The case for Pumped Storage Units in the Indian Electricity Sector

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***Abstract*—We prove the case for using efficiently managed pumped storage systems in Indian electricity market. We apply our analysis and quantify the savings of building the storage system with data from the Maharashtra State Electricity Board (MSEB). We provide a heuristic algorithm that beats the current gold standard approach of Dynamic Programming in terms of computational complexity. We conclude with a brief and cogent motivation for the use of pumped storage systems in the sector.**

Keywords-storage, renewable energy, pumped storage, control policy

I. INTRODUCTION

Across the world, there is now an increasing focus on improving energy efficiency and trying to incorporate the renewable sources of energy. As many of these renewable sources of energy are intermittent in nature, the only sustainable way to incorporate this kind of energy into the modern day electric grid is to introduce electric energy storage systems.

The other big area of interest is demand response, which is an essential component of the smart grid. Demand response infrastructure is quite expensive and many of the techniques of demand response are still being debated at the research level. Although we remain positive about the future of smart appliances, it will take several years to incorporate it. Crampes and Moureaux [7], in their work verify that demand response and storage act as two separate agents to bring about smoothing at both ends of the electricity supply chain. However, it is the conclusion of several economic studies [5] that overall efficiency can be obtained by the meaningful usage of both technologies. At this time, storage technology is a more economical and viable option to smooth out production costs compared to demand response. Hence, in this article we propose the propagation of several pumped storage systems across India to act as a buffer to varying demand.

II. THE INDIAN ELECTRIC GRID

Unlike many other countries, the electricity sector in India is still predominantly regulated by Public Sector Undertakings. There are pros and cons to this kind of system and there have been recent attempts to gradually deregulate the market. The accounted inefficiency losses in the electric grid is up to 30-45% [8] which is well above the average in most developed and developing countries [1].

India is fortunately blessed with an excellent river system that spreads across the land and hence is a great resource to apply for the energy needs of the developing nation. India currently has a hydropower potential of 84,000 MW [9]. While coal continues to be the main source of national power, the increasing carbon price and politically sensitive issues make it less viable in the long term. Many areas across the country including Tamil Nadu and Maharashtra have shown tremendous wind potential. These sources of energy are unique in that, they require a sizeable initial investment. However, they have the capacity to produce "free" energy at no marginal cost.

The current procedure to manage peak hour demand in India is to switch on a second turbine which has huge latency costs and flexibility issues. We propose using a centrally managed pumped storage unit to perform this function in a more effective way. The issue with pumped storage units, however is that the current techniques of managing such a unit are geared towards profit maximization in a market setting which does not entirely fit the Indian scenario. Several times, the storage unit is operated in conjunction with a thermal power plant. The operator generally cannot afford or does not have access to heavy computational techniques. With this in view, we propose a model to capture the savings of a pumped storage.

III. MODEL OF THE PUMPED STORAGE UNIT

Pumped storage units as an active instrument of providing electricity were discovered in the early eighties and have been increasingly used ever since [2]. During periods of low demand, water is pumped up to an elevated reservoir using electric energy. When the need arises to produce electric energy, water is allowed to gush down and run the turbines producing electricity. This process is generally quite inefficient and has losses up to the tune of 15%. Overall it serves as an easy mechanism to store electric energy in terms of gravitational potential energy. A good survey of the various issues of a pumped storage unit in the smart grid context is available in [4].

There have been several techniques of complex optimization suggested including Simulated Annealing [11], GA etc. The focus of most of these papers has been

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maximizing the profit of the unit when they are participating in a competitive market as a price taker. More recently, a paper by Kanakasabapathy et al [10] details bidding strategies for a pumped storage unit and tests the model against data from the New York market. However, the Indian market is centralized and the state level Power pool has Universal Service Obligations to satisfy consumer demand. As the nation proceeds becomes one of the world's economic powers, blackouts will become unacceptable to the Indian consumer, hence we would be required to necessarily satisfy a time varying stochastic demand at minimum cost. We do not consider the need for ancillary markets in this model.

