Transitioning to Networked Microgrids: Leveraging Existing Capacity and Technologies

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Transmission Network in Michigan, Wisconsin, and Illinois
69-kV, 115-kV, 138-kV, and 345-kV Transmission Circuits

Location of Michigan Technological University Campus in Houghton Michigan
Keweenaw Distribution Grids

**UPPCO Distribution Network** with 10,000+ Distribution Transformers (DTs). Each DT is with about 5 customers
- **160MW** (peak load)
- **120MW** (average)
- NO SCADA/DMS
- NO Smart meters for UPPCO

**Michigan Tech campus** 7,000+ Customers
- **7MW** (peak load)
- **4.5MW** (average)
- 11 building with AMI meters
- Building management system

All feeders are radial and unbalanced.
Distribution Transformers (Loads) in Houghton Downtown
Value Stream of Networked Microgrids and Key Players

Transmission Network
- Improved system reliability
- Infrastructure enhancement and expansion
- Energy usage reduction

Distribution Network
- Electricity trading
- Power quality improvement
- Sustainable investment strategies
- Net-meter is the key

Advanced communication – Observability and reconfigurability
Distributed generation (DG) + Microgrid (DG + Load) - Adequacy
ROAD Prioritization

<table>
<thead>
<tr>
<th></th>
<th>Reliability</th>
<th>Reconfigurability</th>
<th>Observability</th>
<th>Ancillary Service</th>
<th>Dynamic Pricing Market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-Term Priority</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>Mid-Term Priority</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Long-Term Priority</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Ownership Models:
1. **Observability**: Utility, non-microgrid consumers
2. **Reliability**: Utility, investor, microgrid consumers
3. **Reconfigurability**: Utility, investor
4. **Ancillary Service**: Utility, investor, distribution system operators (DSO)
5. **Dynamic Pricing Market**: Utility, investor, microgrid consumers, DSO
The values of smartphone:
• It’s a phone
• It’s a GPS
• It’s a music player
• It’s a video recorder
• It’s an email reader
• It’s an Internet browser
• Free video conferencing around the world
• Other apps...

• **10 years ago, USD90 monthly bill is expensive!**
  USD100-USD200 becomes affordable to consumers!

  • Telephone company takes the installment payment
  • Smartphone vendors make sure new technological features are included
  • PowerON works with iPhone to recycle these products so that consumers would get new featured phone
  • Consumers driven! The customers have choices!
  • New smartphone comes out every 1 or 2 years!

• How about Energy? What choices do consumers have?
Under what contracts do microgrids help consumers to payoff initial investment?

Do we care these if the SAIDI, SAIFI, and CAIDI = 0?
Do we care if electricity tariff is the same at all time?
Intelligent Transportation vs. Smart Grid

- **Infrastructure-based** sensing techniques
  - Smart Roads: High costs of fixed sensors along infrastructure
    - Installation
    - Operation
    - Maintenance
    - Reliable traffic info

- **Vehicle-based** Sensing Techniques
  - Smartphone
    - Assisted GPS
    - Social network data
  - Connected vehicle technology

**Very Few Successful Applications**

Smart roads (1980-2007)

Connected vehicles and autonomous driving (Future)

Smart roads and vehicles (2007-present)
(real-time traffic navigation, location-based service)
OBSERVABILITY
## AMI Infrastructure Deployment

### AMI Energy Meter Quantity

<table>
<thead>
<tr>
<th>Year</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>1,900,000</td>
</tr>
<tr>
<td>2011</td>
<td>9,600,000</td>
</tr>
<tr>
<td>2012</td>
<td>13,300,000</td>
</tr>
<tr>
<td>2013</td>
<td>15,300,000</td>
</tr>
<tr>
<td>2014</td>
<td>15,300,000</td>
</tr>
</tbody>
</table>

### AMI Energy Meter Percentage

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>2%</td>
</tr>
<tr>
<td>2011</td>
<td>8%</td>
</tr>
<tr>
<td>2012</td>
<td>9%</td>
</tr>
<tr>
<td>2013</td>
<td>11%</td>
</tr>
<tr>
<td>2014</td>
<td>11%</td>
</tr>
</tbody>
</table>

