Intelligent System Strategies for Reconfiguration of Power Systems Including Distributed Generation and Intentional Islanding

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Outline of Presentation

• Development of Power Flow with Distributed Generations and Reconfiguration for Restoration of Unbalanced Distribution Systems

• Multi-Agent Based Reconfiguration of an Electric Propulsion System for All Electric-Ships

• Fast Reconfiguration Algorithm Development for Shipboard Power Systems

• Application of Genetic Algorithm for Reconfiguration of Shipboard Power System (SPS)

• Shipboard Power System Restoration Using Binary Particle Swarm Optimization
Development of Power Flow with Distributed Generations and Reconfiguration for Restoration of Unbalanced Distribution Systems

SARIKA KHUSHALANI
Overview

Distribution Substation

Residential and Industrial Loads

Distributed Generators

Normal State

Distribution Power Flow with DG

Data

Topology

DG Info

Backward/Forward

Node Voltages and Branch Currents

Outage State

Data

Topology

Fault Info

Optimization

Restored State

Restoration
Overview…

- DG Placement
- Contingency Analysis
- Developed Distribution Power Flow with DG
- Capacitor Placement
- Loss Reduction
- Volt/Var Control
- Restoration
Overview...

Generating Plant

Step-up Transformer

Circuit Breakers

Transmission System

Transformers in Transmission Substation

Distribution System

Feeder-1

SS

TS

Feeder-2

SS

Feeder-3

SS

Generating Plant

Step-up Transformer

Circuit Breakers

Transmission System

Transformers in Transmission Substation

Distribution System

Shipboard Distribution System

Terrestrial Distribution System
Power Flows

Distribution

- Three-Phase Analysis
- Unbalance Systems
- Mutually Coupled Lines
- Component Models
- Load Characteristics
- Large number of branches/nodes
- Ill Conditioned
- Single Source

Transmission

- Single-Phase Analysis
- Balance Systems
- Transposed Lines
- No Separate Components
- Constant Power
- Small number of branches/nodes
- Not Ill Conditioned
- Studied for Long
- Multiple Sources

Steady State
Reconfiguration And Restoration

- Changing the status of open/closed switches and altering topological structure of feeder is reconfiguration.

- Reconfiguration is mainly done for:
  - Loss reduction
  - Relieve overloads-Load Balancing
  - Volt/Var Support
  - Restoration

- Achieving new configuration after fault - Reconfiguration for restoration of supply.
Power Flow

- Fundamental calculations-steady state behavior-in power systems-power flow
- Power flow can be used to optimize circuit usage, voltage profile, kW and kVar losses, transformer tap settings, equipment limitations and economic planning
- It is a necessary first step in a stability study to establish power flows and machine power angles before the initiation of a disturbance
- The study is used for optimization of a power system and distribution automation, which needs repeated fast power flow solutions
Distributed Generation

- DG is small capacity generation installed on distribution side
- Portable, Flexible, Diversifiable, Controllable
- Reduces delivery cost and makes more efficient use of grid
- Avoid many hidden costs of centralization
- Environmental and social benefits
- Black start capability and spinning reserve
- Can cause reversal of current on some lines
- Can energize portion of the system separated from utility and creates an island
Restoration Problem...

- Multiobjective problem converted to single objective by introduction of weights
- Objectives are
  - Maximize the amount of power supplied
  - Priority to vital loads
  - Minimize number of switch operations
- Additionally the system should be kept radial.
- Tested on IEEE 13-node, IEEE 37-node and ship distribution test cases.
Model of SPS

Modeled as
**LINGO**

- LINGO is a tool for linear and nonlinear optimization, to formulate large problems concisely, solve them, and analyze the solution.
IEEE13-Node Feeder Data

### Spot Load Data

<table>
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<tr>
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# IEEE37-Node Feeder Data

## Segment Data

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## Spot Loads

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## Transformer Data

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## Underground Cable Configurations

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<td>1,000,000 AA, CN</td>
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<td>515</td>
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</table>
# Healy Data

## Bus Data

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Bus Type</th>
<th>Scheduled Voltage (pu)</th>
<th>Scheduled Generation, P (MW)</th>
<th>Scheduled Load, P (MW)</th>
<th>Scheduled Load, Q (MVAR)</th>
</tr>
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<tbody>
<tr>
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<td>YØ</td>
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<td>(slack)</td>
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## Branch Data (10 MVA base)

<table>
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<tr>
<th>Start Bus</th>
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<th>Branch Type</th>
<th>Branch Resistance (pu)</th>
<th>Branch Reactance (pu)</th>
<th>Transformer Tap</th>
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<tr>
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<td>T</td>
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<td>11</td>
<td>T</td>
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<td>12</td>
<td>L</td>
<td>0.000237</td>
<td>0.000408</td>
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</tr>
<tr>
<td>12</td>
<td>13</td>
<td>T</td>
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<td>0.321594</td>
<td>1.0</td>
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<td>0.321594</td>
<td>1.0</td>
</tr>
</tbody>
</table>

![Diagram of electrical system](image)

Ref – Dr. Baldwin
Formulation for SPS

Objective

Max \sum_{i \in L} W'_{VL} S'_{VL_i} + W'_{SVL} S_{SVL_i} + W'_{NVL} S_{NVL_i}

Subject to

AC Constraints

PG_i - PD_i = \sum_j V_j V_{ij} \cos(\theta_{ij} + \delta_j - \delta_i)

