Attack-resilient Control for Optimal Protection Coordination of Microgrid

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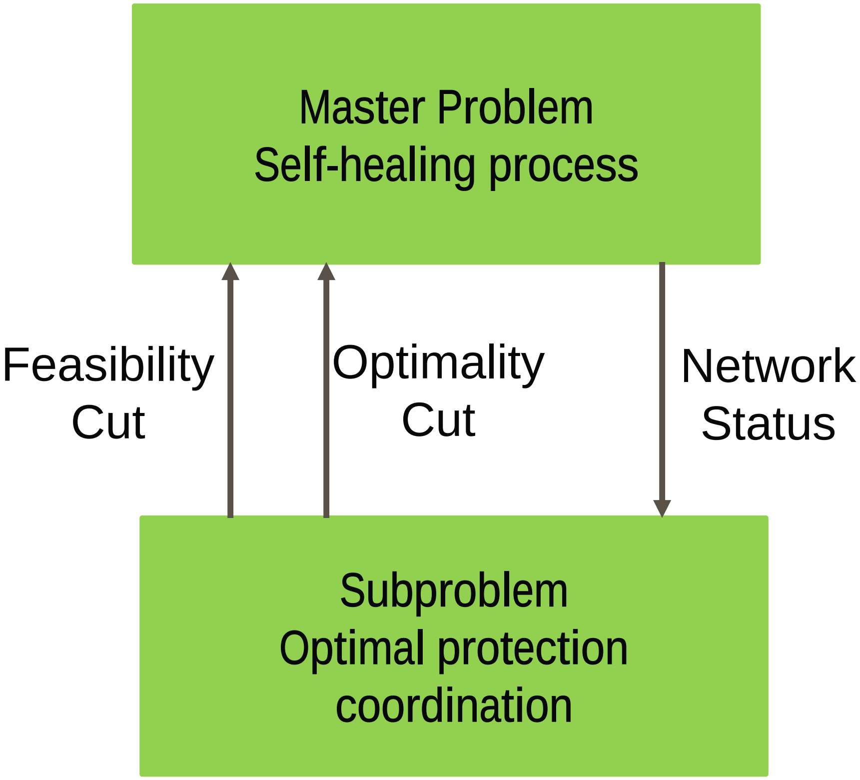
Outline

- Attack resilient control
- Resilient Control Model
- Self-Healing Problem (Master Problem)
- Overcurrent Relay Coordination
- Overcurrent Relay Coordination Subproblem
- Case Study
- Conclusion

Attack resilient control

- Attack resilient control provides defense in depth to a CPS.
- Robust control algorithms enhance security by providing security at the application layer.
- **Application**: Vista Switches in IIT-Microgrid Campus. Inteli-team and RF based control of protection devices in Microgrid.
- **Motivation**: Resilient control and robust coordination of protection system and devices.

Resilient Control Model



Master Problem
Self-healing process

Feasibility Cut

Optimality Cut

Network Status

Subproblem
Optimal protection coordination

Self-Healing Problem (Master Problem)

- What is Self-healing?
  - The microgrid capability to autonomously detect and isolate unexpected events in order to protect local electric loads

- Self-healing process includes two major tasks of **Restoration** and **Reconfiguration**
  - Restoration: To transfer loads in out-of-service area to energized zones based on certain operational objectives.
  - Reconfiguration: To economically change the distribution network topology.

Self-Healing Master Problem

- Micro-generation cost:

$$\sum_{i=1}^{NG}[\underbrace{a_i I_{i,t} + b_i P_{i,t} + c_i P_{i,t}^2}_{\text{Fuel Cost}} + \underbrace{SU_{i,t}}_{\text{Start up cost}} + \underbrace{SD_{i,t}}_{\text{Shut down cost}}]$$

Upper and lower limits
Ramp rate
Min-on-time
Min-off-time Constraints

- Load shedding cost:

$$C_{LS,d,t} = VOLL\cdot(\underbrace{D_{d,t}}_{\text{Base line demand}} - P_{d,t})$$