We consider an infinite horizon model with cyclic demand spread over N (=24) periods. At the beginning of each period t, there is a certain amount of stored energy $s_{t-1}(\geq 0)$ carrying over from the previous period. There is a demand quantity $d_t(\geq 0)$ that needs to be satisfied during the current period. To satisfy this demand, a certain production quantity $q_t(\geq 0)$ is generated during this period. If the production quantity exceeds the current demand $(q_t > d_t)$, the excess energy is stored with an efficiency of α. If the current demand is higher than the production quantity $(q_t \leq d_t)$, the extra energy needed to satisfy the current demand is taken from the storage. We assume energy can be withdrawn from the storage with full efficiency. We note that this does not reduce the generality of the system because the value of α can be suitably modified to incorporate the inefficiencies in both storage and withdrawal into one variable. We further assume that there is a limit to the storage capacity C (i.e., $s_t \leq C$ for all t).

The storage level for the next period is related to the above variables in the following way:

$$s_t = s_{t-1} + (q_t - d_t)^+ \alpha - (q_t - d_t)^- \quad (1)$$

where a^+=max(a,0) and a^-=-min(a,0).

Let $\mathbf{D}_r = (d_1, d_2, \ldots, d_r)$ be the vector representing demands from periods 1 through r. Let $\mathbf{Q}_r = (q_1, q_2, \ldots, q_r)$ be the vector representing production quantities from 1 through r. During each period t, there is a production cost $c(q_t)$ associated with the production quantity q_t. We assume that the cost function c(q) is strictly convex and increasing. The inventory (or the net amount of stored energy) at the end of r periods is given by $I(\mathbf{Q}_r, \mathbf{D}_r) = s_0 + \sum_{t=1}^{r} [(q_t - d_t)^+ \alpha - (q_t - d_t)^-] = s_r$. For this model, we assume that the starting inventory s_0=0 but this can change suitably depending on the exact specifications in future sections. $C(\mathbf{Q}_r) = \sum_{t=1}^{r} c(q_t)$ is the total production cost of a production plan $\mathbf{Q}_r$.

A. *Optimization problem*

We formulate the problem to be a constrained multivariable optimization which depends on the cost function.

$$L = C(\mathbf{Q}_n) + \sum_{r=1}^{n} \lambda_r (I(\mathbf{Q}_r, \mathbf{D}_r) - C) - \sum_{r=1}^{n} \mu_r I(\mathbf{Q}_r, \mathbf{D}_r) \quad (2)$$

We apply the Karush-Kuhn-Tucker conditions to get:

$\nabla L = 0$
$C \geq I(\mathbf{Q}_r, \mathbf{D}_r) \geq 0$
$\lambda_r (I(\mathbf{Q}_r, \mathbf{D}_r) - C) = 0$ and $\mu_r I(\mathbf{Q}_r, \mathbf{D}_r) = 0$

for which, $\lambda_r \geq 0$ and $\mu_r \geq 0$ for all $1 \leq r \leq n$.

IV. EFFICIENT HEURISTIC POLICY

The goal of the optimal operation is to minimize the costs with respect to the constraints of satisfying demand across a cycle as described in the previous section. The optimization can be solved using the Lagrangian equation (2). The solution consists of two demand parameters whose calculation consists of a reasonably time consuming algorithm [12].

We propose the following heuristic approximation that is much easier to compute and manage. The simple intuition behind our method is methodically produce very close to the average demand during every period and use the storage unit as a buffer to satisfy excess demand during periods of high demand and store excess production during periods of low demand. This way, one can capture the savings from convexity of costs by starting with a large enough buffer. In this section, we compute the smallest value of the buffer (i.e., storage unit capacity) and provide the efficient production policy based on the estimated parameters of the model described in the previous section.

