Modular Articles for Quicker Graduations*

Eric Munsing[1]

***Abstract*— Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus.**

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I. Introduction and Motivation

Despite extensive use in financial applications to achieve consensus between non-trusting parties [1], blockchains have seen limited deployment in the energy space [2] and have not been considered for coordinating DERs to manage network constraints [3].

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

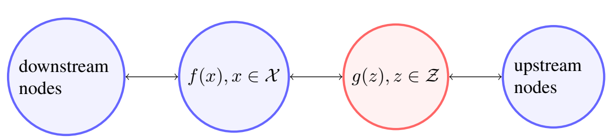

Fig. 1. Sample problem structure, with arrows showing shared variables.

II. Blockchains and smart contracts

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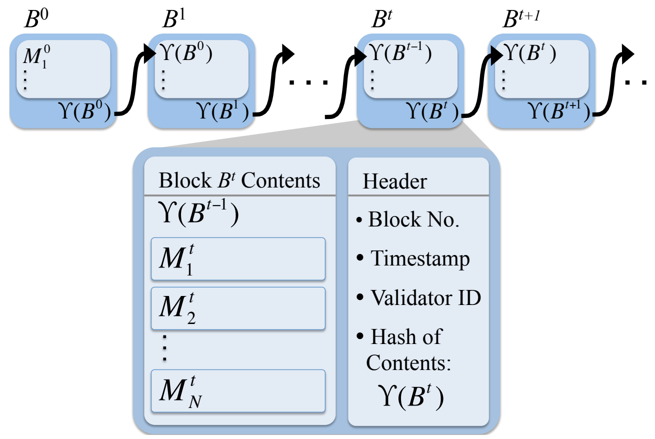

Fig. 2. Symbolic representation of the data in a blockchain, showing blocks B^0 to B^{t+1} with detail of block B^t. Blocks are linked by their cryptographic hashes $\Upsilon(B^t)$, securing the contents from alteration and allowing transparent auditing of system history. Messages M_i^t contain information about changes to the system state, such as energy transfers or payments.

The general architecture of blockchains is described in [4] and illustrated in Fig. 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.

III. Prior Literature

As discussed in [5], Microgrids are electricity networks may operate in both grid-connected and self-sufficient modes. Surveys of approaches to microgrid management can be found in [6], [7]. Decentralized algorithms have been explored for coordinating electric vehicles [8], [9], smart inverters [10], and for fleets of diverse DERs [11], [12],

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IV. 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 [14], 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 $(i, \pi(i))$.

$$p_i = P_i - \sum_{k \in \delta(i)} P_k + \mathrm{r}_i l_i, \quad i = 0, \ldots, n \tag{1a}$$

$$q_i = Q_i - \sum_{k \in \delta(i)} Q_k + \mathrm{x}_i l_i, \quad i = 0, \ldots, n \tag{1b}$$

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

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

where $S_0 = 0 + \mathbf{i}0$ at the slack bus. Equations in (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 [15].

V. 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.

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VI. Implementation: Test network

Details available at:
`github.com/emunsing/energyblockchain`
Figure 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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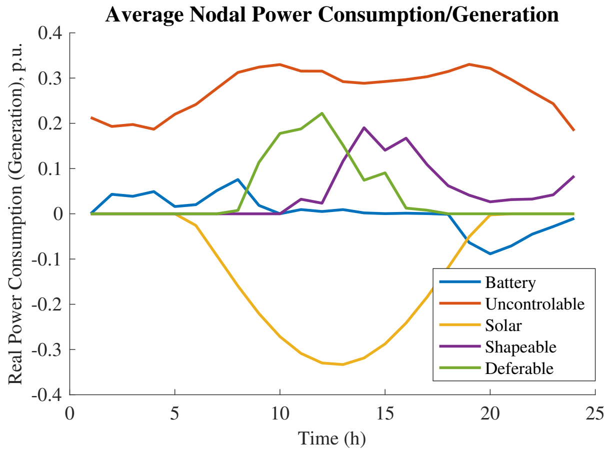

Fig. 3. Schedule of commitments generated by the ADMM algorithm and stored to the smart contract.

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VII. Conclusions

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Appendix

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:

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

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.

A. 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.