Example Dissertation Using Modular LaTeX

by

Eric Munsing

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

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of the

University of California, Berkeley

Committee in charge:

Assistant Professor Scott J. Moura, Chair
Professor Art Rosenfeld
Professor Richard Feynman

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Abstract

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- Chapter 1 provides background on the technical challenges of this work.
- Chapter 2 Develops a novel approach to solving important problems.
- The Appendices present tutorial material on the tools used throughout the paper, and are supplemented by the code in the author's github repository: `https://github.com/emunsing/tutorials`

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To @ShitAcademicsSay

For keeping me sane in the midst of the impossible

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Acknowledgments

I would like to thank my arms for always being on my side, my legs for always supporting me, and my fingers because I can always count on them.

Chapter 1

Background and Motivation

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1.1 Introduction

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Prior Literature

As discussed in [1–4], the findings from [5, 6] are clearly refuted. Nunc sed pede. Praesent vitae lectus. Praesent neque justo, vehicula eget, interdum id, facilisis et, nibh. Phasellus at purus et libero lacinia dictum. Fusce aliquet. Nulla eu ante placerat leo semper dictum. Mauris metus. Curabitur lobortis. Curabitur sollicitudin hendrerit nunc. Donec ultrices lacus id ipsum.

This is in contrast with the methods of [7, 8], and the conventional modeling of [1, 9–11]. Nunc velit. Nullam elit sapien, eleifend eu, commodo nec, semper sit amet, elit. Nulla lectus risus, condimentum ut, laoreet eget, viverra nec, odio. Proin lobortis. Curabitur dictum arcu vel wisi. Cras id nulla venenatis tortor congue ultrices. Pellentesque eget pede. Sed eleifend sagittis elit. Nam sed tellus sit amet lectus ullamcorper tristique. Mauris enim sem, tristique eu, accumsan at, scelerisque vulputate, neque. Quisque lacus. Donec et ipsum sit amet elit nonummy aliquet. Sed viverra nisl at sem. Nam diam. Mauris ut dolor. Curabitur ornare tortor cursus velit.

1.2 Formulation

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k	Time index, from 0 to time horizon N
Δt	Time step size (hours)
$c(k)$	Energy flow into the battery at time k (kW)
$d(k)$	Energy flow out of the battery at time k (kW)
$\mathrm{P}_{\mathrm{charge}}$	Maximum charge power capacity of the system (kW)
$\mathrm{P}_{\mathrm{discharge}}$	Maximum discharge power capacity of the system (kW)
$\mathrm{c}_{\mathrm{grid}}(k)$	Nodal electricity clearing price ($/kWh)
η_{in}	One-way system efficiency when charging
η_{out}	One-way system efficiency when discharging
$E(k)$	Energy level in reservoir at time k
$\mathrm{E}_{\mathrm{min}}$	Minimum allowable energy level as portion of capacity
$\mathrm{E}_{\mathrm{max}}$	Maximum allowable energy level as portion of capacity
$\mathrm{E}_{\mathrm{init}}$	Starting energy level of the storage system
h	Reservoir capacity (h), in hours of peak discharge
γ	Annualized cost of constructing one kWh of reservoir capacity ($/kWh/yr)

Data

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As clearly demonstrated in Figure 1.1

