Distance and Time Overcurrent Relay Coordination with an Autosolver Framework

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Powering A New Direction In System Protection

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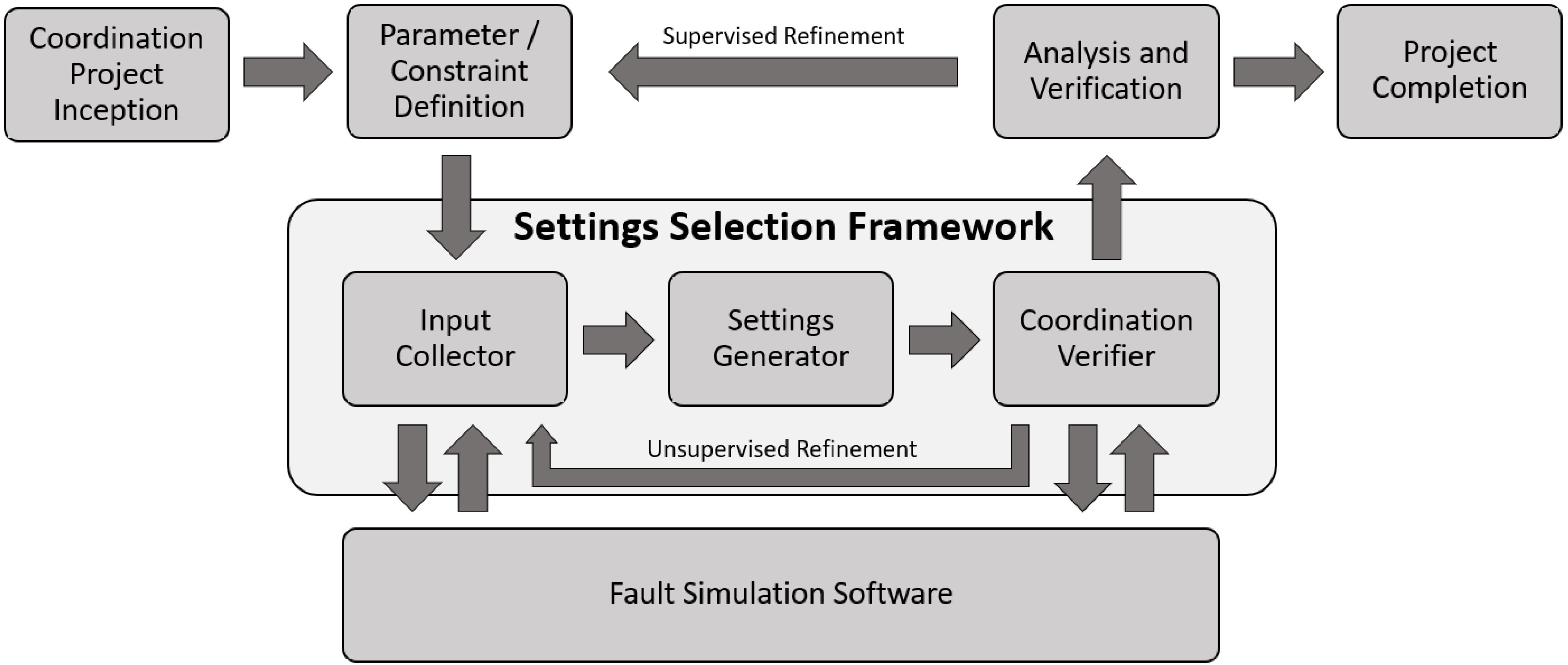
Presentation Outline

- Motivation and Introduction + Framework Overview?
- Heterogeneous Element Coordination
- Customizable Solution Optimization
- Contingencies and Constraint Relaxation
- Future Work
- Questions

Motivation

- Grid is growing and becoming increasingly complex
- Coordination can be difficult and time-consuming
- Coordination solver was previously presented
- Department of Energy SBIR grant
- Improvements made

Coordination Auto Solver Framework



System Specifications

- Aspen OneLiner 15.6
- IBM CPLEX 12.9
- C++20 compiled with Microsoft Visual Studio 2019, 16.9.3
- Windows 10
- SARA 3.0.25