### AMI Assets

<table>
<thead>
<tr>
<th>AMI Assets</th>
<th>Quantity</th>
<th>Incurred Cost</th>
<th>Number of Entities</th>
<th>Average Cost / Entity</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMI Energy Meters</td>
<td>15,260,497</td>
<td>$2,545,320,028.00</td>
<td>81</td>
<td>$31,423,704.05</td>
</tr>
<tr>
<td>Communications networked and hardware that enable two way communications</td>
<td></td>
<td>$627,632,212.00</td>
<td>78</td>
<td>$8,046,566.82</td>
</tr>
<tr>
<td>IT hardware, systems, and applications that enable AMI features and</td>
<td></td>
<td>$634,170,814.00</td>
<td>75</td>
<td>$8,455,610.85</td>
</tr>
<tr>
<td>functionalities</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other AMI related costs</td>
<td></td>
<td>$279,756,638.00</td>
<td>105</td>
<td>$2,664,348.93</td>
</tr>
<tr>
<td><strong>Total AMI cost</strong></td>
<td></td>
<td><strong>$5,000,000,000.00</strong></td>
<td></td>
<td><strong>$50,590,230.66</strong></td>
</tr>
</tbody>
</table>

**Average cost per AMI energy meter = $167**  
**Average cost of 50,000 units of AMI energy meter with other costs = $550**

Source: [https://www.smartgrid.gov/recovery_act/deployment_status/ami_and_customer_systems](https://www.smartgrid.gov/recovery_act/deployment_status/ami_and_customer_systems)
Computerized Management Systems of Distribution Grid

Automated Feeder Switches (RCS) Installed and Operational

<table>
<thead>
<tr>
<th>Automated feeder switches</th>
<th>Quantity</th>
<th>Total cost incurred</th>
<th>Number of entities</th>
<th>Cost/entity</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated capacitors</td>
<td>10575</td>
<td>$117,902,992</td>
<td>45</td>
<td>$2,620,066.49</td>
<td>7%</td>
</tr>
<tr>
<td>Automated regulators</td>
<td>7983</td>
<td>$18,145,453</td>
<td>31</td>
<td>$585,337.19</td>
<td>1%</td>
</tr>
<tr>
<td>Feeder monitors</td>
<td>4441</td>
<td>$114,664,599</td>
<td>29</td>
<td>$3,953,951.69</td>
<td>10%</td>
</tr>
<tr>
<td>Substation monitor</td>
<td>19977</td>
<td>$124,530,744</td>
<td>19</td>
<td>$6,554,249.68</td>
<td>16%</td>
</tr>
<tr>
<td>Fault current limiter</td>
<td>0</td>
<td>$217,200</td>
<td>3</td>
<td>$72,420.00</td>
<td>0%</td>
</tr>
<tr>
<td>Distribution automation / substation communication networks</td>
<td></td>
<td>$259,948,222</td>
<td>59</td>
<td>$4,405,902.07</td>
<td>11%</td>
</tr>
<tr>
<td>Distribution management systems</td>
<td></td>
<td>$254,951,550</td>
<td>40</td>
<td>$6,373,788.75</td>
<td>16%</td>
</tr>
<tr>
<td>IT hardware, systems, and applications that enable distribution functionalities</td>
<td></td>
<td>$72,216,061</td>
<td>32</td>
<td>$2,256,751.91</td>
<td>6%</td>
</tr>
<tr>
<td>Other electric distribution automation related costs</td>
<td></td>
<td>$422,251,609</td>
<td>88</td>
<td>$4,798,313.74</td>
<td>12%</td>
</tr>
<tr>
<td>Total</td>
<td>8649</td>
<td>$429,506,107</td>
<td>50</td>
<td>$8,590,122.14</td>
<td>21%</td>
</tr>
</tbody>
</table>

Average cost per feeder switching device = $49,659.63
Average cost of 200 units of feeder switching device with other costs = $116,933

Source: https://www.smartgrid.gov/recovery_act/deployment_status/distribution
Reliability System States

• Emergency (E) Conditions
  – Frequent fault occurrence events
  – Single or 2 feeders de-energized within an hour