QG_i - QD_i = \sum_j V_j V_{ij} \sin(\theta_{ij} + \delta_j - \delta_i)

PG_i^{\min} \leq PG_i \leq PG_i^{\max}

QG_i^{\min} \leq QG_i \leq QG_i^{\max}

L_i = B_i * L_i^{\max} * SW_i

L_i \leq L_i^{\max} * SW_i

I_{ij} \leq I_{ij}^{\max}

V_i^{\min} \leq V_i \leq V_i^{\max}

\delta_i^{\min} \leq \delta_i \leq \delta_i^{\max}

SW_i = 1 \quad SW_j = 0 \quad SW_i + SW_j = 1

DC Constraints

\sum_i I_{in_i} = \sum_i I_{out_i} + L_i

V_i = V_j + I_{i_{-j}} * Z_{i_{-j}}

PG_i^{\min} \leq PG_i \leq PG_i^{\max}

L_i = B_i * L_i^{\max} * SW_i

L_i \leq L_i^{\max} * SW_i

I_{ij} \leq I_{ij}^{\max}

V_i^{\min} \leq V_i \leq V_i^{\max}

SW_i = 1 \quad SW_j = 0 \quad SW_i + SW_j = 1
Test Case-II

<table>
<thead>
<tr>
<th>Load P1/P2</th>
<th>Vital</th>
<th>Semi Vital</th>
<th>Non Vital at P1</th>
<th>Non Vital at P2</th>
<th>Switch position</th>
<th>Total Generation Gen</th>
<th>DG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load 1/2</td>
<td>0.5MW</td>
<td>1 MW</td>
<td>0.5MW</td>
<td>0.5MW</td>
<td>SW1 closed</td>
<td>6.87 MW</td>
<td>3.6 MW</td>
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<tr>
<td>Load 3/4</td>
<td>0.5MW</td>
<td>1 MW</td>
<td>0.5MW</td>
<td>0.5MW</td>
<td>SW4 closed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load 9/10</td>
<td>0.5MW</td>
<td>1 MW</td>
<td>0.5MW</td>
<td>0.5MW</td>
<td>SW9 closed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load 11/12</td>
<td>0.5MW</td>
<td>1 MW</td>
<td>0.5MW</td>
<td>0.5MW</td>
<td>SW11 closed</td>
<td></td>
<td></td>
</tr>
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</table>
Test Case-III

<table>
<thead>
<tr>
<th>Load P1/P2</th>
<th>Vital</th>
<th>Semi Vital</th>
<th>Non Vital at P1</th>
<th>Non Vital at P2</th>
<th>Switch position</th>
<th>Total Generation</th>
<th>DG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load 1/2</td>
<td>0.5MW</td>
<td>1 MW</td>
<td>0.0MW</td>
<td>0.0MW</td>
<td>SW1 closed</td>
<td>2.54 MW</td>
<td>4.00 MW</td>
</tr>
<tr>
<td>Load 3/4</td>
<td>0.5MW</td>
<td>1 MW</td>
<td>0.5MW</td>
<td>0.5MW</td>
<td>SW3 closed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load 9/10</td>
<td>0.5MW</td>
<td>0.76 MW</td>
<td>0.0MW</td>
<td>0.0MW</td>
<td>SW10 closed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load 11/12</td>
<td>0.5MW</td>
<td>0.74 MW</td>
<td>0.0MW</td>
<td>0.0MW</td>
<td>SW11 closed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Formulation for Terrestrial Systems

**Objective**

Max \( \sum_{i \in n} IL_i^Ph \)

**Subject to**

\[ V^Ph_{ij} = SW_{ij}(V^Ph_i - \sum_{m=a} Z^Phm_{ij}I^Ph_{ij} + slack^Ph_{ij}(1-SW_{ij})) \]

\[ \sum I^Ph_{ij} - \sum_{r} I^Ph_{jr} - IL_j^Ph = 0 \]

\[ I^Ph_{ij} = SW_{ij} * slackcurr^Ph_{ij} \]

\[ V^Ph_i \leq V^Ph_{i, min} \leq V^Ph_{i, max} \]

\[ I^Ph_{ij} \leq I^Ph_{ij, max} \]

**Constraints**

\[ IL_i^Ph = T_i^Ph * IL_{i, max}^Ph \]

\[ IL_i^Ph \leq IL_{i, max}^Ph \]

\[ I^Ph_{ij} \leq I^Ph_{ij, max} \]

\[ \sum_{br_i} SW_{br} \leq n-1 \]

\[ SW_{ij} + SW_{jk} = 1 \]

**Equality Constraints**

**Voltage Limits**

\[ V^Ph_{i, min} \leq V^Ph_{i} \leq V^Ph_{i, max} \]

**Source Constraints**

\[ I^Ph_{ij} \leq I^Ph_{ij, max} \]