- Utility Cost

$$C_{u,t} = \underbrace{\lambda_{u,p,t}}_{\text{Real time price}} P_{u,t}$$

Upper and lower limits
Constraints

- Energy Storage System (ESS)
- Switching cost

Charging/discharging limits
Min-on-discharging
Constraints

$$C_{SW,t} = c_{SW}\cdot\Big(\sum_{z_{n,m,t}\in NO} z_{n,m,t} + \sum_{z_{n,m,t}\in NC}(1 - z_{n,m,t})\Big)$$

Closed-loop or
Radial Constraints

Self-Healing Master Problem (Cont'd)

- Constraints
  - Real power balance
  - Reactive power balance
  - Feeder section flow
  - Voltage limits
- Output
  - Network Status

$$\min \quad \mathbf{c}^T \mathbf{x}$$

$$\mathbf{A}\mathbf{x} \le \mathbf{b}$$

Overcurrent Relay Coordination

- After running the self-healing process, when the network topology is changed, the short circuit currents which passed through the relays are varied.
- Consequently, the operating times of primary and backup relays will be changed. To consider the effects of these changes, the new set of coordination constraints corresponding to the network topology should be investigated in subproblem.
- According to the new grid topology the short circuits current and pick up currents of over current relays are calculated

Overcurrent Relay Coordination (Cont'd)

- The operation time of an OCR is an inverse function of the short circuit current passing through it.
- OCR parameters:
  - Time-dial settings of the relay,
  - Tuning parameter: A and B are taken to be 0.14 and 0.02
  - The pickup current, which is the minimum value of current above which the relay starts to operate.

$$t_{n,m} = \frac{A}{\left(\frac{I_{F,m}}{I_{P,n}}\right)^{B} - 1} \cdot TDS_n$$

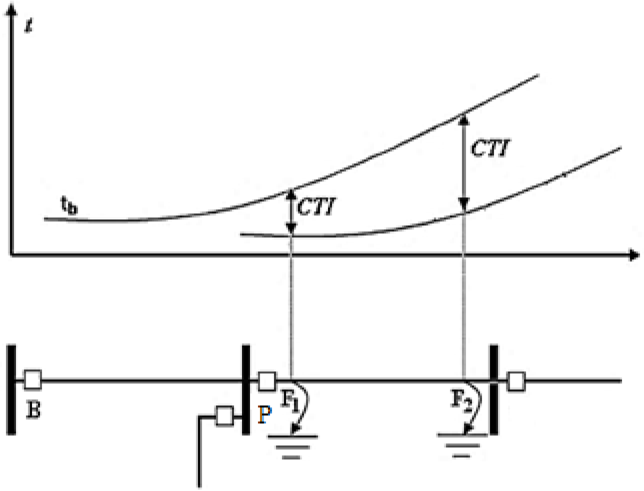
Overcurrent Relay Coordination (Cont’d)

- Coordination condition needs to be satisfied
  - A minimum gap in time between the operation of primary and backup relays, known as the coordination time interval (CTI), must be maintained. In this paper, is taken to be 0.2 s.

$$t_{n,m}^{b_k} - t_{n,m}^{p} \geq CTI \qquad \forall n,(m,k)$$

$$TDS_{n,\min} \leq TDS_n \leq TDS_{n,\max}$$

- The discrimination times between the operating times of relays for faults occurring at (near end fault) and (far end fault)



Overcurrent Relay Coordination Subproblem

- The objective is to minimize the coordination times of all relays, while maintaining the conditions of protection coordination:

$$\min_{\textbf{TDS}} \qquad J = \sum_{n=1}^{N} \sum_{m=1}^{M} \left(t_{n,m}^{p} + \left(\sum_{k=1}^{K} t_{n,m}^{b_k} \right) \right)$$

S.t. Protection Coordination Const.