1.3 Results

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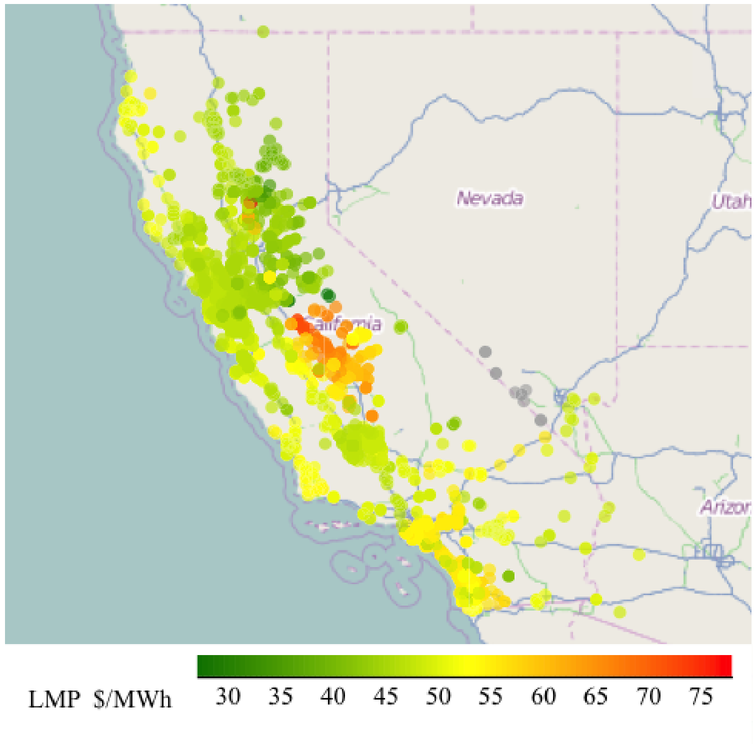

Figure 1.1: Example of Location Marginal Price (LMP) distribution on the CAISO grid. Each circle represents an LMP node on the the CAISO grid. Data from 4PM PDT, August 18 2013

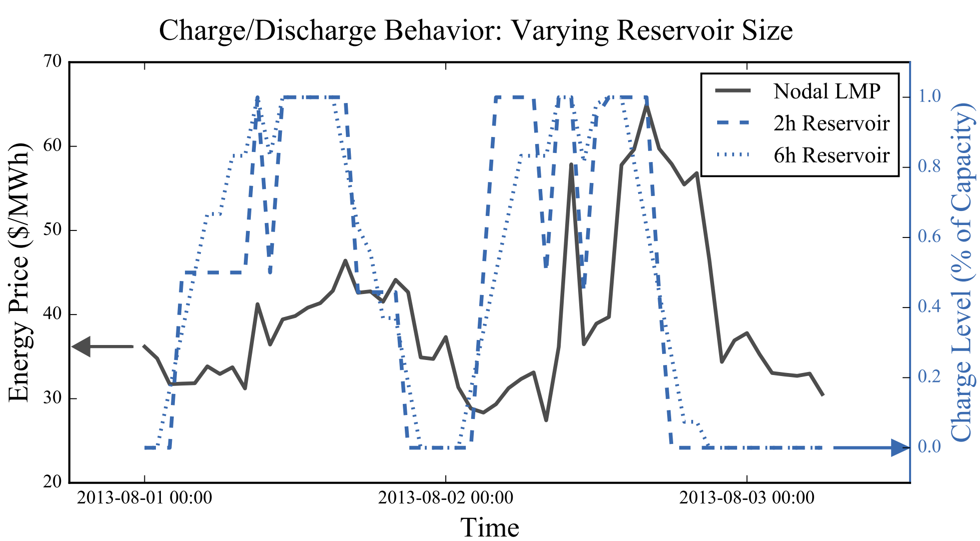

Figure 1.2: Aenean massa. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Donec quam felis, ultricies nec, pellentesque eu, pretium quis, sem. Nulla consequat massa quis enim.

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1.4 Conclusion

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1.5 Potential Improvements

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Chapter 2

Blockchain-Coordinated Decentralized Optimization

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2.1 Introduction and Motivation

Despite extensive use in financial applications to achieve consensus between non-trusting parties [12], blockchains have seen limited deployment in the energy space [13] and have not been considered for coordinating DERs to manage network constraints [14].

We structure the remainder of the paper as follows: Section 2.2 provides a brief overview of blockchains and smart contracts. Section 2.3 provides a survey of previous literature on dispatch of DERs in microgrids, decentralized optimization techniques, and blockchain use in energy applications. Section 2.4 presents the formulation of the optimal power flow problem.

