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Optimal Coordination of Distance and Overcurrent Relays with Sparse Placement

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Introduction

Notes specific the this presentation/paper

- Relays in this paper are all inverse-time
- Inverse-time overcurrent and overcurrent used interchangeably

To maintain selectivity and reduce the operating times

- MINLP (Mixed Integer Nonlinear Programming) Optimization approach proposed
- Systematically determine relay settings using genetic algorithm (GA)

Proposed Method (MINLP/GA approach)

Overcurrent (OC) and distance relays often used in combination for transmission and sub-transmission protection

- Main goal is to minimize system-wide outages
  - Maintain selectivity: Done by time-grading relays
  - Depending upon number of units along fault path, time grading can result in undesirable large operating times
- Literature typically assumes full network coverage
  - Relay on each line
  - May be impractical when considering budget limitations
- In practice
  - Relays may be sparsely place as a cost-saving measure

Optimization Problem Formulation (OC Relays)

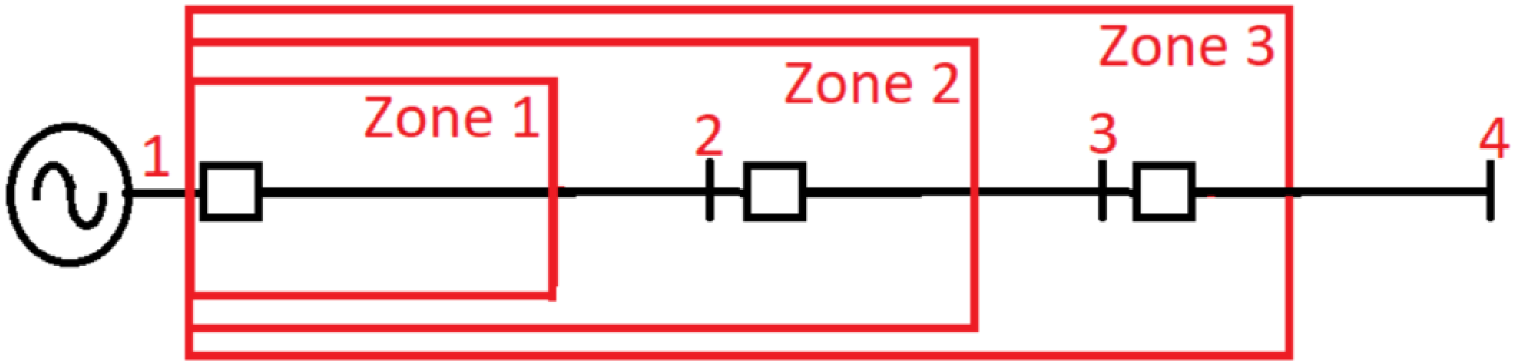
$$M_{ij} = \frac{|I_{ij}|}{I_{ij}^{pickup}} \dashrightarrow \textbf{multiples of pickup current}$$

$$T = \begin{cases} TDS\left(\frac{k}{M^{\alpha} - P} + c\right) + B, \text{if } M^{\alpha} > P \\ \infty, \quad \text{otherwise} \end{cases} \dashrightarrow \textbf{OC relay operating time}$$

Γ	Relay Type	Description	k	c	α	P	B
1	U1	Moderately Inverse	0.0104	0.0226	0.02	1	0
2	U2	Inverse	5.95	0.018	2	1	0
3	U3	Very Inverse	3.88	0.0963	2	1	0
4	U4	Extremely Inverse	5.67	0.0352	2	1	0
5	U5	Short-Time Inverse	0.00342	0.0062	0.02	1	0

Optimization Problem Formulation (Distance Relays)

- Standard Distance Relay Settings
  - Zone 1 covers:
    - 80-85% of line 1-2
  - Zone 2 covers:
    - All of line 1-2
    - 50% of line 2-3
  - Zone 3 covers:
    - All of line 1-2
    - All of line 2-3
    - Overreaches the end of line 2-3 to cover 25% of line 3-4



- Distance relay approximates line impedance as
  - $Z_f^{est} = \frac{V_f^{meas}}{I_f^{meas}}$

Optimization Problem Formulation (Distance Relays)

$$Z_f^{est} = \frac{V_f^{meas}}{I_f^{meas}} \dashrightarrow \textbf{estimated fault impedance}$$

