Available Energy Assessment and Recovery in Water Distribution Systems

Ilker T. Telci
Graduate Student

MESL
February 7, 2012
Problem Definition

- Given a water distribution system (WDS) under operation:
  - Evaluation of available excess energy and
  - Optimal design of an energy recovery system for WDSs.

Micro hydropower plants:
- Number
- Location
- Capacity
- Operation schedule
Constraints of a Water Distribution System

- Demand Flows

- Pressure Heads
  - Excess: Leakage and structural damage
  - Too low: Operational problems

Dover Township WDS, Toms River, NJ
Study Area

- 8 pumping locations
- No pressure reducing valves

<table>
<thead>
<tr>
<th>Diameter (in)</th>
<th>Number of links</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>124</td>
</tr>
<tr>
<td>12</td>
<td>3434</td>
</tr>
<tr>
<td>10</td>
<td>52</td>
</tr>
<tr>
<td>8</td>
<td>6007</td>
</tr>
<tr>
<td>6</td>
<td>5361</td>
</tr>
<tr>
<td>4</td>
<td>510</td>
</tr>
<tr>
<td>2</td>
<td>560</td>
</tr>
<tr>
<td>Total</td>
<td>16048</td>
</tr>
</tbody>
</table>
Available Excess Energy

\[ \Delta E_i = \int \gamma q \Delta h dt = \gamma \sum_{t=1}^{t=T} q_i \Delta h_i \Delta t \] excess energy at demand node \( i \)

\[ EE = \sum_{i=1}^{N} \Delta E_i \] total excess energy in the system in the period from \( t = 1 \) to \( t = T \).

\( \Delta h \) = pressure head above 20 psi \( EE \approx 1.4 \text{GWh/year} \)

Total excess energy input by the pumps = 1.6 GWh/y

Excess Energy (GWh/y) at inlet pipes.
Pressure Violations

- Turbine at location 3.
- Full operation.

- Simulation Time: 1 Year
- One month is represented by 1 day of simulation.
- Time step = 1 hour
- Number of time steps $12 \times 24 = 288$
Turbine Operation Scheduling Problem

- A turbine is located at the pumping station 3.
  - Continuous operation causes pressure constraint violations.
- What is the optimal operation schedule for this turbine?

Optimization Problem:

Decision variable:
operation schedule

Objective:
Maximize the amount of energy recovered

such that
Minimum pressure in the network is above some limit.
Turbine Scheduling

**Turbine On:**
Bypass pipe closed, Turbine open

**Turbine Off:**
Bypass pipe open, Turbine closed
Turbine Operation Scheduling

Trial and error example

Pressure violations occur at $t=14$ hr.

Decision on the turbine at this time affects the pressure distributions at future times.

Pressure Distribution at $t=18h$ when turbine was closed only at $t=14h$

Pressure Distribution $t=18h$ for full turbine operation
Turbine Operation Scheduling Problem

Trial and error

- Turn off the turbine for the times when pressure constraint violations occur.

- Trial and error procedure did not work.

- The operational decision for a given time step affects the pressure distribution in the future time steps.

- Also trial and error procedure does not guarantee maximum energy recovery.

- Genetic algorithm is used to solve this optimization problem.
Turbine Operation Scheduling Problem
Genetic Algorithms

An individual’s chromosome

(1: Turbine is on; 0: Turbine is off)

Population
Type: Integer
Size: 100-500

Stopping Criteria
Generations: 200
Consecutive Stall Generations: 40
Fitness Function Tolerance: $10^{-8}$
Turbine Operation Scheduling Problem

Fitness Function

Dimensionless Time, \( T = \frac{t}{t_{sim}} = \frac{t}{288\text{ h}} \)

Dimensionless Energy, \( E = \frac{e_T}{e_o} = \frac{e_T}{17633.52\text{ kWh}} \)

Fitness Value = \( 1000(1 - T) - E \)

Minimize (Fitness Value):
Lower the fitness value, better the individual.