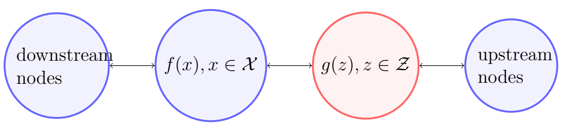

Figure 2.1: Sample problem structure, with arrows showing shared variables.

2.2 Blockchains and smart contracts

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The general architecture of blockchains is described in [15] and illustrated in Fig. 2.2. Etiam pede massa, dapibus vitae, rhoncus in, placerat posuere, odio. Vestibulum luctus commodo lacus. Morbi lacus dui, tempor sed, euismod eget, condimentum at, tortor. Phasellus aliquet odio ac lacus tempor faucibus. Praesent sed sem. Praesent iaculis. Cras rhoncus tellus sed justo ullamcorper sagittis. Donec quis orci. Sed ut tortor quis tellus euismod tincidunt. Suspendisse congue nisl eu elit. Aliquam tortor diam, tempus id, tristique eget, sodales vel, nulla. Praesent tellus mi, condimentum sed, viverra at, consectetuer quis, lectus. In auctor vehicula orci. Sed pede sapien, euismod in, suscipit in, pharetra placerat, metus. Vivamus commodo dui non odio. Donec et felis.

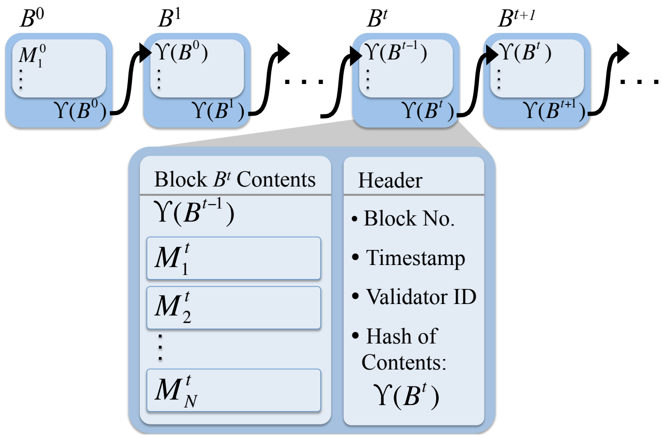

Figure 2.2: Symbolic representation of the data in a blockchain, showing blocks B^0 to B^{t+1} with detail of block B^t. Blocks are linked by their cryptographic hashes $\Upsilon(B^t)$, securing the contents from alteration and allowing transparent auditing of system history. Messages M_i^t contain information about changes to the system state, such as energy transfers or payments.

2.3 Prior Literature

As discussed in [16], Microgrids are electricity networks may operate in both grid-connected and self-sufficient modes. Surveys of approaches to microgrid management can be found in [17, 18]. Decentralized algorithms have been explored for coordinating electric vehicles [19, 20], smart inverters [21], and for fleets of diverse DERs [22–24]. Vivamus eu tellus sed tellus consequat suscipit. Nam orci orci, malesuada id, gravida nec, ultricies vitae, erat. Donec risus turpis, luctus sit amet, interdum quis, porta sed, ipsum. Suspendisse condimentum, tortor at egestas posuere, neque metus tempor orci, et tincidunt urna nunc a purus. Sed facilisis blandit tellus. Nunc risus sem, suscipit nec, eleifend quis, cursus quis, libero. Curabitur et dolor. Sed vitae sem. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Maecenas ante. Duis ullamcorper enim. Donec tristique enim eu leo. Nullam molestie elit eu dolor. Nullam bibendum, turpis vitae tristique gravida, quam sapien tempor lectus, quis pretium tellus purus ac quam. Nulla facilisi.

