Optimal Time-of-Use Management with Power Factor Correction Using Behind-the-Meter Energy Storage Systems

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Abstract

In this paper, we propose an approach to maximize the economic benefit of BTM energy storage for TOU management while providing power factor correction. This approach is best suited for large commercial or industrial customers who are often billed for their high peak demand and penalized for their low power factors.

Methodology

An MILP problem is formulated to find the optimal ESS's hourly charge/discharge real and reactive powers that minimizes the monthly electricity bills while correcting the power factor of the customers. The constraints of this problem include:

- **Energy storage constraints:** state of charge constraints.
- **Inverter constraints:** charge/discharge power constraint, inverter's reactive power constraint, output power factor constraint.

The problem is then transformed to a Linear Programming (LP) problem using a Minimax technique. The approach assumes perfect foresight of data and therefore provides the results for the best-case scenario.

Formulation

Objective function: $\min\{\mathrm{k_{pf}}(\mathrm{C_E^m}+\mathrm{C_D^m})+\mathrm{C_N^m}\}$

$$\mathrm{C_E^m}=\tau\sum_{i\in \mathrm{H^m}}\alpha_i P_i^{\mathrm{net}}\mathrm{pr}_i \qquad \mathrm{C_N^m}=\tau\sum_{i\in \mathrm{H^m}}(1-\alpha_i)P_i^{\mathrm{net}}\mathrm{pr}_i^{\mathrm{s}}$$

$$\mathrm{C_D^m}=\max_{i\in \mathrm{H^m}}\{P_i^{\mathrm{net}}\}\mathrm{d_{max}^m}+\max_{j\in \mathrm{H_{pk}^m}}\{P_j^{\mathrm{net}}\}\mathrm{d_{pk}^m}+\max_{k\in \mathrm{H_{ppk}^m}}\{P_k^{\mathrm{net}}\}\mathrm{d_{ppk}^m}$$

Minimax technique:

$$\alpha_i=\begin{cases}1 & \text{if } P_i^{\mathrm{net}}\geq 0\\ 0 & \text{otherwise}\end{cases} \Leftrightarrow \begin{cases}\alpha_i P_i^{\mathrm{net}}=\max\{P_i^{\mathrm{net}},0\}\\ (1-\alpha_i)P_i^{\mathrm{net}}=P_i^{\mathrm{net}}-\max\{P_i^{\mathrm{net}},0\}\end{cases}$$

Storage constraints:

$$S_i=\gamma_{\mathrm{s}}S_{i-1}+\gamma_{\mathrm{c}}(P_i^{\mathrm{c}}-P_i^{\mathrm{lc}})\tau-(P_i^{\mathrm{d}}+P_i^{\mathrm{ld}})\tau/\gamma_{\mathrm{d}}$$

$$0\leq S_i\leq \overline{S} \qquad \tau\sum_{i\in \mathrm{H}}\left(\gamma_{\mathrm{c}}(P_i^{\mathrm{c}}-P_i^{\mathrm{lc}})-(P_i^{\mathrm{d}}+P_i^{\mathrm{ld}})/\gamma_{\mathrm{d}}\right)=0$$

Inverter constraints:

$$\begin{aligned}&0\leq Q_i^{\mathrm{c}}\leq \tan\overline{\Phi}P_i^{\mathrm{c}}\\ &0\leq Q_i^{\mathrm{d}}\leq \tan\overline{\Phi}P_i^{\mathrm{d}}\\ &(P_i^{\mathrm{c}})^2+(Q_i^{\mathrm{c}})^2\leq(\overline{P})^2\\ &(P_i^{\mathrm{d}})^2+(Q_i^{\mathrm{d}})^2\leq(\overline{P})^2\end{aligned} \xrightarrow{\text{Linearize}} \begin{aligned}&a_1Q_i^{\mathrm{c}}+b_1P_i^{\mathrm{c}}\leq c_1\overline{P}\\ &a_2Q_i^{\mathrm{c}}+b_2P_i^{\mathrm{c}}\leq c_2\overline{P}\\ &a_1Q_i^{\mathrm{d}}+b_1P_i^{\mathrm{d}}\leq c_1\overline{P}\\ &a_2Q_i^{\mathrm{d}}+b_2P_i^{\mathrm{d}}\leq c_2\overline{P}\end{aligned}$$

$$\begin{aligned}&a_1=1-\cos(\overline{\Phi}/2) && a_2=\cos(\overline{\Phi}/2)-\cos(\overline{\Phi})\\ &b_1=\sin(\overline{\Phi}/2) && b_2=\sin(\overline{\Phi})-\sin(\overline{\Phi}/2)\\ &c_1=\sin(\overline{\Phi}/2) && c_2=\sin(3\overline{\Phi}/2)\end{aligned}$$

