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A Transactive Approach for Service Restoration Utilizing Customer Load Flexibility and Grid-Edge Resources

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Background and Motivation

- **Grid-edge resources** can improve flexibility and **service restoration** in distribution systems.
- Direct load control poses **privacy** and **autonomy** concerns.
- **Transactive energy systems** can engage customers through price signals; their **use during outage conditions** is a topic of emerging research.

Optimization and modeling

A. Resource-level optimization

1. **Critical and non-critical loads**
   If the market price is low enough, they consume their entire demand.
2. **Flexible loads**
   Alter their consumption to maximize consumer surplus based on the market price and their utility functions.
3. **Distributed generators**
   Alter their production to maximize producer surplus based on the market price and their utility functions.
4. **Prosumers**
   Determine their optimal market consumption, generation consumed on-site, and generation sold to the market to maximize the sum of their consumer surplus and their producer surplus.

B. Power flow and voltage constraints

We adopt a **3-phase linear DistFlow** model and introduce slack variables to determine the **power flow and voltage violations**.

$$p_{i\varphi}^{s+}, p_{i\varphi}^{s-}, q_{i\varphi}^{s+}, q_{i\varphi}^{s-}, v_{i\varphi}^{s+}, v_{i\varphi}^{s-}$$

C. Price update equation

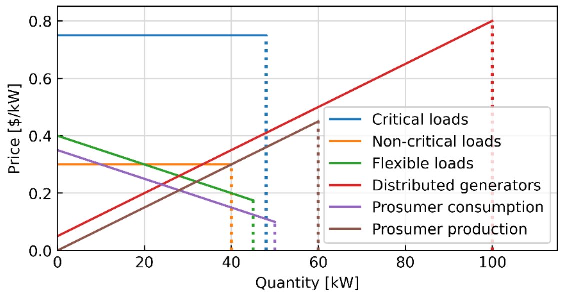
$$\lambda_{k+1} = \lambda_k + \gamma \sum_{i\in\mathcal{N}} \sum_{\varphi\in\Phi} (p_{i\varphi}^{s+} - p_{i\varphi}^{s-} + \underbrace{v_{i\varphi}^{s-} - v_{i\varphi}^{s+}})$$

Increase if demand > supply

Decrease if demand > supply

Increase if overvoltage, decrease if undervoltage

This **transactive energy system** engages a variety of **market participants** who value service restoration through **utility functions**.



The **primal-dual algorithm** is used to compute the **competitive equilibrium** and **maximize social welfare**.

Algorithm 1 Algorithm for transactive energy market

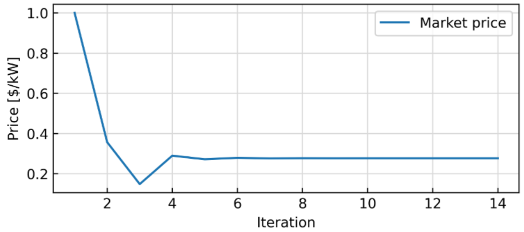
```
Input: Customer utility functions and resource limits
Output: Optimal market price, $\overline{\lambda}$
Initialize market price, $\lambda_k = \lambda_0$, done = False
while not done do
    Solve resource-level optimizations to maximize customer surpluses at price $\lambda_k$.
    Check for power flow, voltage violations.
    Calculate the updated price ($\lambda_{k+1}$).
    if ($|\lambda_{k+1} - \lambda_k|/\lambda_k \leq 0.00001$) then
        $\overline{\lambda} = \lambda_k$, done = True
    else
        update market price, $\lambda_k = \lambda_{k+1}$
    end if
end while
return $\overline{\lambda}$
```

Numerical Results

The proposed approach is implemented on a **modified IEEE 123-bus** test system. It is modeled in **Pyomo** and solved using **GLPK**.

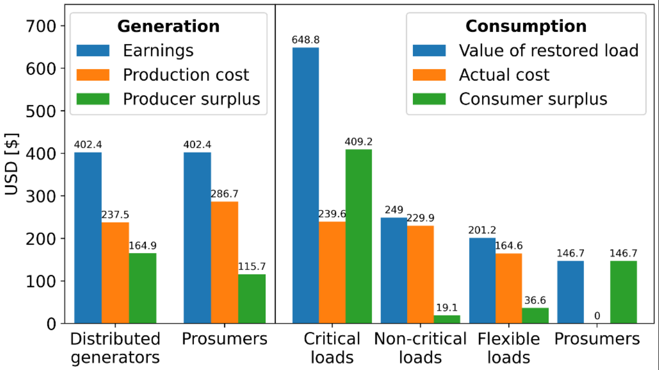
A. Market Price

The simulation converged to an optimal market price of 0.277 $/kW in 12.7 seconds.

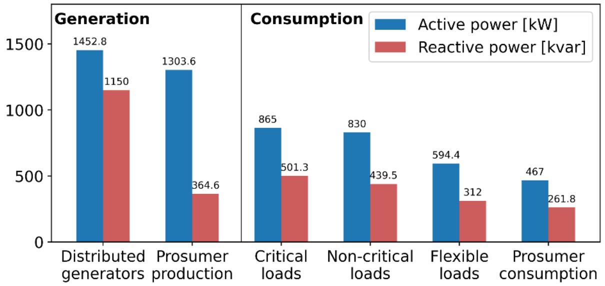


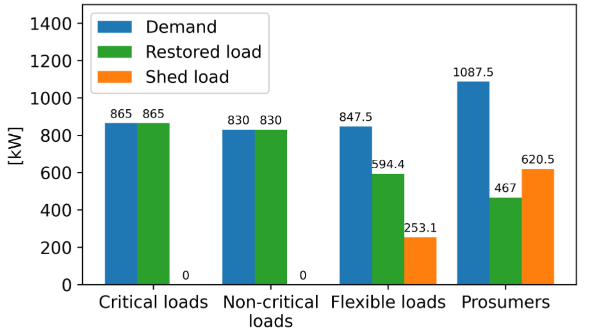
B. Customer Costs

Overall social welfare = sum of surpluses ($892.2).



C. Service Restoration





Conclusions

- Market mechanism for grid-edge flexibility and DERs to **aid in service restoration**.
- System **resilience** is improved through decreased shed load.
- Utility functions must represent **the accurate value of lost load** during an outage for this approach to be **equitable**.

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