Feasibility Subproblem

$$\omega(zl_{n,m,t}) = \min_{\mathbf{S1,S2}} \sum_{n} \sum_{m} S1_{n,m,t} + S2_{n,m,t}$$

$$s.t.\quad t^{b_k}_{n,m,t}(F_1) - t^{p}_{n,m,t}(F_1) + S1_{n,m,t} \ge CTI$$

$$t^{b_k}_{n,m,t}(F_2) - t^{p}_{n,m,t}(F_2) + S2_{n,m,t} \ge CTI$$

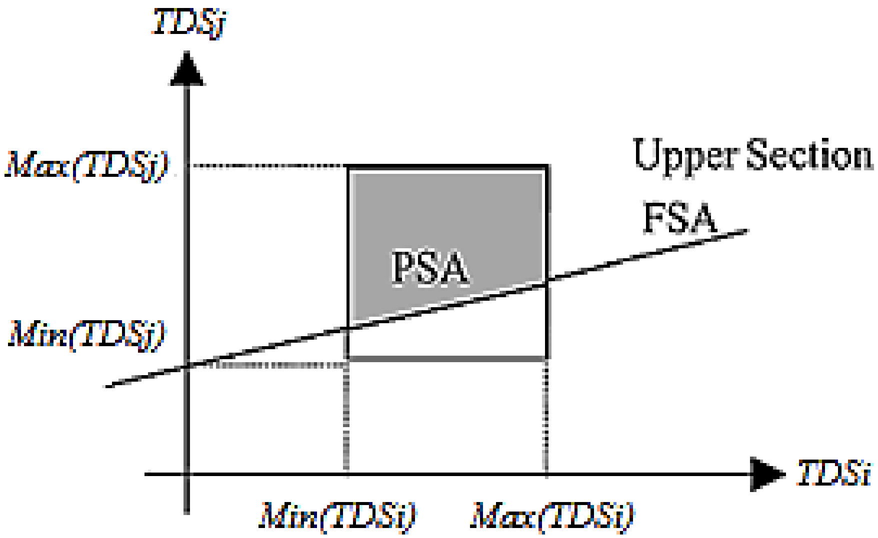
$$TDS_{n,t,\min} \le TDS_n \le TDS_{n,t,\max}$$

$$zl_{n,m,t} = \hat{z}l_{n,m,t} \leftrightarrow \pi_{n,m,t}$$

$$I_{P,n,t} = \sum_{m \sim n} V_{m,t} \cdot y_{n,m} \cdot zl_{n,m,t}$$

$$\mathbf{Z} = [Z_{n,m,t}],\ \mathbf{Y} = [y_{n,m} \cdot zl_{n,m,t}],\ \mathbf{Z} = \mathbf{Y}^{-1}$$

$$I_{F,n,t} = \frac{\hat{V}_{n,t}}{Z_{n,n,t} + kZ_F}$$



$$\boxed{\hat{\omega} + \pi_{n,m,t}(zl_{n,m,t} - \hat{z}l_{n,m,t}) \le 0}$$

Optimality Subproblem

$$\min \qquad J_t = \sum_{n=1}^{N} \sum_{m=1}^{M} \left(t_{n,m,t}^{p} + \left(\sum_{k=1}^{K} t_{n,m,t}^{b_k} \right) \right)$$

$$t_{n,m,t}^{b_k}(F_1) - t_{n,m,t}^{p}(F_1) \geq CTI$$

$$t_{n,m,t}^{b_k}(F_2) - t_{n,m,t}^{p}(F_2) \geq CTI$$

$$TDS_{n,t,\min} \leq TDS_n \leq TDS_{n,t,\max}$$

$$z_{upper} = \hat{J}_t + \mathbf{c}^T \cdot \hat{\mathbf{x}}$$

If the $\left| z_{upper} - z_{lower} \right| \leq \varepsilon$ then stop the process, otherwise generate the optimality cut: $z_{lower} \geq \hat{J}_t + \mathbf{c}^T \cdot \mathbf{x}$ and add to the second master problem