**Load Limits**

**Line Limits**

**Switching Constraints**

**Constraints in LINGO**

\[ V^Ph_{ij} = SW_{ij}(V^Ph_i - \sum_{m=a} Z^Phm_{ij}I^Ph_{ij} + slack^Ph_{ij}(1-SW_{ij})) \]

\[ \sum I^Ph_{ij} - \sum_{r} I^Ph_{jr} - IL_j^Ph = 0 \]

\[ I^Ph_{ij} = SW_{ij} * slackcurr^Ph_{ij} \]

\[ V^Ph_i \leq V^Ph_{i, min} \leq V^Ph_{i, max} \]

\[ I^Ph_{ij} \leq I^Ph_{ij, max} \]

\[ IL_i^Ph = T_i^Ph * IL_{i, max}^Ph \]

\[ IL_i^Ph \leq IL_{i, max}^Ph \]

\[ I^Ph_{ij} \leq I^Ph_{ij, max} \]

\[ \sum_{br_i} SW_{br} \leq n-1 \]

\[ SW_{ij} + SW_{jk} = 1 \]
Algorithmic Complexity

- Two types of switching are considered
  - Switch Pairs:
    - **Shorter Time**: Less Combinations
    - Status of the switches not included in switch pairs are fixed
    - **No radiality constraint enforced**:
      - Only one of the switches in a switch pair can be ON/OFF
      - Fails to give restored system
  - Without Switch Pairs:
    - **Longer Time**: More Combinations
    - Defined status of the switches differs in IEEE13 and 37 node systems
      - Only switches corresponding to faulted section are set to zero and all other switch statuses are variable - $2^{14}$ combinations
      - Only switches corresponding to faulted section are set to zero and switch statuses in the de-energized area are variable – $2^6$ to $2^{39}$ combinations
    - **Radiality constraint enforced**
Case 1-Fault at 2-3
Case 2-Fault at 7-8
Case 2 - Fault at 7-8

Cannot be closed
Case 1-Fault at 5-6 and 28-29
Case 2-Fault at 5-6 and 28-29
Case 2 - Fault at 5-6 and 28-29
Case 2 - Fault at 5-6 and 28-29
Case 2-Fault at 5-6 and 28-29
Multi-Agent Based Reconfiguration of an Electric Propulsion System for All Electric-Ships

Qiuli Yu
Mississippi State University
Introduction

• **Agent**
  – A software (or hardware) entity
  – Can sense changes in its environment
  – Autonomously reacts to changes in the environment
  – Three key attributes: reactivity, pro-activeness, and social-ability

• **Multi-Agent Systems (MAS)**
  – A loosely coupled network composed of several agents
  – Agents interact with their environments
  – Agents communicate with each other
  – Whole problem is beyond the individual capabilities or knowledge of each agent
**Introduction**

- **Characteristics of a MAS**
  - Each agent has a limited viewpoint into the whole system
  - Control of the whole system is distributed and there is no system global control
  - Data are decentralized
  - Each agent is running asynchronously

- **MAS Applications in Power Systems**
MAS Design and Implementation

Topology of the MAS

- For every component, an agent and a circuit breaker are associated with it
- The MAS has the same topology as the propulsion system
- An agent can only communicate with its neighboring agents
- No global control exists in the MAS
- Two propulsion systems (primary and auxiliary)—to increase survivability
- At one time only one propulsion system is connected to system
Bus Agent → Transformer Agent → Rectifier Agent → Inverter Agent → Motor Agent

Fault signal

Bus Agent → Transformer Agent → Rectifier Agent → Inverter Agent → Motor Agent

Auxiliary System

Switch-on signal
MAS Design and Implementation

Reconfiguration Algorithm

• Assume that a fault happen in the primary propulsion system

• The protection system
  – detect the fault
  – send a fault signal to the corresponding agent

• The corresponding agent acts

• The primary bus agent acts

• The auxiliary bus agent acts

• The auxiliary propulsion system connects into the common bus (power sources) and begins to work
Motor agent is acting

Switch on
Switch off with fault
Open without fault
Agents in primary propulsion are acting
Agents in auxiliary propulsion are acting
MAS Design and Implementation

Reconfiguration Characteristic

• After reconfiguration
  – Old auxiliary propulsion system $\rightarrow$ new primary propulsion system
  – Old primary propulsion system $\rightarrow$ new auxiliary propulsion system

• Signal flow direction
  – Fault signal flows according to the upstream direction
  – “Switch-on” signal flows according to the downstream direction

• The primary bus agent and the auxiliary bus agent are mutually exclusive
  – At one time, only one bus agent can normally work
  – Another bus agent has to be set up to be open, and vice versa
MAS Design and Implementation

Agent Design

• Three different agents
  – terminal agent
  – intermediate agent
  – bus agent

• Terminal agent – has only one neighboring agent (upstream agent), such as motor agent

• Intermediate agent – has neighboring agents in both upstream and downstream sides, such as the transformer agent, rectifier agent, and inverter agent

• Bus agent – has three sides of neighboring agents: upstream neighboring agents, downstream neighboring agents, and neighboring bus agents
MAS Design and Implementation

Agents
- Bus Agent
  - Bus Agent P
    - Receive signal from downstream
    - Send signal to auxiliary bus
  - Bus Agent A
    - Receive signal from primary bus
    - Send signal to downstream
- Intermediate Agent
  - Intermediate Agent P
    - Receive signal from downstream
    - Send signal to upstream
  - Intermediate Agent A
    - Receive signal from upstream
    - Send signal to downstream
- Terminal Agent
  - Terminal Agent P
    - Send signal to upstream
  - Terminal Agent A
    - Receive signal from upstream

P: Primary propulsion system
A: Auxiliary propulsion system
MAS Design and Implementation

• Intermediate agent includes more behaviors
• Three inputs:
  – Name of its upstream agent
  – Name of its downstream agent
  – Working condition (fault status)
• Three working conditions:
  – Normal (without fault and in primary propulsion system)
  – Fault
  – Open (without fault and in auxiliary propulsion system)
• Three behaviors:
  – Cyclic behavior – communication with downstream agent
  – Ticker behavior – communication with upstream agent
  – One-shot behavior – sending signal
Begin

Include class library

Get inputs by Reading arguments

Register itself In the yellow page

Communication with downstream agent

Communication with upstream agent

Receive fault flag of downstream agent

Fault?