Case Studies

A water treatment facility (300kW peak load) in New Mexico is considered:

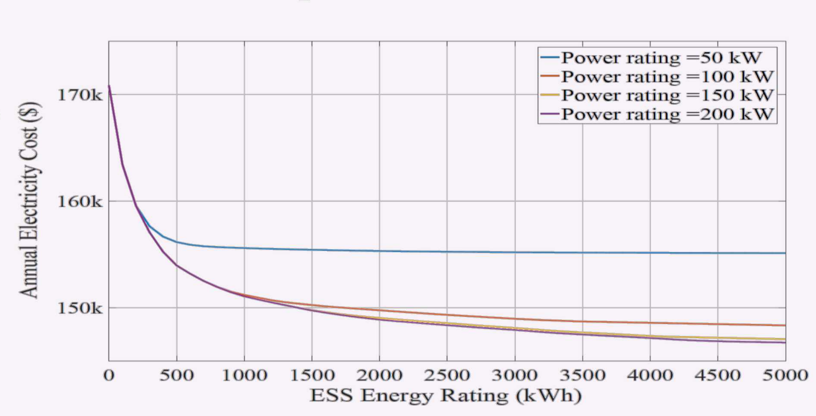
- 100kW on-site PV.
- Fixed energy rate and TOU demand rate are applied.
- Penalty is applied for power factor lower than 0.9.

Energy rate: $\mathrm{pr}=0.04537$ [$\$/kWh$]
Peak-hour (6am-9pm) demand rate: $\mathrm{d_{pk}}=24.69$ [$\$/kW$]
Off-peak (9pm-6am) demand rate: $\mathrm{d_{opk}}=6.12$ [$\$/kW$]
Net-metering rate: $\mathrm{pr_s}=0.03$[$\$/kWh$]

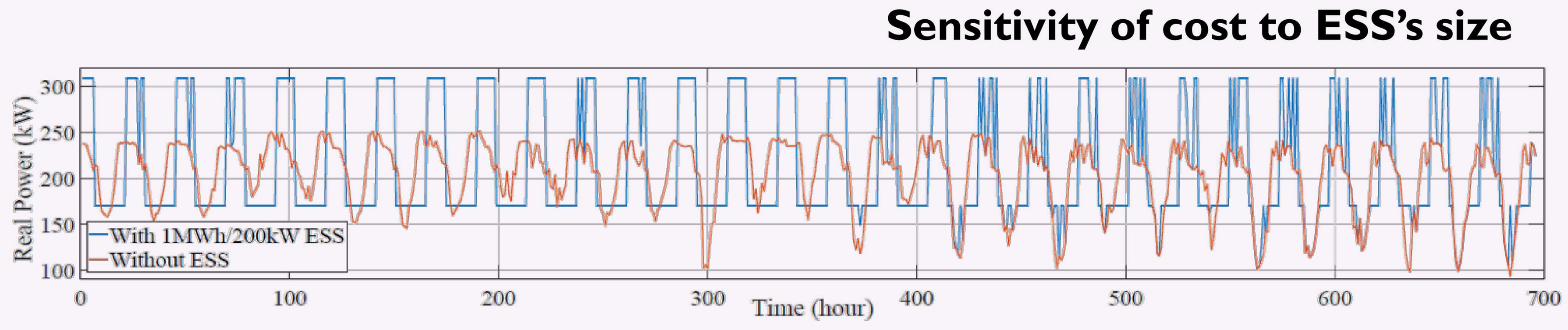
Image Credit – New Mexico Environment Department

Case I: TOU management without pf correction

- Optimal size: 200kW/1MWh.
- Total saving: $30k (16.8%)
- Peak demands have been shifted to off peak hours.