Second Master Problem

$$\min \quad z_{lower}$$

$$z_{lower} \geq \mathbf{c}^T \cdot \mathbf{x}$$

$$\mathbf{A} \cdot \mathbf{x} \leq \mathbf{b}$$

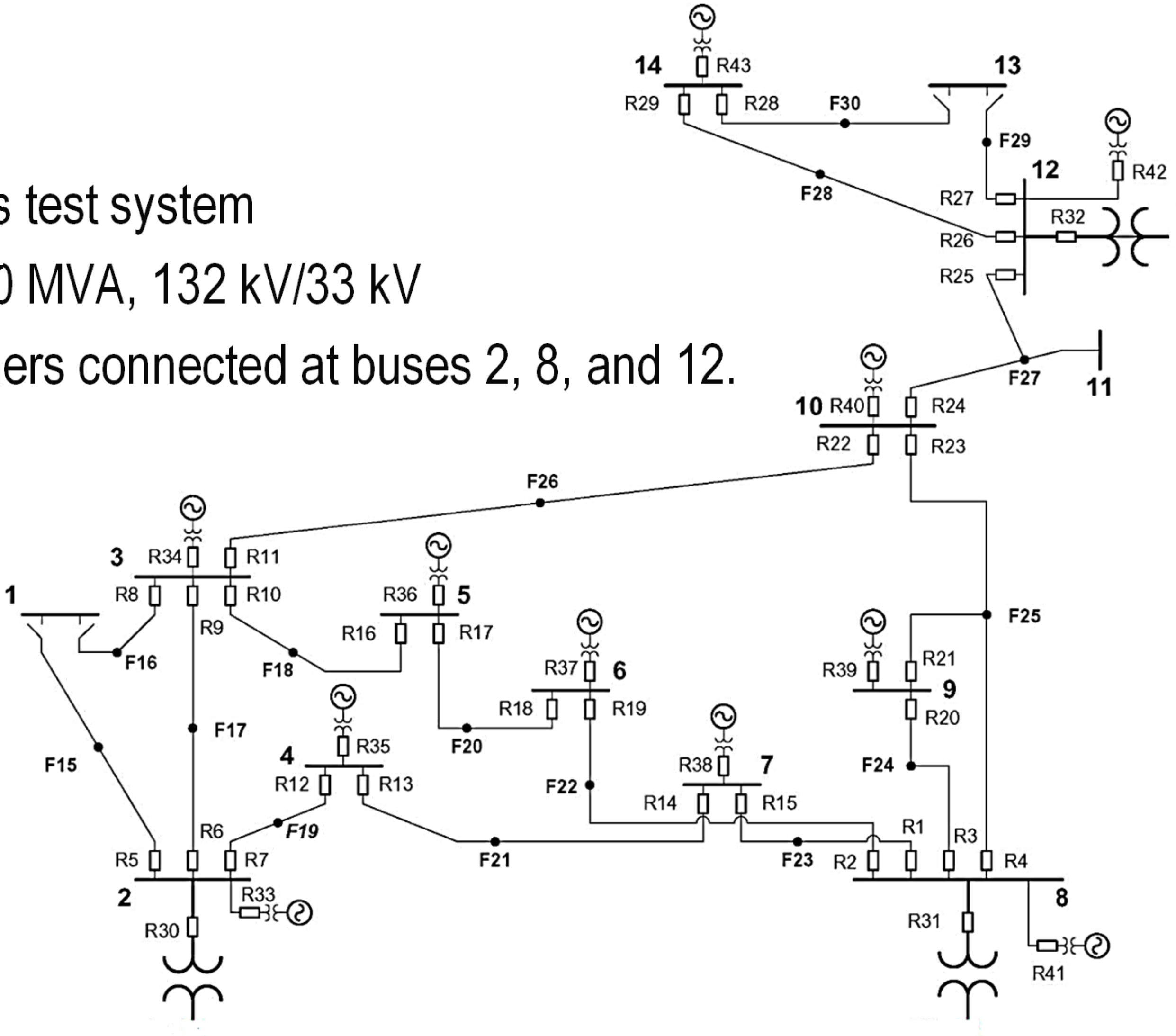
$$z_{lower} \geq \hat{J}_t + \mathbf{c}^T \cdot \mathbf{x}$$

$$\hat{\omega} + \pi_{n,m,t}(zl_{n,m,t} - \hat{z}l_{n,m,t}) \leq 0$$

Send the transmission line, feeder, transformer status to feasibility and optimality subproblems.