Yes

Change its own fault flag to fault

Print fault flag

Continue

No

Fault?

Yes

No

Cyclic behavior

Ticker behavior

One-shot behavior

Send fault flag to upstream agent

Send fault flag to upstream agent

i = i + 1

Read propulsion agent

Yes

i = 0

No

Find upstream agents?

Yes

No

Update list of Propulsion agents

10 second?

Yes

No

Continue

i = i + 1

End of flowchart
Simulation and Results

C>java jade.Boot

Bus: BusAgent(Bus1 Normal Open Transformer)
Transformer: IntermediateAgent(Bus Rectifier Normal)
Rectifier: IntermediateAgent(Transformer Inverter Normal)
Inverter: IntermediateAgent(Rectifier Motor Normal)
Motor: TerminalAgent(Inverter Fault)
Bus1: BusAgent(Bus Open Normal Transformer1)
Transformer1: IntermediateAgent(Bus1 Rectifier1 Open)
Rectifier1: IntermediateAgent(Transformer1 Inverter1 Open)
Inverter1: IntermediateAgent(Rectifier1 Motor1 Open)
Motor1: TerminalAgent(Inverter1 Open)

Agents get their start-up inputs from the command line
Final working status of every agent in the MAS

- **Switch on**
- **Switch off with fault**
- **Open without fault**
Key References

Fast Reconfiguration Algorithm Development for Shipboard Power Systems

Yan Huang
Mississippi State University
Research Goals

- Develop fast reconfiguration algorithms based on the zone-based differential fault detection scheme:
  - Apply graph theory in shipboard power system topology representation
  - Develop computationally-efficient algorithms to find post-fault configuration meeting designated objectives
Fast Reconfiguration

- Reconfiguration: The process of altering the topological structures of power system by changing the status (open/closed) of connection devices such as circuit breakers and switches.

- Fast reconfiguration
  - Right after fault is isolated and before loads are de-energized (a few power cycles).
  - As a part of protection system which is continuously monitoring the system power flow and system topology information.
Fast Reconfiguration Objectives

- Maintain power generation-load balance to improve the stability of the remaining system after fault detection and isolation.
- Supply power to unaffected loads to the maximum extent
- Reduce the loss of high priority loads to the minimum through load shedding, if necessary
Shipboard Power Systems Representation Using Graph Theory

Why use graph theory:
1. Simplify system representation
2. Visualize power system topology and operations
3. Represent all system topology changes as graph operations
Four-generator Power System
System Representation as a Directed Graph

<table>
<thead>
<tr>
<th>Components In Power System</th>
<th>Elements In Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator, Bus bar, Cable, Load</td>
<td>Vertex</td>
</tr>
<tr>
<td>Circuit Breaker</td>
<td>Edge</td>
</tr>
</tbody>
</table>

(*Edge direction is decided by the CT connection)
Numerical Representation of Graph

Bus Edge-to-Vertex Matrix (8*18 matrix)

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<th>BK#</th>
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<th>3</th>
<th>4</th>
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<th>6</th>
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<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
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<td>+1</td>
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<td>0</td>
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<td>+1</td>
<td>+1</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>Bus5</td>
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<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
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<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>Bus7</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Bus8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
</tr>
</tbody>
</table>

BRK Status

\[
\text{BRK\_ST} = [1\ 1\ 1\ 1\ 0\ 1\ 1\ 0\ 0\ 1\ 1\ 1\ 1\ 0\ 1\ 1\ 1\ 1]\;
\]

Present System Connectivity Matrix

\[
E_{\text{to\_V\_Updated}}(i,j) = E_{\text{to\_V}}(i,j) \times \text{BRK\_ST}(j)
\]
Numerical Representation of Graph Cont.

Breaker Type (1. Generator BRK, 2. Tie BRK, 3. Load BRK)

<table>
<thead>
<tr>
<th>BK#</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Instantaneous Power Flow through breakers

\[ \text{BRK\_Flow} = [23, 2, 20, 20, 0, 2, 2, 0, 0, 22, 2, 20, 20, 0, 2, 1, -1, 1]; \text{ (MW)} \]

Generator Capacity

\[ \text{GEN\_CAPACITY} = [1, 36; 7, 4; 10, 36; 16, 4]; \]

Load Priority (larger number means higher priority)

\[ \text{Load\_Priority} = [2, 1; 4, 2; 6, 1; 11, 2; 13, 2; 15, 2]; \]
Power Flow Balance for Each Bus

- Replace the real time power flow from generator with Generator capacity
- Under normal condition:
  - Individual Vertex Power sum \( \geq 0 \)
  - For example, \( V1\_Power\_Sum = e1 - e2 - e3 - e18 = 23\text{MW} \)
Power Flow Balance for Each Bus Cont.