• Extreme Emergency (XE) Conditions
  – Massive system disruption during natural calamity
  – Rare event
  – Potentially multiple substation de-energized
Current Status of Distribution System

Diagram of a distribution system with various components including:
- Feeder Head (Root of Tree)
- Primary Network
- Secondary Network
- (Fictive) Bus
- Distribution Transformer
- Capacitor
- Industrial/Commercial Consumer
- Residential Consumer

The diagram illustrates the connectivity and flow of the distribution system, with arrows indicating the direction of current.
A Feeder with uDMS

- **Primary Network**: Feeder Head (Root of Tree)
- **Secondary Network**: Distribution Transformer, Capacitor, (Fictive) Bus, Distribution Transformer, Industrial/Commercial Consumer, Residential Consumer, Existing Meter, Existing Meter

- **(Fictive) Bus**
- **Distribution Transformer**
- **Capacitor**
- **Industrial/Commercial Consumer**
- **Residential Consumer**
- **Existing Meter**
uDMS + Microgrids

(Fictive) Bus
Distribution Transformer
Capacitor
Industrial/Commercial Consumer
Residential Consumer

Existing Meter
New AMI Meter

Primary Network
Secondary Network
uDMS + Microgrids + Distributed Generation
uDMS + DG + Microgrids + Tie Switches
• **38+ buildings**
• **11** buildings with IP-based meters (in **GRAY** color)
• **3** feeders
• **1** UPPCO injection
• **4** generating units
• Each building is connected **1** primary and **1** backup feeders
Mobile Device Setup for Pictorial Data Acquisition

Building 20: Mechanical Engineering & Engineering Mechanics (MEEM)

Electrical Room

Electromechanical Meter

Mobile Device for 208V Meter

Mobile Device for 480V Meter
Cyberinfrastructure of Campus Distribution System
Pictorial Data Extraction from Electromechanical Meters

Image Archive from the Cloud

Image Segmentation

Segmented Images for Preprocessing

Power Consumption Sample

- Sample Data
- per 15min average consumption
- per 30min average consumption
- per 1hour average consumption

Time (hour) vs. kW
**Image Data Extraction Algorithm**

**TABLE I**

<table>
<thead>
<tr>
<th>Angle (Degree)</th>
<th>Clockwise</th>
<th>Anticlockwise</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-36</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>36-72</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>72-108</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>108-144</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>144-180</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>180-216</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>216-252</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>252-288</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>288-324</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>324-360</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

\[
\text{Angle} = \tan^{-1}\left(\frac{\text{abs}(Y_{\text{mid}} - Y_{\text{center}})}{\text{abs}(X_{\text{mid}} - X_{\text{center}})}\right)
\]

*where* $X_{\text{mid}}$, $Y_{\text{mid}}$ and $X_{\text{center}}$, $Y_{\text{center}}$ *present* the coordinate of midpoint and center of circle respectively. Under normal conditions, the adjacent pointers in traditional electromechanical analog meters may have an inverse numeric plate. This is why there are two columns of numbers in Table I. After obtaining the deviation angle, we need to add corresponding angle according to pointer’s order and quadrant. E.g. anticlockwise and the second quadrant, here, the result should be Angle plus 90 degree.
MEEM Building Load Estimation for 208V and 480V Circuits Between March 22, 2014 and March 30, 2014
Existing Campus-Wide Metering Infrastructure: Smart Meters and Frequency Disturbance Recorder (FDR)

Existing Campus Microgrid and Metering Databases
Next Phase of Sensor/Actuator Infrastructure

Exploratory Expansion of Engineering Technology with Social and Computational Sciences