Case Study

- Input Data:
  - 30 – Bus test system
  - Three 50 MVA, 132 kV/33 kV transformers connected at buses 2, 8, and 12.



Case Study (Cont’d)

- Input Data:
  - DGs are located at various buses in the system as shown in figure. Each DG is rated at 10 MVA, operates at unity power factor, and feeds the system through a 480 V/33 kV transformer.

  - 43 directional OCRs.

Case Study (Cont’d)

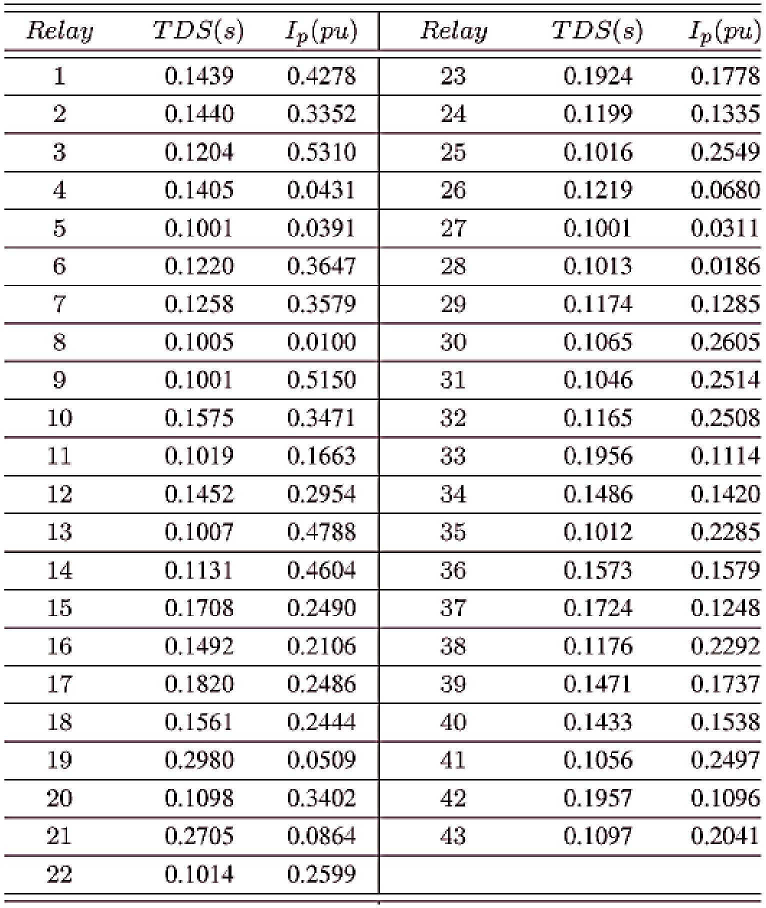
- Attack Scenarios
  - Case 01: No attack. Microgrid grid-connected mode.
  - Case 02: Attacks on power devices. (On main breaker of utility substation, Islanded mode).
  - Case 03: Attacks on protective elements.

Case Study (Case 01)

