy there is a charging strategy C_j for the j-th device needed to realize G_j. The G_j are related to C_j by device parameters $\underline{x}_j$. The triplet $(\underline{x}_j, G_j, C_j)$ defines the energy storage device. On the other hand, the strategy C_j is described by the sequence i_j and the power in-put $\pi_{i,j}$ during these intervals.

To fix the ideas the various parameters mentioned above will be discused for the specific example of a pumped hydro system. Let $\dot{q}_o$ and $\dot{q}_i$ designate the output and input flow rates at a given time t, and let h_e denote the head across the turbine.

Clearly,

$$q_o = \sum i_j \dot{q}_o$$

When there is no loss of water, obviously

$$q_o = q_i$$

The power input and output expressed by

$$\pi_i = \alpha \eta_m \eta_p \dot{q}_i h_e$$

and

$$\pi_i = \alpha \eta_g \eta_t \dot{q}_o h_e$$

Where α is a constant, η_m, η_g are respectively the efficiencies for the motor generator, while η_p, η_t are the efficiencies of the pump and turbine.

Let us define the total charging and discharging times by

$$t_g = \sum i_j$$
$$t_c = \sum i_j$$

The decision vector $\underline{X}$ is three dimensional and is given by :

$$\underline{X} = \begin{matrix} h_e \\ \dot{q}_i \\ t_g/t_c \end{matrix}$$

The operator D (decision operator) is of importance in finding the answer to the basic question of optimizing G and C. Two possible variations to this problem exists: the energy system is known and one wishes to optimize its performance; in the other the system is not known and it is required to deduce the optimum characteristic for an energy storage system to be identified.

We do not intend to enter into an extensive discussion of systems theory, instead we will illustrate the idea of modelling by showing the general philosophy used in formulating the optimization problem for a hydro system.

We have indicated above that a given storage system is described by decision variables. We now identify objective functions, such as, cost, reliability, sensitivity, etc..., we also consider constraints imposed on the storage system. These constraints are actually related to the electric load on the power network: peak demand, instantaneous demand, operating constraints, etc ... .

The optimization one now seeks is to minimize the cost operation of the storage system subject to its meeting the load (i.e., the constraints). A representative example is shown in Figure 6 and the solution of the problem is given as derived by jacobi (20).

4. Prediction Of Power Systems Development :

The influence of energy storage systems in improving the economics, reliability, and performance of an electric power is also seen in the prevalent longrange thinking in the prediction of the electric power systems of the future.

It is interesting to review some of the predictions that had been made a decade ago. At that time the jump in the cost of fuel could not have been foreseen, neither could one have guessed at the resistance of the public to nuclear fission energy. In a well thought out power development for the 1970 - 2030 years, Kusko (21) stated from a number of premises which appeared plausible at the time: population increase, intensification of nuclear fission power, technological improvements in the art of electric transmission, projected power need (on the basis of extrapolation), and increased regulating controls to monitor environmental impacts.

Whereas most of Kusko's assumptions still hold today, a few have changed radically and it is expected to see energy storage play a very important role in the future.

The difficulty of securing capital for the financing of future power plants expansions as well as the uncertainty in demand predictions will put more emphasis on a need for improved electric load management. Peak load shaving and load levelling will become necessary to maximize the utilization of power system investment.

The uncertain future of nuclear fission energy will mean that the projected power plants with capacities in excess of 2,000 MW may not materialize as quickly. Should nuclear fusion technology come to fruition by the turn of the century, module sizes for the turbines and/or generators used with such reactors could be in the range between 2,000 and 10,000 MW. With these large sizes for the generators, there is a definite economic advantage in maintaining the reactors at a full load to provide the baseload, and for the energy storage to take care of peak loads.

Another development expected to take place is a proliferation of small power plants (solar, fuel cells, low head hydro,...), all of which would not be able to operate unless energy storage systems, as well as improvement in energy management techniques, would make it possible to intertie all these small plants to the network.

5. CONCLUSIONS :

In conclusion, it is projected to see in the future a large spectrum of energy storage systems with a wide spectrum of capacities and dynamic response.

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