\( t \) : First pressure constraint violation time.
\( t_{sim} \) : Simulation time.
\( \Delta t \) : Time step.
\( P_t \) : Power generated by the turbine at time \( t \).
\( e_T \) : Energy produced at the turbine.
\( e_o \) : Energy of the flow passing through the turbine pipe without the turbine.

\[ e_o = \int_{0}^{t_{sim}} \gamma QH dt \]
Turbine Operation Scheduling Problem

Parameters

Turbine 1: NC150200

Turbine 2: NC100200

Pressure Limits:
1) $P_{\text{min}}=20$ psi
2) $P_{\text{min}}=15$ psi

Population size:
Different population sizes are tried.
Turbine Operation Scheduling Problem

Discarded, non-feasible results

Turbine: NC100200
Pressure Limit: 20 psi
Population size: 102

Best fitness value = 222.171
Pressure violation time = 224 hr
Turbine Operation Scheduling Problem
Feasible results

Turbine: NC100200
Pressure Limit: 20 psi
Population size: 300

Best fitness value: -0.0537
Pressure violation time = NA
### Turbine Operation Scheduling Problem

#### Results – Energy Budget for the System

*Energy used by the pumps without the turbine is 3,458,769 kWh/y*

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Pressure Limit</th>
<th>Population Size</th>
<th>Turb En. (kWh/y)</th>
<th>Pump En. Decrease * (kWh/y)</th>
<th>Net Energy Gain (kWh/y)</th>
<th>% Energy Production of the Turb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC150200</td>
<td>20</td>
<td>108</td>
<td>53368</td>
<td>54282</td>
<td>107650</td>
<td>49.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>152</td>
<td>59464</td>
<td>74586</td>
<td>134050</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>104</td>
<td>51882</td>
<td>124068</td>
<td>175950</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>152</td>
<td>74028</td>
<td>118442</td>
<td>192470</td>
<td>38.5</td>
</tr>
<tr>
<td>NC100200</td>
<td>20</td>
<td>300</td>
<td>28424</td>
<td>136726</td>
<td>165150</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>300</td>
<td>32331</td>
<td>148219</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>300</td>
<td>32331</td>
<td>180550</td>
<td></td>
</tr>
</tbody>
</table>
### Turbine Operation Scheduling Problem

**Results – Energy Budget for the Pumps**

<table>
<thead>
<tr>
<th>Pump</th>
<th>Energy Consumed by the Pumps</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Turbine</td>
<td>NC1000200 PmIn=20 ps</td>
</tr>
<tr>
<td></td>
<td>(kWh/y)</td>
<td>(kWh/y)</td>
</tr>
<tr>
<td>20003</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20004</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20005</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20011</td>
<td>54235.35</td>
<td>56516.6</td>
</tr>
<tr>
<td>20013</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20019</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20020</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20021</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20022</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20023</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20024</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20025</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PAI_1</td>
<td>328974.5</td>
<td>324952.2</td>
</tr>
<tr>
<td>PAI_2</td>
<td>64980.95</td>
<td>64313</td>
</tr>
<tr>
<td>PAI_3</td>
<td>90567.45</td>
<td>86574.35</td>
</tr>
<tr>
<td>PAI_4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PAI_5</td>
<td>197180.3</td>
<td>137891.9</td>
</tr>
<tr>
<td>PAI_6</td>
<td>374559.35</td>
<td>312279.5</td>
</tr>
<tr>
<td>PAI_7</td>
<td>100612.55</td>
<td>94381.7</td>
</tr>
<tr>
<td>PAI_8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PAI_9</td>
<td>117570.15</td>
<td>109802.95</td>
</tr>
<tr>
<td>PAI_10</td>
<td>302643.4</td>
<td>237031</td>
</tr>
<tr>
<td>PAI_11</td>
<td>204133.55</td>
<td>204651.85</td>
</tr>
<tr>
<td>PAI_12</td>
<td>368368.95</td>
<td>364390.45</td>
</tr>
<tr>
<td>PAI_13</td>
<td>126990.8</td>
<td>126363.4</td>
</tr>
<tr>
<td>PAI_14</td>
<td>14426.45</td>
<td>15216.85</td>
</tr>
<tr>
<td>PAI_15</td>
<td>315830.1</td>
<td>338213.45</td>
</tr>
<tr>
<td>PAI_16</td>
<td>34419.5</td>
<td>38095.05</td>
</tr>
<tr>
<td>PAI_17</td>
<td>505984.9</td>
<td>515511.65</td>
</tr>
<tr>
<td>PAI_18</td>
<td>248083.2</td>
<td>247604.85</td>
</tr>
<tr>
<td>PAI_19</td>
<td>9122.55</td>
<td>9122.55</td>
</tr>
<tr>
<td>PAI_20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total En. Consumed</td>
<td>3458867</td>
<td>3322792.1</td>
</tr>
</tbody>
</table>