- No attack, Microgrid grid-connected mode.
- Total coordination times

of the system due to all

simulated faults T = 89.6837 Sec



$Relay$	$TDS(s)$	$I_p(pu)$	$Relay$	$TDS(s)$	$I_p(pu)$
1	0.1439	0.4278	23	0.1924	0.1778
2	0.1440	0.3352	24	0.1199	0.1335
3	0.1204	0.5310	25	0.1016	0.2549
4	0.1405	0.0431	26	0.1219	0.0680
5	0.1001	0.0391	27	0.1001	0.0311
6	0.1220	0.3647	28	0.1013	0.0186
7	0.1258	0.3579	29	0.1174	0.1285
8	0.1005	0.0100	30	0.1065	0.2605
9	0.1001	0.5150	31	0.1046	0.2514
10	0.1575	0.3471	32	0.1165	0.2508
11	0.1019	0.1663	33	0.1956	0.1114
12	0.1452	0.2954	34	0.1486	0.1420
13	0.1007	0.4788	35	0.1012	0.2285
14	0.1131	0.4604	36	0.1573	0.1579
15	0.1708	0.2490	37	0.1724	0.1248
16	0.1492	0.2106	38	0.1176	0.2292
17	0.1820	0.2486	39	0.1471	0.1737
18	0.1561	0.2444	40	0.1433	0.1538
19	0.2980	0.0509	41	0.1056	0.2497
20	0.1098	0.3402	42	0.1957	0.1096
21	0.2705	0.0864	43	0.1097	0.2041
22	0.1014	0.2599			

Case Study (Case 02)

- Attack on the main breaker of utility substation. Grid-connected to Islanded mode.
- Total coordination times