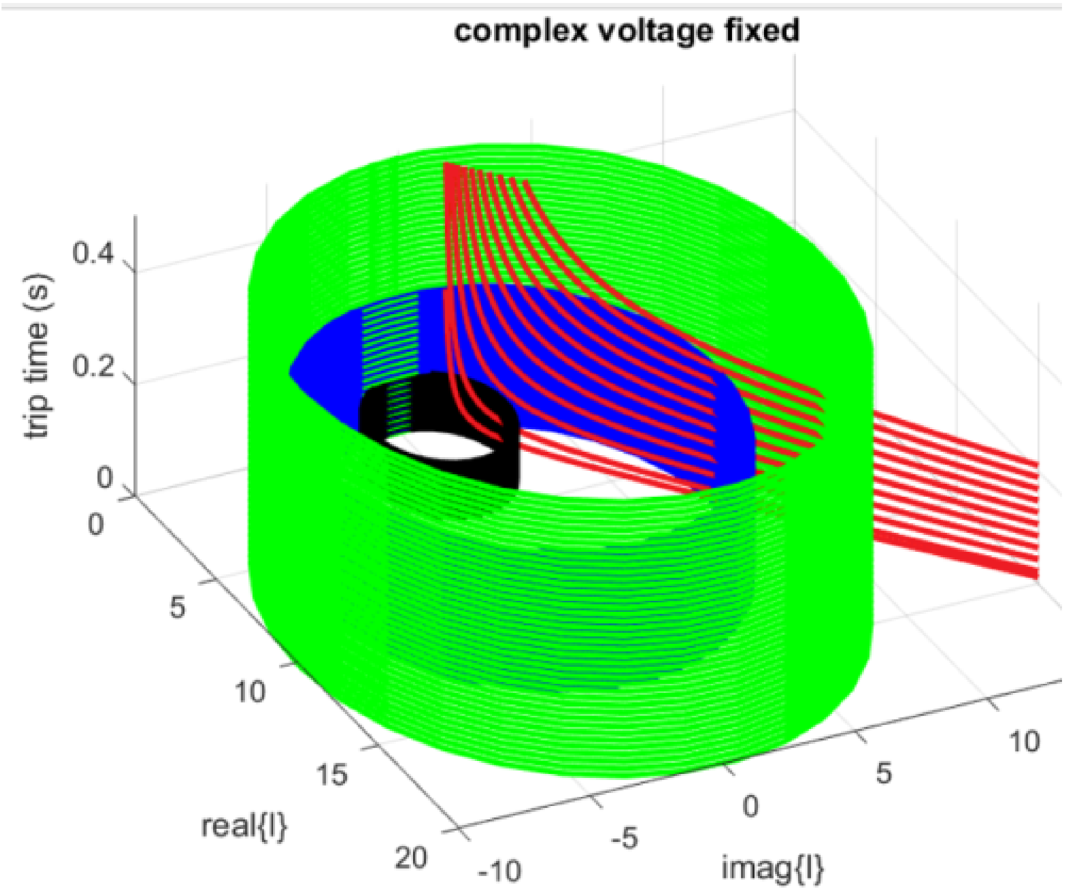
$$T = \begin{cases} 0, \text{if } Z_f^{est} \le Z_{zone\,1} \\ d_2, \text{if } Z_f^{est} \le Z_{zone\,2} \\ d_3, \text{if } Z_f^{est} \le Z_{zone\,3} \\ \infty, \quad \text{otherwise} \end{cases} \dashrightarrow \textbf{distance relay operating time}$$

It must hold that

$$d_1 = 0 \le d_2 \le d_3$$

Overcurrent/Distance coordination

- Distance relays cannot back up overcurrent relays
- Plot to right (full plot is 5-dimensional)
  - Voltage held fixed to reduce to 3-dimensional plot
- Cylinders are relay profiles
  - **Primary**
  - **Secondary**
  - **Tertiary**
- Slice of inverse-time OC relay curve family is plotted in **red**
  - Full plot rotates around vertical axis
- Not possible to bound OC curves with distance relay trip cylinders