For Example, if the generator is tripped

Before Fault

\[ V1_{\text{Power}} = e1 - e2 - e3 - e18 = 23 \text{ MW} \]

After Fault Isolation (G1 is tripped off the system)

\[ V1_{\text{Power}} = - e2 - e3 - e18 = -13 \text{ MW} \]

\[ \text{Zone Balance} = [EtoV_{\text{Updated}}] \times [BRK_{\text{Flow}_{\text{Updated}}}]^T \]
Basic Reconfiguration Procedure

- Triggered when any unfaulted bus has negative power balance. For multiple vertexes with negative power sum, vertex with the largest power deficit is selected as the start node for search.
- Breadth-first search is used to find the path of vertexes, which can supply power to the negative power bus.
- Stop search when a path of vertexes with balanced power is found or there is not such a path exist.
- If there is not such a path, load will be shed according to its priority until power balance is achieved.
Incident matrix, generator capacity, load priority, breaker status vector, and latched power flow

Detect a fault?

No

Update breaker status vector, connectivity vector, zone power balance

Yes

Any zone with negative power balance?

No

Yes

Find a path with positive power balance?

Yes

No

Shed low priority load along the path to enforce non-negative power balance

Breaker operation output

end
Load Shedding Process Sequence

1. Any path with negative power balance, find all loads connected to this path

2. Shed the load with capacity more than the total generator capacity in this path

3. Update the path power balance, if any load shed

4. Path with negative power balance?
   - No
   - Yes

   If Yes:
   - Start from low priority load(s). Among the same priority loads, check all possible load combinations and find the combination with the minimum capacity that is bigger than the path power deficit

   If Yes:
   - Shed the load(s) of the particular load combination

End
Test Case Model 1

Model 1. Non-symmetrical system with three generators
## Test Results for Model 1

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Faulted Bus Number</th>
<th>Negative Power Bus</th>
<th>Possible Power Supply Bus Sequence</th>
<th>Possible Load Shedding</th>
<th>Break Reconfiguration (Open/Close)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>B1 (G1)</td>
<td>B2 B4</td>
<td>B2-B3 B4-B5-B6</td>
<td>No</td>
<td>BK4 (C)</td>
</tr>
<tr>
<td>Case 2</td>
<td>B3 (G2)</td>
<td>B2</td>
<td>B2-B1-B4-B5-B6</td>
<td>Yes (L1, L2, L3)</td>
<td>BK3, 5, 8 (O) BK4 (C)</td>
</tr>
<tr>
<td>Case 3</td>
<td>B6 (G3)</td>
<td>B5</td>
<td>B5-B4-B1-B2-B3</td>
<td>No</td>
<td>BK4 (C)</td>
</tr>
<tr>
<td>Case 4</td>
<td>B1, B3 (G1, G2)</td>
<td>B2 B4</td>
<td>No B4-B5-B6</td>
<td>No</td>
<td>BK4(C)</td>
</tr>
<tr>
<td>Case 5</td>
<td>B1, B6 (G1, G3)</td>
<td>B2 B5 B4</td>
<td>B2-B3 No No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 6</td>
<td>B3, B6 (G2, G3)</td>
<td>B2 B5</td>
<td>B2-B1-B4-B5 B5-B4-B1-B2</td>
<td>Yes (L5)</td>
<td>BK11 (O) BK4 (C)</td>
</tr>
</tbody>
</table>

(Fault at different locations)
Test Case Model 2

Four-generator system with no-symmetrical generation contribution
## Test Results for Model 2

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Faulted Bus Number</th>
<th>Negative Power Bus</th>
<th>Possible Power Supply Bus Sequence</th>
<th>Possible Load Shedding</th>
<th>Break Reconfiguration (Open/Close)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 7</td>
<td>B1 (G1)</td>
<td>B2</td>
<td>B2-B3-B4</td>
<td>No</td>
<td>BK5, 8, 9 (C)</td>
</tr>
<tr>
<td>Case 8</td>
<td>B3 (G2)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 9</td>
<td>B5 (G3)</td>
<td>B6</td>
<td>B6-B7-B8-B1</td>
<td>No</td>
<td>BK14 (C)</td>
</tr>
<tr>
<td>Case 10</td>
<td>B7 (G4)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 11</td>
<td>B1, B3 (G1, G2)</td>
<td>B2</td>
<td>No</td>
<td>No</td>
<td>BK14 (C)</td>
</tr>
<tr>
<td>Case 12</td>
<td>B1, B5 (G1, G3)</td>
<td>B6</td>
<td>B6-B7</td>
<td>Yes</td>
<td>BK4, 13,15 (O) BK5, 14 (C)</td>
</tr>
<tr>
<td>Case 13</td>
<td>B3, B7 (G2, G4)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 14</td>
<td>B5, B7 (G3, G4)</td>
<td>B6</td>
<td>No Possible Generation</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

(Fault at different locations)
Test Case Model 3

Four-generator system with symmetrical generation contribution
# Test Results for Model 3