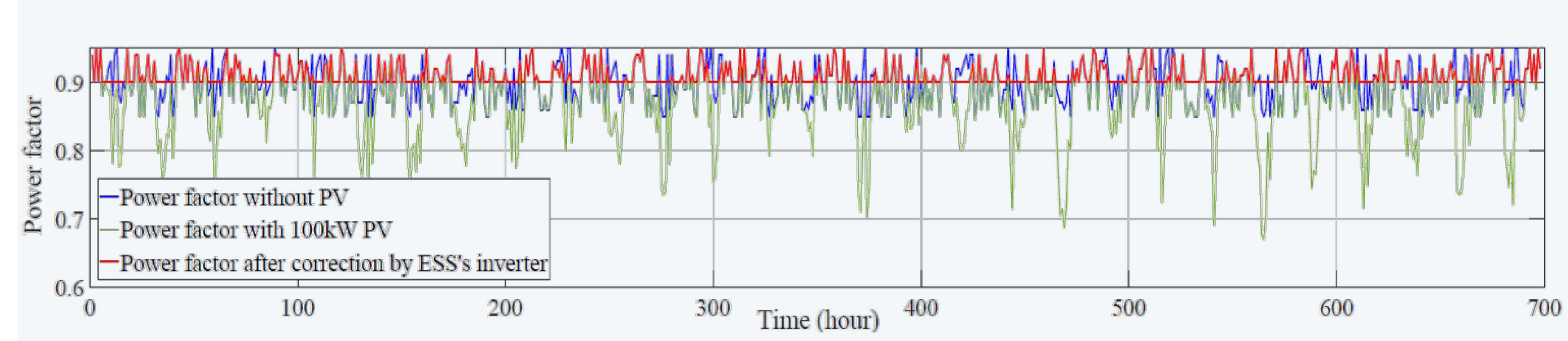


Sensitivity of cost to ESS's size

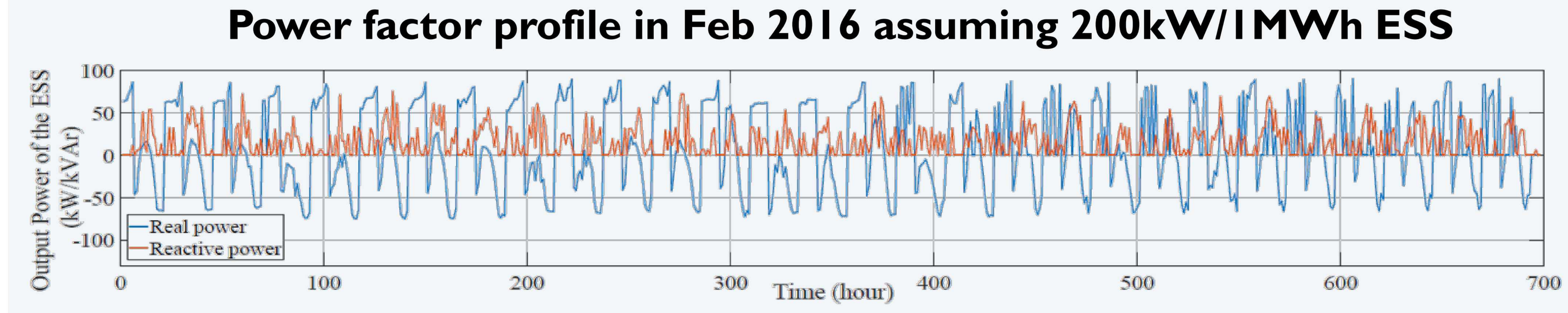


Net load during Feb 2016

Case II: TOU management with pf correction



Power factor profile in Feb 2016 assuming 200kW/1MWh ESS



Real and reactive power profile in Feb 2016 assuming 200kW/1MWh ESS

Conclusions

- In this paper, the benefits of behind-the-meter ESSs for TOU management with power factor correction have been studied.
- Specifically, the contributions of this paper include:
  1. A formulation of the optimal TOU management combined with power factor correction for BTM energy storage.
  2. A Minimax technique for transforming the energy storage MINLP problem to a LP problem.
  3. Results from case studies at a waste water treatment plant in New Mexico.

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