Next Phase of Cyberinfrastructure Addition
Load Estimation from Mobile Devices

Transportation Systems

Power Load Estimation

Human Mobility Dynamics

Power Load Dynamics

FB: Flurry: Google/Facebook account for 35% of U.S. mobile usage

- Google's (GOOG) services account for 18% of time spent by U.S. consumers on iOS/Android devices, and Facebook's (FB) services 17%, according to analytics firm Flurry's latest stats. Google's figure includes a 4% share for YouTube. Facebook's doesn't yet account for WhatsApp.
- Pressuring Google's usage share, web browsing activity to which search activity is tightly linked, accounts for only 14% of all time spent, down from 20% a year earlier. In addition, half that time is claimed by Apple's Safari, which carries steep search traffic acquisition costs for Google.
- Google is trying to address the browsing/app issue in part by making its search engine more useful for finding/discovering content within apps. But progress has been gradual.
- Nonetheless, as noted by Flurry, estimator estimates Google accounted for 40% of 2013 global mobile ad spend, well above Facebook's 17.5%. Contributing factors: Google's mobile search (and search ad) hegemony, a solid mobile display ad position, and Android's dominant position in most international markets.
- Flurry thinks Twitter (TWTR) has just a 1.5% usage share. It's worth noting comScore estimates Twitter's app was only used by 22.8% of U.S. smartphone users in January. 77.6% used Facebook's core app, and 27.5% Instagram. Five different Google apps were used by over 40% of users.
Utilization of Ubiquitous Devices

1. Smart meters (fully observable)
2. Mobile phone pictorial data (partially observable)
3. Human mobility dynamics with smartphone assisted GPS (load estimation)
System Observability Improvement

• Smart meters vs. mobile devices? Value stream for consumers, utility-owned companies, and other stakeholders?

• Older generation of mobile device
  – Pictorial datasets
  – That might require incentive for users to take pictures of the existing electromechanical devices

• Mobile devices of users can help to predict the flow of people around city and estimate energy consumptions
  – GPS assisted devices determine where the user would be
RELIABILITY
MTU and Houghton Community Distribution Grids
Bottleneck of the Power Grid

Massive disruption that de-energizes two 69-kV sub-transmission system will lead to Blackout!
Strategic Infrastructure Enhancement with 5 Major Milestones

- Case 1(a): Distribution feeders without uDMS (E)
- Case 1(b): Distribution feeders without uDMS (XE)
- Case 2(a): uDMS system without tie-switches (E)
- Case 2(b): uDMS system without tie-switches (XE)
- Case 3(a): uDMS with tie-switches (E)
- Case 3(b): uDMS with tie-switches (XE)
- Case 4(a): uDMS system with (tie-switches) + (DG+RCS) (E)
- Case 4(b): uDMS system with (tie-switches) + (DG+RCS) (XE)
- Case 5(a): uDMS system with (tie-switches) + (DG+RCS) + (microgrids) (E)
- Case 5(b): uDMS system with (tie-switches) + (DG+RCS) + (microgrids) (XE)

Most Distribution System Today

Ongoing Enhancement

Networked Microgrids
Determination of Sub-System Energization States

We use a graph $G = (V, E)$ to model the whole distribution system. The edges set $E$ represents the switches/breakers/reclosers, and the vertices set $V$ denotes the sub-system nodes connected by switches/breakers/reclosers. The following variables are defined:

- $M_i$: Incidence matrix representing system topology. If vertex $i$ is connected to edge $j$, then $M_i[i, j] = 1$, otherwise, 0.
- $V_r$: Row vector indicating the open/close status of switches/breakers/reclosers. If switch $i$ is closed, then $V_r[i] = 1$, otherwise, 0.
- $V_s$: Row vector indicating the location of power sources. If vertex $i$ is a substation-transformer or associated with a DG, then $V_s[i] = 1$, otherwise, 0.
- $V_e$: Row vector indicating energization status. If vertex $i$ is energized, then $V_e[i] = 1$, otherwise, 0.
- $M_a$: Adjacent matrix representing the system topology. If vertex $i$ is adjacent to vertex $j$, then $M_a[i, j] = 1$, otherwise, 0.
- $C$: Row vector indicating the number of customers associated with each sub-system node.

The algorithm 1 is developed to determine the energization status for each subsection of the distribution system.