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Faulted Bus Number</th>
<th>Negative Power Bus</th>
<th>Possible Power Supply Bus Sequence</th>
<th>Possible Load Shedding</th>
<th>Break Reconfiguration (Open/Close)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 15</td>
<td>B1 (G1)</td>
<td>B2</td>
<td>B2-B3-B4-B5-B6-B7-B8</td>
<td>Yes (L2)</td>
<td>BK4 (O) BK5, 8, 9, 14, 17 (C)</td>
</tr>
<tr>
<td>Case 16</td>
<td>B3 (G2)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 17</td>
<td>B5 (G3)</td>
<td>B6</td>
<td>B6-B7-B8-B1-B2-B3-B4</td>
<td>Yes (L5)</td>
<td>BK13 (O) BK 5, 8, 14, 17, 18 (C)</td>
</tr>
<tr>
<td>Case 18</td>
<td>B7 (G4)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 19</td>
<td>B1, B3 (G1, G2)</td>
<td>B2</td>
<td>No Possible Generation</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 20</td>
<td>B1, B5 (G1, G3)</td>
<td>B6</td>
<td>B6-B7 B2-B3</td>
<td>Yes (L2, L5)</td>
<td>BK4, 13 (O) BK 5, 14 (C)</td>
</tr>
<tr>
<td>Case 21</td>
<td>B3, B7 (G2, G4)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Case 22</td>
<td>B5, B7 (G3, G4)</td>
<td>B6</td>
<td>No Possible Generation</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

(Fault at different locations)
Test Case Model 4

Larger power system with distributed generators
## Test Results for Model 4

### Fault Results for Model 4

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Faulted Bus Number</th>
<th>Negative Power Bus</th>
<th>Possible Power Supply Bus Sequence</th>
<th>Possible Load Shedding</th>
<th>Break Reconfiguration (Open/Close)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 23</td>
<td>B1 (G1)</td>
<td>B2, B13</td>
<td>B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13</td>
<td>Yes (L2,L4,L5,L6,L7,L8,L10,L11,L12,L13)</td>
<td>BK4, 9, 12, 14, 19, 24, 27, 29, 33, 34 (O) BK7, 15, 16, 17, 23, 28, 30 (C)</td>
</tr>
<tr>
<td>Case 24</td>
<td>B4 (G2)</td>
<td>B3, B5</td>
<td>B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5</td>
<td>Yes (L7)</td>
<td>BK14 (O) BK7, 15, 16, 17, 23, 28, 30 (C)</td>
</tr>
<tr>
<td>Case 25</td>
<td>B8 (G3)</td>
<td>B9</td>
<td>B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7</td>
<td>Yes (L2,L4,L6,L7,L8,L10,L11,L12,L13)</td>
<td>BK4, 9, 14, 27, 29, 34 (O) BK7, 15, 16, 23, 28, 30 (C)</td>
</tr>
<tr>
<td>Case 26</td>
<td>B9 (G4)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case 27</td>
<td>B10 (G5)</td>
<td>B11</td>
<td>B11-B12-B13-B1</td>
<td>No</td>
<td>BK 30 (C)</td>
</tr>
<tr>
<td>Case 28</td>
<td>B1, B4 (G1, G2)</td>
<td>B2, B3, B5, B13</td>
<td>B2-B3-B5-B6-B7-B13-B12-B11-B10</td>
<td>Yes (L2,L3)</td>
<td>BK4, 6 (O) BK7, 15, 16, 28, 30 (C)</td>
</tr>
<tr>
<td>Case 29</td>
<td>B1, B8 (G1, G3)</td>
<td>B2, B9, B13</td>
<td>B2-B3-B4-B5-B6-B7-B9-B10-B11-B12-B13</td>
<td>Y (L3,L9)</td>
<td>BK6, 21 (O) BK 7, 15, 16, 23, 28, 30 (C)</td>
</tr>
<tr>
<td>Case 30</td>
<td>B4, B10 (G2, G5)</td>
<td>B3, B5, B11</td>
<td>B3-B2-B1-B13-B12-B11-B5-B6-B7-B8</td>
<td>Y (L3)</td>
<td>BK6 (O) BK7, 15, 16, 28, 30 (C)</td>
</tr>
<tr>
<td>Case 31</td>
<td>B8, B10 (G3, G5)</td>
<td>B9, B11</td>
<td>B11-B12-B13-B1</td>
<td>No</td>
<td>BK 28, 30 (C)</td>
</tr>
</tbody>
</table>

(Fault at different locations)
Test Results Summary

- Test results accuracy was verified through hand-checking.
- The fast reconfiguration algorithm accurately enforces the power generation-load balance of the un-faulted part of the power system.
- Load shedding results meet the defined rules.
Key References


Application of Genetic Algorithm for Reconfiguration of Shipboard Power System (SPS)

Koteshwar R. Padamati
GA for the reconfiguration problem

- The genetic algorithm is a stochastic method designed to find global optima for a wide range of problems.

- The procedure can be applied to broad range of objective function and topology, making it useful for functions that are highly nonlinear.