**Increased energy consumption at the pump after turb.**

**Decreased energy consumption at the pump after turb.**

---

**Map:**

The image shows a map with various routes and labels, indicating the distribution of energy consumption across different areas. The map is color-coded to represent energy consumption levels, with different shades indicating varying levels of energy usage.
### Turbine Operation Scheduling Problem

#### Results – Order of magnitudes

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Pressure Limit</th>
<th>Population Size</th>
<th>Turb En. (kWh/y)</th>
<th>Pump En. Decrease * (kWh/y)</th>
<th>Net Energy Gain (kWh/y)</th>
<th>% Energy Production of the Turb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC150200</td>
<td>20</td>
<td>108</td>
<td>53368</td>
<td>54282</td>
<td>107650</td>
<td>49.6</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>152</td>
<td>59464</td>
<td>74586</td>
<td>134050</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>104</td>
<td>51882</td>
<td>124068</td>
<td>175950</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>152</td>
<td>74028</td>
<td>118442</td>
<td>192470</td>
<td>38.5</td>
</tr>
<tr>
<td>NC100200</td>
<td>20</td>
<td>300</td>
<td>28424</td>
<td>136726</td>
<td>165150</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>300</td>
<td>32331</td>
<td>148219</td>
<td>180550</td>
<td>17.9</td>
</tr>
</tbody>
</table>

*Energy used by the pumps without the turbine is 3,458,769 kWh/y

HDR feasibility study for Skagit county public utility district.

Giugni et. al. 2009
Turbine Operation Scheduling Problem

Two turbines at different locations

Chromosome length = 2 x 288 = 576
Turbine Operation Scheduling Problem
Two turbines at different locations – Results (No feasible solutions yet)

Both turbines NC150200
Pressure Limit: 20 psi
Population size :400

Best fitness value = 218.667
Pressure violation time = 225 hrs
Turbine Operation Scheduling Problem
Two turbines at different locations – Results (No feasible solutions yet)

Both turbines NC100200
Pressure Limit: 20 psi
Population size: 400

Best fitness value = 552.052
Pressure violation time = 129 hrs

Turbine at location 4 ← Current Best Individual → Turbine at location 3
Fitness function based on pressure

Pressure Violation Magnitude, \( P_v = \sum_{j=1}^{N_t} \sum_{i=1}^{N_n} \left[ \min \left( 0, P_{\text{min}} - P_{i,j} \right) \right]^2 \)

Fitness Value = \( 1000P_v - e_T \)

- \( i \): Node index.
- \( j \): Time index.
- \( N_t \): Number of time steps
- \( N_n \): Number of nodes
- \( p_{i,j} \): pressure at \( i^{th} \) node at time \( j \).
- \( P_{\text{min}} \): Minimum pressure constraint.
- \( e_T \): Energy produced at the turbine.

- This search was started approximately 1 month ago.
- This fitness function has not produced a best solution yet.
Next Steps

- Appropriate population size for 2-turbine cases is being analyzed.

- Preliminary results show that 3-turbine case will be computationally expensive.

- The network has been converted into a gravity driven system and similar analysis will be performed on this new network.
Thank you...