Step 1: Compute average demand for cycle: $a = \frac{\sum_{i=1}^{N} d_i}{n}$
Step 2: Compute minimal buffer requirement during each period of cycle: $b_j = \sum_{i=1}^{j} (d_i - a)$ for all i from 1 to n. The minimum required buffer capacity is given by the following formulate: $B = \max(b_i) - \min(b_i)$
Step 3: CONTROL POLICY

We start with a buffer capacity B at the beginning of period 1. As the demand is realized, during each period, we have the following control policy.

Define two constants, $e = c'^{-1}(\frac{(1-\alpha)}{2} c'(a))$ and $w = c'^{-1}(c'(e)/\alpha)$. We use the following policy for i=1 to n-1.

$$q_i = \begin{cases} b & \text{if } d_i \leq e \\ d_i & \text{if } s < d_i \leq w \\ w & \text{else} \end{cases} \quad (3)$$

And for i=n, we have the following $q_n = d_n - s_{n-1}$.

The idea behind the procedure is to produce the same value whenever production is in excess of demand to a certain

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quantity e and produce the same value whenever production is below the demand to a certain quantity w.

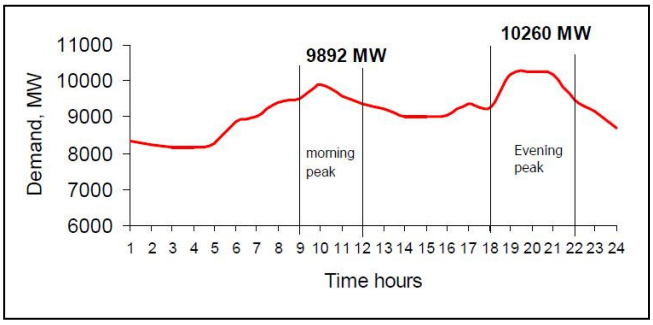

Figure 1. Typical day load curve reported by MSEB

V. RESULTS FROM DATA

We choose the Maharashtra State Electricity Board's daily consumption curve because there is plenty of data available for the demand consumption of this grid. There are many elevated points situated close to the Arabian Sea which are excellent spots for location of low cost pumped storage units. We assume that the power grid has access to a modern day thermal production unit with costs as described in the annual report of the MSEB [6]. We consider the average price of power to be increasing linearly from 4 Rs/KWh at 8000 MW to 6 Rs/KWh at 10000 MW. This is an approximation based on the estimated cost of fuel and the generation expenses given in the Mahagen Co Report [6] assuming a linearly increasing production cost. We use the average load curve on a typical day as shown in Fig. 1. This data was used from the work of Rangan Bannerjee [3].

We assume an alpha= 0.85 (i.e. 15% losses) and apply the heuristic policy as per section IV. Doing the evaluations, the total savings in production cost is approximately 5%. We assume that the storage capacity is also based on the assumption given in the model. We note that as more intermittent renewable sources of energy become part of the grid, and storage efficiency increases, the percentage savings in production costs will also increase.

VI. CONCLUSION

We have shown in the previous sections that there is a huge potential for savings by using pumped storage units in the Indian electricity markets. The unique features of the electricity sector in India make it a suitable climate to be applying the principles demonstrated in this article. We have clearly quantified that our proposed method is extremely simple for industrial managers to adopt and proves to be better than the current industry standard. Our proposed method is computationally fast and has immediate savings on practical systems. We infer that the special situation of the Indian market makes our unique methodology much more effective than the general techniques of storage management described in the literature. To our knowledge, we are the first paper to discuss the optimal operation of a pumped storage unit in tandem with a thermal plant with a cost minimization setting. Further, we provide a heuristic policy that is easy to implement and provides savings.

Future questions would be to see the optimal control of these storage units to the application of renewable energy. Another direction is to optimally select the choice of storage as lead acid batteries and other recent storage technologies become available in the market. Each of these storage units have specific inefficiency factors, investment costs, maintenance costs and energy life making them appropriate choices for unique situations across the different classes of consumers.

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