- Since the reconfiguration problem is highly nonlinear over a domain of discrete variables, the genetic algorithm is a good candidate procedure.
Problem Formulation

- The objective function considered here is to maximize the total number of loads supplied in the formed island after a fault is encountered.
- The loads are classified as non-vital, semi-vital and vital loads. These loads (MW) are multiplied by a weighting factor.
- The objective function is defined as follows:

Maximize \[ L_1 + L_2 + L_3 + \ldots + L_n \]

Subject to \[ P_{gen} \geq P_{load} \]
Fitness function is defined as:

\[
F = W_M \left[ x(1)L_1 + x(2)L_2 + x(3)L_3 + \ldots + x(n)L_n \right] + W_p \left[ P_1 x(1)L_1 + P_2 x(2)L_2 + P_3 x(3)L_3 + \ldots + P_n x(n)L_n \right]
\]

Where,

- ‘\(x'\) is the switch configuration.
- \(x(i) = 1\) indicates breaker closed for \(i = 1, 2, \ldots, n\).
- \(x(i) = 0\) indicates breaker open for \(i = 1, 2, \ldots, n\).
- \(L_1, L_2, L_3, \ldots, L_n\) are load values (MW).
- \(P_1, P_2, P_3, \ldots, P_n\) are priorities of loads.
- \(W_M\) is weighting factor for load selection based on magnitude.
- \(W_P\) is weighting factor for load selection based on priority.
Genetic Algorithm-Terminology

- Each possible solution $x$ is referred to as a chromosome. For the reconfiguration problem, $x$ refers to the switch configuration.
- The content or value of the chromosome will be referred to as its genetic code. For instance, the genetic code of $x$ can be $[0,1,0,1,0,0]$.
- Each position in the chromosome $x$ is referred to as a gene, and its particular value, 0 or 1, is an allele.
- The population consists of a set of $x$ values.
- The term generation indicates a population at a specific point in time.
Genetic Algorithm-Flow Chart

Begin

Initialize population

gen = 0

Evaluation

Assign Fitness

Termination Condition met?

Yes
Stop

No
Reproduction

Crossover

Mutation

gen = gen+1
Reconfiguration Process

- EtoV matrix, BRK Status, Power flow, Gen. Cap., Load Priority

  - Detect a fault?
    - Yes
      - Update BRK Status, Connectivity Vector, Zone power balance
      - Any zone with negative power balance?
        - Yes
          - Find a path with positive power balance?
            - Yes
              - Reconfigure the system using a genetic algorithm
            - No
              - Breaker operation output
        - No
          - Reconfigure the system using a genetic algorithm
    - No
      - Breaker operation output
        - End
Reconfiguration Process Cont’d...

- Triggered when any unfaulted bus has negative power balance. For multiple vertices with negative power balance, vertex with the largest power deficit is selected as the start node for search.
- Breadth-first search is used to find the path of vertices, which can supply power to the negative power bus.
- Stop search when a path of vertices with balanced power is found or no path exists.
- Extract the loads and generators along the path and use genetic algorithm for finding the post-fault optimal configuration.
Results

8-bus Power System
## Results Cont’d…

<table>
<thead>
<tr>
<th>Test case</th>
<th>Faulted Bus Number</th>
<th>Negative power bus</th>
<th>Possible power supply path</th>
<th>Load Shedding</th>
<th>Breaker reconfiguration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>B1</td>
<td>B2</td>
<td>B2-B3-B4-B5-B6-B7</td>
<td>Yes (L4)</td>
<td>BK 11 (O) BK 5, 8, 9, 14 (C)</td>
</tr>
<tr>
<td>Case2</td>
<td>B3</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case3</td>
<td>B5</td>
<td>B6</td>
<td>B6-B7-B8-B1-B2-B3-B4</td>
<td>Yes (L1)</td>
<td>BK 2 (O) BK 14, 5,8 (C)</td>
</tr>
<tr>
<td>Case4</td>
<td>B7</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case5</td>
<td>B1, B3</td>
<td>B2</td>
<td>No possible generation</td>
<td>Yes L2</td>
<td>BK4(O)</td>
</tr>
<tr>
<td>Case6</td>
<td>B1, B5</td>
<td>B6, B2</td>
<td>B6-B7-B8-B2-B3-B4</td>
<td>Yes L2, L5</td>
<td>BK 4, 13(O) BK 5, 8, 14 (C)</td>
</tr>
<tr>
<td>Case7</td>
<td>B3, B7</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case8</td>
<td>B5, B7</td>
<td>B6</td>
<td>No possible generation</td>
<td>Yes (L5)</td>
<td>BK 13 (O)</td>
</tr>
</tbody>
</table>
Key References


Shipboard Power System Restoration Using Binary Particle Swarm Optimization

Nikhil Kumar
Summer Internship at Mississippi State University

Department of Electrical Engineering
Institute of Technology
Banaras Hindu University
Varanasi, India 221005
What is PSO?

- Relatively recent heuristic search method proposed by Kennedy and Eberhart in 1995
  - Stochastic optimization Technique
  - Inspired by the swarm behavior of birds in flight
  - Particles communicate their best information among each other
  - Adjustment of particles’ trajectory according to its own flying experience as well as that of the swarm
  - Particles never die, rather they get updated
PSO algorithm

- Potential solution as a particle in a d-space having coordinates $x_i = (x_{i1}, x_{i2}, \ldots, x_{id})$
  - Position updated by adding the velocity to it.
- Velocity update, position update, and fitness calculations repeat until a desired convergence criterion
- Algorithm stops when maximum change in best fitness becomes smaller than specified tolerance or maximum iteration is reached
PSO algorithm …

- Set population size, maximum number of iterations and stopping criterion
- Randomly select feasible solutions $x_{id}$
- Compute $p_{id}$ (best previous position of particle $x_{id}$) from each $x_{id}$
- Compute $p_{gd}$ (the position of the best particle among all)
- Now calculate velocity of each particle as:
  $$v_{id} = w*v_{id} + c1*rand*(p_{id} - x_{id}) + c2*rand*(p_{gd} - x_{id})$$
PSO algorithm …