2.4 Optimal Dispatch Formulation

The distribution network is modeled as an undirected radial graph $\mathcal{G}(\mathcal{N}, \mathcal{E})$, consisting of a set of nodes $\mathcal{N}$ and a set of distribution lines (a.k.a. edges) $\mathcal{E}$ connecting these nodes. Using the notation described in [25], we index the nodes in $\mathcal{N}$ by $i = 0, 1, \ldots, n$, where node 0 represents the root node (substation) and other nodes in $\mathcal{N}$ represent branch nodes. We also denote a line in $\mathcal{E}$ by the pair (i, j) of nodes it connects where j is closer to the feeder 0. We call j the parent of i, denoted by $\pi(i)$, and call i the child of j. Denote the child set of j as $\delta(j) := \{i : (i, j) \in \mathcal{E}\}$. Thus a link (i, j) can be denoted as $(i, \pi(i))$.

$$p_i = P_i - \sum_{k \in \delta(i)} P_k + \mathrm{r}_i l_i, \quad i = 0, \dots, n \tag{2.1a}$$

$$q_i = Q_i - \sum_{k \in \delta(i)} Q_k + \mathrm{x}_i l_i, \quad i = 0, \dots, n \tag{2.1b}$$

$$v_i = v_{\pi(i)} + 2(\mathrm{r}_i P_i + \mathrm{x}_i Q_i) - (\mathrm{r}_i^2 + \mathrm{x}_i^2) l_i, i = 1, \dots, n \tag{2.1c}$$

$$l_i = \frac{P_i^2 + Q_i^2}{v_i}, \quad i = 1, \dots, n \tag{2.1d}$$

where $S_0 = 0 + \mathbf{i}0$ at the slack bus. Equations in (2.1) define a system in the variables $(P, Q, l, v) := (P_i, Q_i, l_i, v_i, \ \forall \text{ i} \in \mathcal{N})$, which do not include phase angles of voltages and currents. Given (P, Q, l, v), phase angles can be uniquely determined for radial networks [26].

2.5 Blockchains and ADMM

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repeat
- $\mathbf{P_i}$**:** *Private Optimization, compute locally*
  - Gather private constraints
  - Compute $\tilde{x}_i$ and send to smart contract S_1
- $\mathbf{S_1}$**:** *Security Smart Contract, on blockchain*
  - Check $\tilde{x}_i$ for feasibility
  - If attack detected, flag node i & adjust $\tilde{x}_i$
  - Update u
  - **if** $\|r^k\|_2 \leq \epsilon_{pri}, \ \|s^k\|_2 \leq \epsilon_{dual}$ **then**
    - Compute final schedule and clearing prices
    - Send schedule to S_2
  - **end**

until $\|r^k\|_2 \leq \epsilon_{pri}, \ \|s^k\|_2 \leq \epsilon_{dual}$

Algorithm 1: Computational elements in the microgrid control system. Function $\mathbf{P_i}$ is executed locally by each device participating in the market.

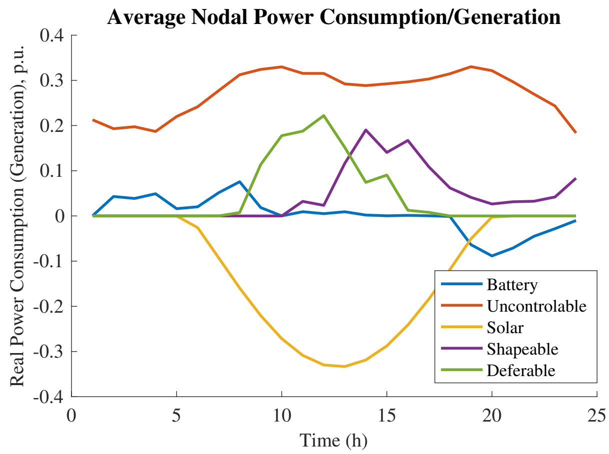

Figure 2.3: Schedule of commitments generated by the ADMM algorithm and stored to the smart contract.