**Algorithm 1**: Energization Status Computing Algorithm

1. $M_e \leftarrow M_i \cdot V_r^T$
2. $M_e \leftarrow M_i \cdot M_a^T$
3. Replace all diagonal elements of $M_e$ with 0
4. $N_{new} \leftarrow $ Number of 0 value elements in $V_s$
5. $N_{old} \leftarrow 0$
6. $V_{old} \leftarrow V_s$
7. while $N_{new} - N_{old} \neq 0$ do
8. $V_{old} \leftarrow V_s$
9. $V_e \leftarrow V_{old} \cdot M_a + V_{old}$
10. end while
11. Replace all non-zero elements in $V_e$ with 1
12. $N_{Total} = (1 - V_e) \cdot C^T$
13. return $V_e, N_{Total}$

![Image: Diagram of Substation A and B with Energization States and Incidence Matrix]
Case 1(a): Distribution Feeders Without uDMS (E)

Total Affected Customers = 3,000 customers
Outage time = 3 hours

SAIDI=0.75; SAIFI=0.25; CAIDI=3
Cost(Opps)=$6,642
Case 1(b): Distribution Feeders Without uDMS (XE)

Total Affected Customers = 12,000 customers
Outage time = 72 hours

SAIDI = 72; SAIFI = 1; CAIDI = 72
Cost(Opps) = $159,408
Case 2(a): uDMS Without Tie-Switches (E)

Total Affected Customers = 3,000 customers then 2,000 customers.
Outage time =3+3/60 hours

\[ \text{SAIDI}=0.5125; \; \text{SAIFI}=0.4167; \; \text{CAIDI}=1.23 \]
\[ \text{Cost(Opps)}=$2,723.2 \]
Case 2(b): uDMS Without Tie-Switches (XE)

Total Affected Customers = 12,000 customers
Outage time = 72 hours

SAIDI=72; SAIFI=1; CAIDI=72
Cost(Opps)=$159,408
RECONFIGURABILITY
Total Affected Customers = 3,000 customers then 1,000 customers.
Outage time =3 + 3/60 hours

SAIDI=0.2625; SAIFI=0.3333; CAIDI=0.7875
Cost(Opps)=$1,743.5
Case 3(b): uDMS System With Tie-Switches (XE)

Total Affected Customers = 12,000 customers
Outage time = 72 hours

SAIDI=72; SAIFI=1; CAIDI=72
Cost(Opps)=$159,408
Feeders Connected to Substations
Radial Network With Normally Closed Switches
Additional Lines and Remote Controllable Tie Switches
Loop/Parallel With Other Feeders
Loop Within A Feeder
Parallel and Loop Feeder
Parallel Feeders
ANCILLARY SERVICE
1. Existing generators can be utilized
   1. LV backup generator (building)
   2. MV backup generator (organization)
2. New site can be selected for MV distributed generators
3. Newly installed LV solar panel for each household can be a small incremental power generation
Total Affected Customers = 3,000 customers then 334 customers.
Outage time =3 + 3/60 hours

SAIDI=0.0960; SAIFI=0.2778; CAIDI=0.3455
Cost(Opps)=$765
Total Affected Customers = 12,000 customers then 8,000 customers. Outage time = \(\frac{3}{60} + 3 \times 24\) hours

\[\text{SAIDI} = 48.05; \text{SAIFI} = 1.6667; \text{CAIDI} = 28.83\]

Cost(Opps) = $63,830
Total Affected Customers = 3,000 customers then 300 customers.
Outage time =\(\frac{3}{60} + 3\) hours

\[
\text{SAIDI}=0.0875; \quad \text{SAIFI}=0.2750; \quad \text{CAIDI}=0.3182
\]
\[
\text{Cost(Opps)}=\$704.45
\]
Case 5(b): uDMS With (Tie-Switches) + (DG+RCS) + (Microgrids) (XE)

Total Affected Customers = 12,000 customers
Outage time = $\frac{3}{60} + 3 \times 24$ hours

SAIDI=40.8; SAIFI=0.5667; CAIDI=72
Cost(Opps)=$159,408
Clustering Algorithms Using Incomplete Information

• Metering infrastructure for each cluster
  – Generation/Load Meters
  – Number of customers per cluster
  – Generation and load balancing?

• Autonomous clusters
  – Switching actions to determine adequacy of each cluster
Conclusion and Future Work

• Ownership models may need to be transient with near-term, mid-term, and long-term implementation.
• MTU campus microgrid to study networked microgrid market driven value streams and technologies.
• Industrial park project is a consumer driven initiative that unique opportunities to test value stream and ownership models.
• Proposed method provides a collection of toolsets as a start for system planning.