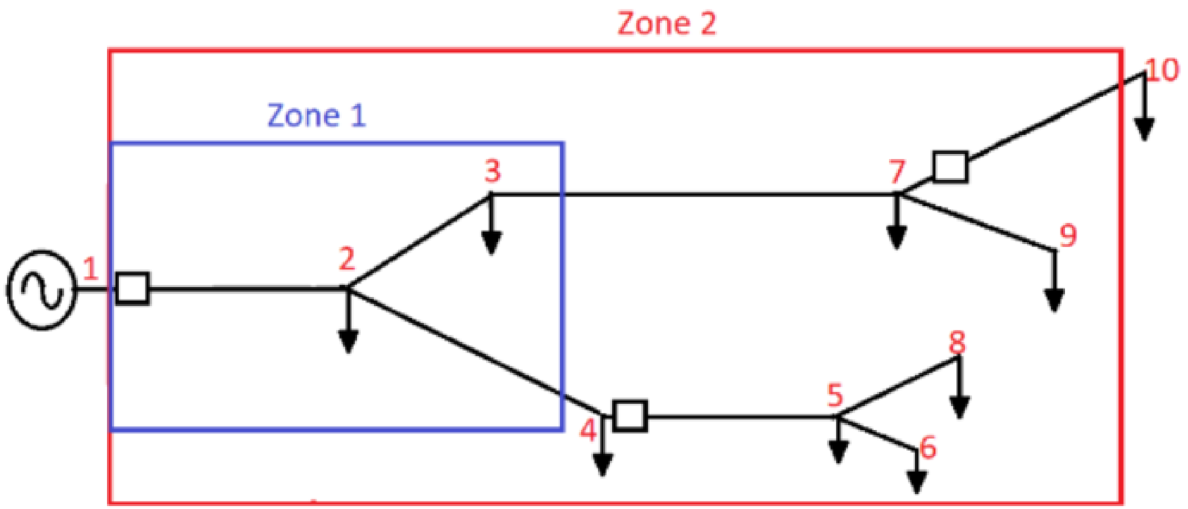


- **Distance relays cannot back up inverse-time OC overcurrent relays**

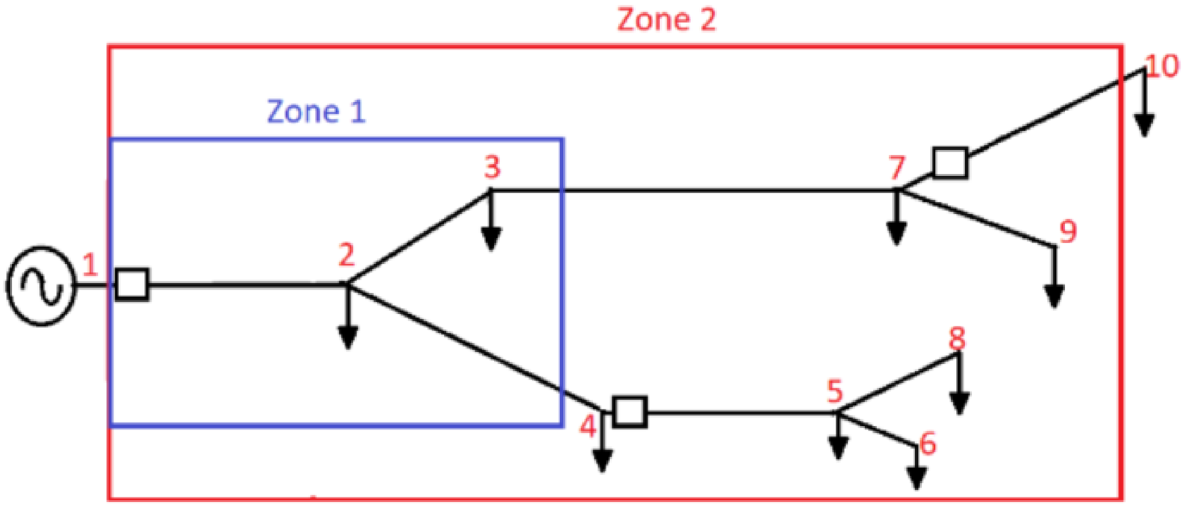
Defining Distance Relay Trip Zones for Sparse Placement (Proposed Method)

Zone 1 Definition

1. Locate source end of line when distance relay is placed (bus 1)
2. Trace path from source end relay (bus 1) to next closed relay (bus 4)
3. Set the Zone reach to 80-90% of the sum of the line impedance along the path
   1. $Z_{z1} = Z_{12} + Z_{24}$
   2. $Z_{zone\,1} = (0.80\ to\ 0.90)Z_{z1}$



Defining Distance Relay Trip Zones for Sparse Placement (Proposed Method)



Zone 2 Definition

1. Locate sending source end (bus 1) of the distance relay
2. Trace path from source end relay (bus 1) to:
   1. The farthest backup relay (bus 7)
   2. The farthest unprotected bus (bus 9)
3. For the paths defined in **Step 2**, determine the path with the maximum impedance Z_{max}. For the example to the right:
   1. $Z_{max} = \max(Z_{12} + Z_{23} + Z_{37}, Z_{12} + Z_{23} + Z_{37} + Z_{79})$

Zone 2 Definition (cont'd)