of the system due to the all

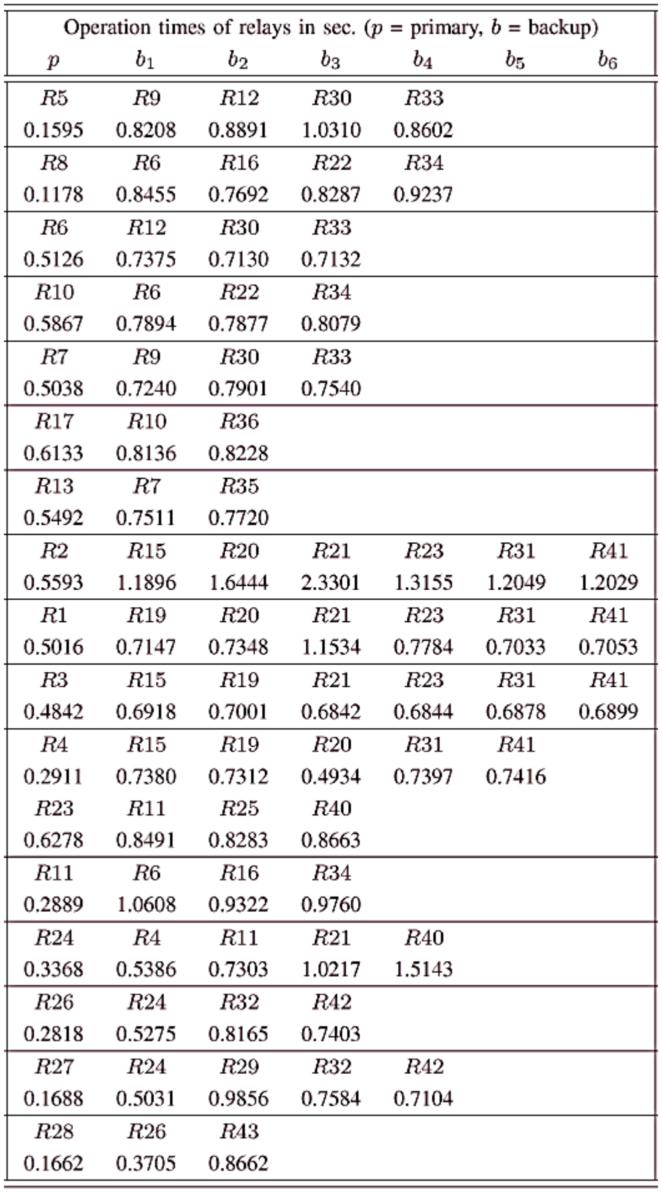
simulated faults T = 187.5686 Sec

Relay	$TDS(s)$	$I_p(pu)$	*Relay*	$TDS(s)$	$I_p(pu)$
1	0.1069	0.6411	23	0.2548	0.1017
2	0.1397	0.3694	24	0.1364	0.0882
3	0.1234	0.5782	25	0.1397	0.1979
4	0.1497	0.0493	26	0.1255	0.0637
5	0.1000	0.0385	27	0.1002	0.0314
6	0.1229	0.3644	28	0.1001	0.0191
7	0.1065	0.5730	29	0.1730	0.0625
8	0.1000	0.0107	30	0.1435	0.2501
9	0.2775	0.1009	31	0.1365	0.2680
10	0.1006	0.5872	32	0.1385	0.2546
11	0.1002	0.1848	33	0.1127	0.3328
12	0.1435	0.2623	34	0.1932	0.1073
13	0.3208	0.0899	35	0.1069	0.2505
14	0.1075	0.4774	36	0.1395	0.1752
15	0.3407	0.0497	37	0.1830	0.1011
16	0.1570	0.2643	38	0.1081	0.2555
17	0.2192	0.1617	39	0.1488	0.1668
18	0.1149	0.4294	40	0.2129	0.0839
19	0.2094	0.1165	41	0.1698	0.1934
20	0.1694	0.1853	42	0.1052	0.3524
21	0.2624	0.1020	43	0.1003	0.2201
22	0.1380	0.2359			

Case Study (Case 03)

- Attack on protective elements
  (Grid-connected mode)
  (R*p*, *p*=1,2,3,4,5,6,7,8,10,11,13,17,…)

  - Breakdown process:
    Breakdown of the relay operation times
    due to simulated faults on all lines
    by using *graph theory*.
  - Set TDS = TDSmin for attacked relays.
    And add the additional coordination const.
    Into the subproblem according to
    the Breakdown relay table.



Operation times of relays in sec. (p = primary, b = backup)

p	b_1	b_2	b_3	b_4	b_5	b_6
$R5$	$R9$	$R12$	$R30$	$R33$		
0.1595	0.8208	0.8891	1.0310	0.8602		
$R8$	$R6$	$R16$	$R22$	$R34$		
0.1178	0.8455	0.7692	0.8287	0.9237		
$R6$	$R12$	$R30$	$R33$			
0.5126	0.7375	0.7130	0.7132			
$R10$	$R6$	$R22$	$R34$			
0.5867	0.7894	0.7877	0.8079			
$R7$	$R9$	$R30$	$R33$			
0.5038	0.7240	0.7901	0.7540			
$R17$	$R10$	$R36$				
0.6133	0.8136	0.8228				
$R13$	$R7$	$R35$				
0.5492	0.7511	0.7720				
$R2$	$R15$	$R20$	$R21$	$R23$	$R31$	$R41$
0.5593	1.1896	1.6444	2.3301	1.3155	1.2049	1.2029
$R1$	$R19$	$R20$	$R21$	$R23$	$R31$	$R41$
0.5016	0.7147	0.7348	1.1534	0.7784	0.7033	0.7053
$R3$	$R15$	$R19$	$R21$	$R23$	$R31$	$R41$
0.4842	0.6918	0.7001	0.6842	0.6844	0.6878	0.6899
$R4$	$R15$	$R19$	$R20$	$R31$	$R41$	
0.2911	0.7380	0.7312	0.4934	0.7397	0.7416	
$R23$	$R11$	$R25$	$R40$			
0.6278	0.8491	0.8283	0.8663			
$R11$	$R6$	$R16$	$R34$			
0.2889	1.0608	0.9322	0.9760			
$R24$	$R4$	$R11$	$R21$	$R40$		
0.3368	0.5386	0.7303	1.0217	1.5143		
$R26$	$R24$	$R32$	$R42$			
0.2818	0.5275	0.8165	0.7403			
$R27$	$R24$	$R29$	$R32$	$R42$		
0.1688	0.5031	0.9856	0.7584	0.7104		
$R28$	$R26$	$R43$				
0.1662	0.3705	0.8662				

Conclusion

- A microgrid protection scheme that is based on optimally setting directional OCRs is proposed, taking into account the attacks.
- The presented results clearly show the advantage of the proposed method in solving the OCRs coordination problem which is robust against topological changes.
- Optimal coordination between distance relays, over current relays and fuses can be considered in this framework.

Thanks