Algorithm 1 Fusce mauris. Vestibulum luctus nibh at lectus. Sed bibendum, nulla a faucibus semper, leo velit ultricies tellus, ac venenatis arcu wisi vel nisl. Vestibulum diam. Aliquam pellentesque, augue quis sagittis posuere, turpis lacus congue quam, in hendrerit risus eros eget felis. Maecenas eget erat in sapien mattis porttitor. Vestibulum porttitor. Nulla facilisi. Sed a turpis eu lacus commodo facilisis. Morbi fringilla, wisi in dignissim interdum, justo lectus sagittis dui, et vehicula libero dui cursus dui. Mauris tempor ligula sed lacus. Duis cursus enim ut augue. Cras ac magna. Cras nulla. Nulla egestas. Curabitur a leo. Quisque egestas wisi eget nunc. Nam feugiat lacus vel est. Curabitur consectetuer.

2.6 Implementation: Test network

Details available at:

`github.com/emunsing/energyblockchain`

Figure 2.3 demonstrates that Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

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2.7 Conclusions

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2.8 Potential Improvements

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Chapter 3

Conclusion

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Appendix A

Decentralized Security- Analytic Solution

A.1 Analytic Solution Notes

The x-update step is an unconstrained quadratic program, and can be solved analytically. For clarity, we let $\gamma = Bz^k + u^k$ and proceed as:

$$
\begin{aligned}
x^{k+1} &= \operatorname{argmin}_x \quad x^T P x + c^T x + \frac{\rho}{2}||Ax + \gamma||_2^2 \\
x^{k+1} &= \operatorname{argmin}_x \quad x^T P x + c^T x + \frac{\rho}{2}(Ax + \gamma)^T (Ax + \gamma) \\
x^{k+1} &= \operatorname{argmin}_x \quad x^T P x + c^T x + \frac{\rho}{2}(x^T A^T A x + 2\gamma^T A x + \gamma^T \gamma) \\
0 &= \frac{\partial}{\partial x}\left(x^T P x + c^T x + \frac{\rho}{2}(x^T A^T A x + 2\gamma^T A x + \gamma^T \gamma)\right) \\
0 &= 2Px + c + \rho A^T A x + \rho \gamma^T A \\
0 &= (2P + \rho A^T A)x + c + \rho \gamma^T A \\
x &= (2P + \rho A^T A)^{-1}(-c - \rho \gamma^T A)
\end{aligned}
$$

Similarly, the z-update step can be solved analytically by letting $\mu = Ax^{k+1} - c + u^k$ and following a similar process to find:

$$z^{k+1} = (2Q + \rho B^T B)^{-1}(-d - \rho \mu^T B)$$

These analytic solutions are used in our implementation to avoid inaccuracies induced from a numeric solution.

Comparison with Central Solution

Because the problem is an unconstrained QP and entries with consensus between a subset of variables, a centralized solution can be computed by composing the cost matrices into a single quadratic problem which can be solved analytically. This is shown here for the case where $c = 0$ and A and B are composed as described above, but also can be computed for other A, B.

We break P and Q into sub-matrices dependent on the number of consensus constraints p, where $P_{11}, Q_{00} \in \mathbb{R}^{p \times p}$ and the other dimensions follow accordingly.

$$P = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$$
$$Q = \begin{bmatrix} Q_{00} & Q_{01} \\ Q_{10} & Q_{11} \end{bmatrix}$$
$$\Pi = \begin{bmatrix} P_{00} & P_{01} & 0 \\ P_{10} & P_{11} + Q_{00} & Q_{10} \\ 0 & Q_{10} & Q_{11} \end{bmatrix}$$

Similarly, the c and d vectors can be combined as

$$\kappa = \begin{bmatrix} c_0 \\ c_1 + d_0 \\ d_1 \end{bmatrix}$$

The problem can then be expressed as an unconstrained minimization problem:

$$\min_w \quad w^T \Pi w + \kappa^T w$$

which is solved by $w^* = -\frac{1}{2}(\Pi^T)^{-1}\kappa$

This central solution was used only for verification.