- Update $x_{id}$ by adding the velocity

$$x_{id} = x_{id} + v_{id}$$

- Calculate fitness function using new $x_{id}$
PSO algorithm …

- If the fitness value of particle i is better than the previous particle, the value is set to i otherwise it remains same as the previous

- If the best $p_{id}$ is better than $p_g$, the value is set to $p_g$

- Continue until maximum iteration number or stopping criteria is achieved

- Particle $p_g$ is the best optimal solution
PSO algorithm …Swarm Movement
Parameters of PSO

- Current velocity, particle’s own memory, and swarm influence incorporated via a summation approach in the equation with three weight factors

- Balance among these factors determines the balance between local and global searching capability

- Large inertia weight corresponds to global search and small inertia weight results in fine tuned local search

- Operator *rand* to ensure good coverage of the design space and avoid entrapment in local optima
PSO algorithm … Penalty Function

- Equality and inequality constraints are included in the objective via penalty function.

- Transformation of constrained problem into an unconstrained problem can be stated as:

\[
\min \ T(x) = f(x) + r_k P(x)
\]

Where

- \( f(x) \): objective function of the constrained problem
- \( r_k \): A scalar denoted as the penalty parameter
- \( P(x) \): function imposing penalties for infeasibility
- \( T(x) \): (pseudo) transformed unconstrained objective
To ensure faster convergence of the algorithm

\[ v_i^{k+1} = k \left[ w_i v_i^k + c_1 \times \text{rand} \times \frac{(pbest_i - x_i^k)}{\Delta t} \right. \]
\[ \left. + c_2 \times \text{rand} \times \frac{(gbest_i - x_i^k)}{\Delta t} \right] \]

\[ k = \frac{2}{2 - \varphi - \sqrt{\varphi^2 - 4\varphi}} \]

Where \( q = c_1 + c_2, q > 4 \)
Binary PSO

- For switching function
  - Switches need to be opened or closed
  - Particles must take values either 0 or 1 only
  - Particles constrained by converting velocity to probability
    \[
    v_{id} = w \cdot v_{id} + c1 \cdot \text{rand} \cdot (p_{id} - x_{id}) + c2 \cdot \text{rand} \cdot (p_{gd} - x_{id})
    \]
    \[
    \text{if } (\text{rand} < S(v_{id}))
    \]
    \[
    \text{then } x_{id} = 1
    \]
    \[
    \text{else } x_{id} = 0
    \]
    \[
    S(x) = 1/(1 + e^{x})
    \]
  - Once updated \(x_{id}\)’s are known, same procedure applies.
Find the solution to keep loads such that stability and reliability of SPS can be enhanced

Objective of this optimization problem can be expressed as:

\[
\text{Fitness} = w_1(L_1 + L_2 \ldots L_n) + w_2(p_1L_1 + p_2L_2 \ldots p_nL_n)
\]

Subject to \( P_{\text{gen}} \geq P_{\text{load}} \)

- \( L_1, L_2 \ldots L_n \) shows load magnitude values
- \( p_1, p_2 \ldots p_n \) shows load priority values
- \( w_1 \) & \( w_2 \) shows the weighing factor for load selection based on load magnitude and load priority respectively
Restoration Process

Incident matrix, generator capacity, load priority, breaker status vector, and latched power flow

Detect a fault?

Yes

Update breaker status vector, connectivity vector, zone power balance

No

Any zone with negative power balance

Yes

Find a path with positive power balance?

No

Apply PSO separately to all formed islands and shed loads

Yes

Breaker operation output

end
## Simulation Results

<table>
<thead>
<tr>
<th>Faulted bus number</th>
<th>-ve Power bus</th>
<th>Power supply bus sequence</th>
<th>Load shed</th>
<th>Breaker reconfiguration (open/close)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1(G1)</td>
<td>B2</td>
<td>B2-B3-B4-B5-B6-B7-B8</td>
<td>L2</td>
<td>BK4(O) BK5,8,9,14,17 (C)</td>
</tr>
<tr>
<td>B3(G2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B5(G3)</td>
<td>B6</td>
<td>B6-B7-B8-B1-B2-B3-B4</td>
<td>L7</td>
<td>BK13(O) BK5, 8,14,17,18(C)</td>
</tr>
<tr>
<td>B7(G4)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B1(G1)  B3(G2)</td>
<td>B2</td>
<td>No generation</td>
<td>L2</td>
<td>-</td>
</tr>
<tr>
<td>B1(G1)  B5(G3)</td>
<td>B6  B2</td>
<td>B6-B7-B2-B3-B4</td>
<td>L2  L5</td>
<td>BK4,13(O) BK5,14(C)</td>
</tr>
<tr>
<td>B3(G2)  B7(G4)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B5(G3)  B7(G4)</td>
<td>B6</td>
<td>No generation</td>
<td>L5</td>
<td>-</td>
</tr>
</tbody>
</table>
Summary

- Presentation discussed various opportunities related to reconfiguration using optimization and intelligent systems.
- Intelligent systems techniques discussed are:
  - Multi-agent systems
  - Genetic Algorithms
  - Particle Swarm Optimization
Thanks for opportunity and for staying late 😊