4. Set Zone 2 to reach 110 to 120% of Z_{max}
   1. $Z_{zone\ 2} = (1.10\ to\ 1.20)Z_{max}$

Assumption

Load impedance at bus k, Z_L^k, is much greater than sum of line impedances.

$$Z_{max} \ll Z_L^k(t), \forall t$$

Full Optimization Problem

$$\min_{\mathbf{x}} f(\mathbf{x}) = \sum_{l=1}^{n_{oc}} T_l(\mathbf{x}_l^{oc}) + \sum_{m=1}^{n_{dist}} T_m\left(\mathbf{x}_m^{dist}\right)$$

subject to:

$$\max_{k \in 1,\ldots,n_{rly}} T_k \leq T_{lim}, \forall k \in K$$ (**max trip time limit**)

$$T_P^{r,L} \leq T_B^{r,L} + CTI, \forall \{P, B | T_P^{r,L}, T_B^{r,L} < \infty\}$$ (**low impedance fault coord.**)

$$T_P^{r,H} \leq T_B^{r,H} + CTI, \forall \{P, B | T_P^{r,H}, T_B^{r,H} < \infty\}$$ (**high impedance fault coord.**)

$$r \in PBRP$$ (**set of primary-backup relay pairs**)

Full Optimization Problem (Cont'd)

$$TDS_k \in \{0.50, 0.51, ..., 15.00\}, \forall k \in OC$$ (**discrete TDSs**)

$$\Gamma_k \in \{1, 2, 3, 4, 5\}, \forall k \in OC$$ (**OC relay type**)

$$0 \leq d_1^k \leq D_{max}, \forall k \in DR$$ (**distance relay zone 1 trip delay limit**)

$$0 \leq d_2^k \leq D_{max}, \forall k \in DR$$ (**distance relay zone 2 trip delay limit**)

$$d_1^k \leq d_2^k + SDI, \forall k \in DR$$ (**Primary/secondary zone coordination for each distance relay**)

Full Optimization Problem (Cont'd)

The optimization is over the vector of control variables

$$\mathbf{x} = \left[\mathbf{x}_1^{oc\,T}, \ldots, \mathbf{x}_{n_{oc}}^{oc\ \ T}, \mathbf{x}_1^{dist\,T}, \ldots, \mathbf{x}_{n_{dist}}^{dist\ \ T}\right]^T$$

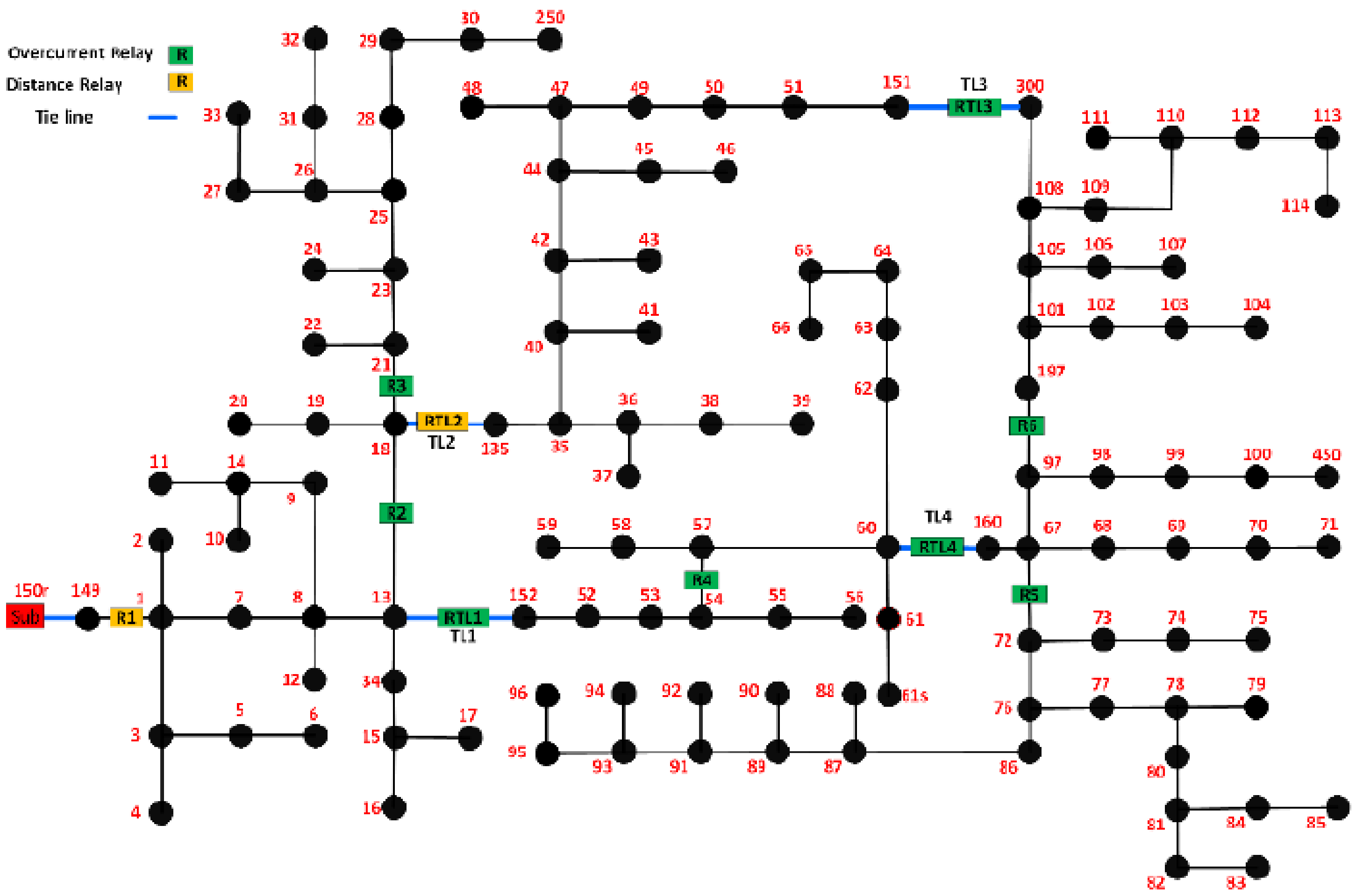
where,

$$\mathbf{x}_l^{oc} = [k_l, P_l, TDS_l, \alpha_l, \Gamma_l]^T$$

and

$$\mathbf{x}_m^{dist} = [d_1^m, d_2^m,]^T \, .$$

IEEE 123-Bus Test Case Results



from	to	name	type	tie line state
149	1	R1	distance	-
13	18	R2	overcurrent	-
18	21	R3	overcurrent	-
57	54	R4	overcurrent	-
67	72	R5	overcurrent	-
197	97	R6	overcurrent	-
13	152	RTL1	overcurrent	open
18	135	RTL2	distance	closed
151	300	RTL3	overcurrent	closed
60	160	RTL4	overcurrent	closed

Results: Maximum Trip Time

GA solution is completed repeatedly

- Each time, the constraint on the maximum trip time is hardened (shortened)
- This is repeated until the solver fails to get the lowest possible maximum trip time
- The CTI (coordination time interval) for the OC relays is 0.25s
- The SDI (Secondary delay interval) for the distance relays is 0.25s
- The longest chain of relay along a fault path is 7, so the theoretical lower bound on the maximum trip time for all relays is 1.75s

T_{lim}	f**(seconds)**	**attempts**	**run #**	T_{max}
5.00	16.20	1	1	4.72
4.50	16.11	1	2	3.11
4.00	17.72	1	3	2.82
3.50	16.54	1	4	3.31
3.00	16.69	1	5	2.69
2.50	16.33	1	6	2.42
2.00	16.16	1	7	2.00
1.80	16.00	1	8	1.78
1.75	fail	2	9	-

Results: OC Relay Phase and Ground Settings for Run #8

name	$I_{pickup}^{phase}(A)$	$I_{pickup}^{ground}(A)$	TDS_{phase}	TDS_{ground}
R2	114.78	122.74	7.1	10.8
R3	189.76	130.64	0.5	11.4
R4	55.549	51.042	0.7	7.7
RTL4	68.386	25.697	6.6	11.7
R5	129.42	94.098	0.5	10
R6	85.724	84.065	3.0	12.9
RTL3	106.16	85.936	13.7	11

Results: Distance Relay Zone 1 and Zone 2 for Delays Run #8

name	$Z_{\text{zone 1}}(\Omega)$	$Z_{\text{zone 2}}(\Omega)$	d_1	d_2
R1	$1.6136\angle 47.8333°$	$1.5380\angle 25.6863°$	1.6717	1.7755
RTL2	$1.2512\angle 19.4882°$	$2.3541\angle 36.3851°$	1.7000	1.3634

Conclusions

Conclusions

- Proposed method allowed for coordination of distance and OC relays with sparse placement
- Essential to protection engineer where limited number of relays/budget available
- Maximum trip time was able to be actively limited using GA to approach theoretical limit

Future Work

- Apply proposed methodology to adaptive protection scheme in real-time
- Consider OC settings capabilities of distance relays (more applicable to adaptive protection)