Heterogeneous Element Coordination

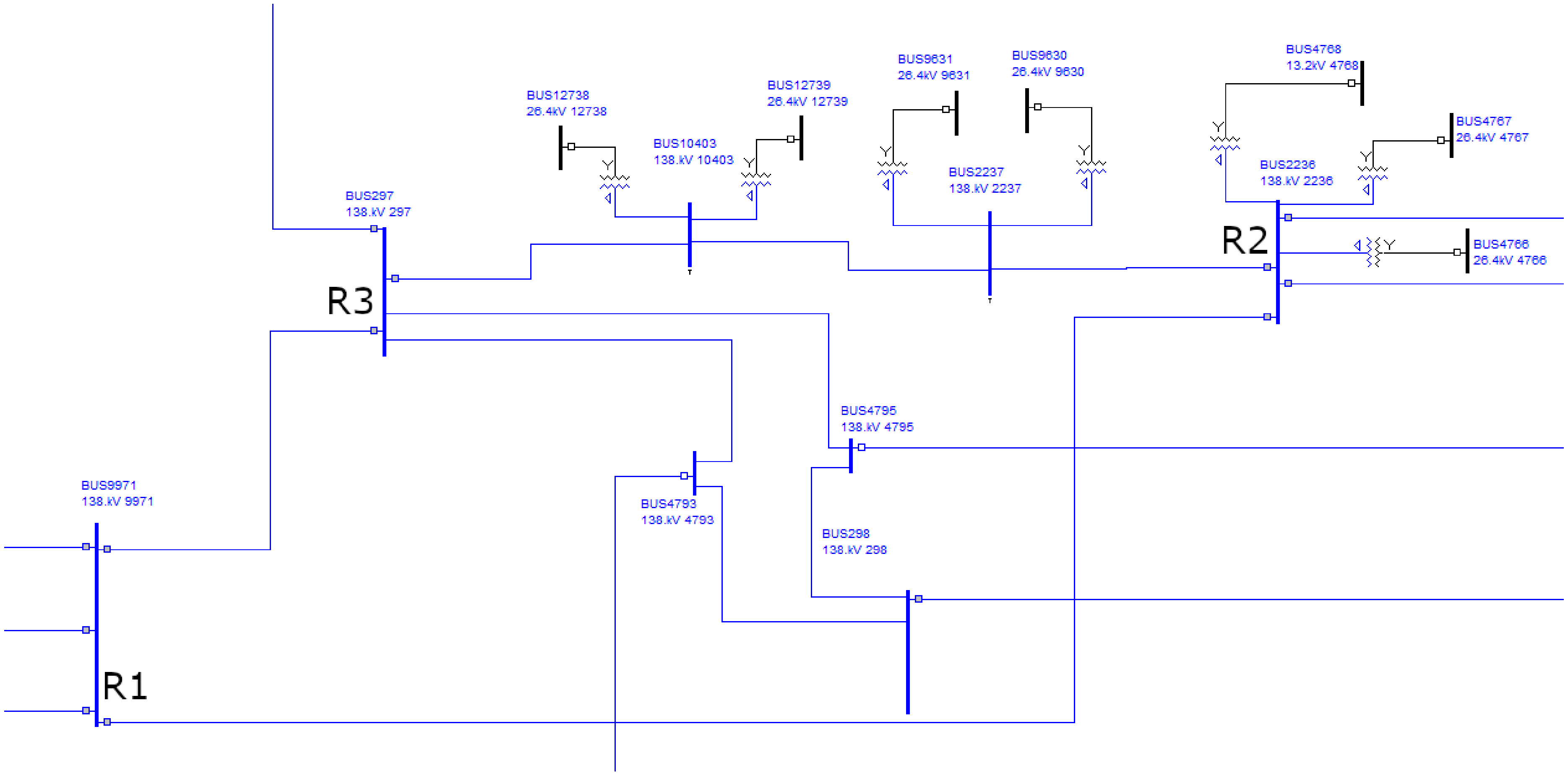
- Easier to achieve coordination when considering distance and overcurrent elements

- **Modeling distance elements**
  - Fix reach settings
  - Solver can change delay setting

- **Modeling instantaneous overcurrent elements**
  - Invariant

- **Total response time**
  - Min of the response time of each element

Perturbation Experiment



Problem Parameters

- Area coordinated to 0.28 seconds, introduce violation
  - R1 Z2 delay to 0.017s
  - Line-end fault on 9971 – 2236
    - R3: TOC 0.139s
    - R1: Z2 0.017s

- Use solver and see if it will restore R1 Z2 delay
  - Curves to be chosen from U curves

Relay	Element	Curve	Pickup	TMS	Reach	Delay
R1	Z1				1.8500	0.0000
	Z2				3.4200	**0.0170**
	TOC	U1	1.0000	3.5600		
	IOC		16.0000			0.1340
R2	Z1				1.7700	0.0000
	Z2				3.3600	0.3330
	TOC	U1	0.6300	1.5800		
	IOC		20.0000			0.1340
R3	Z1				0.6600	0.0000
	Z2				1.8200	0.3830
	TOC	U1	1.2600	0.5000		
	IOC		32.3800			0.1340

Original Settings

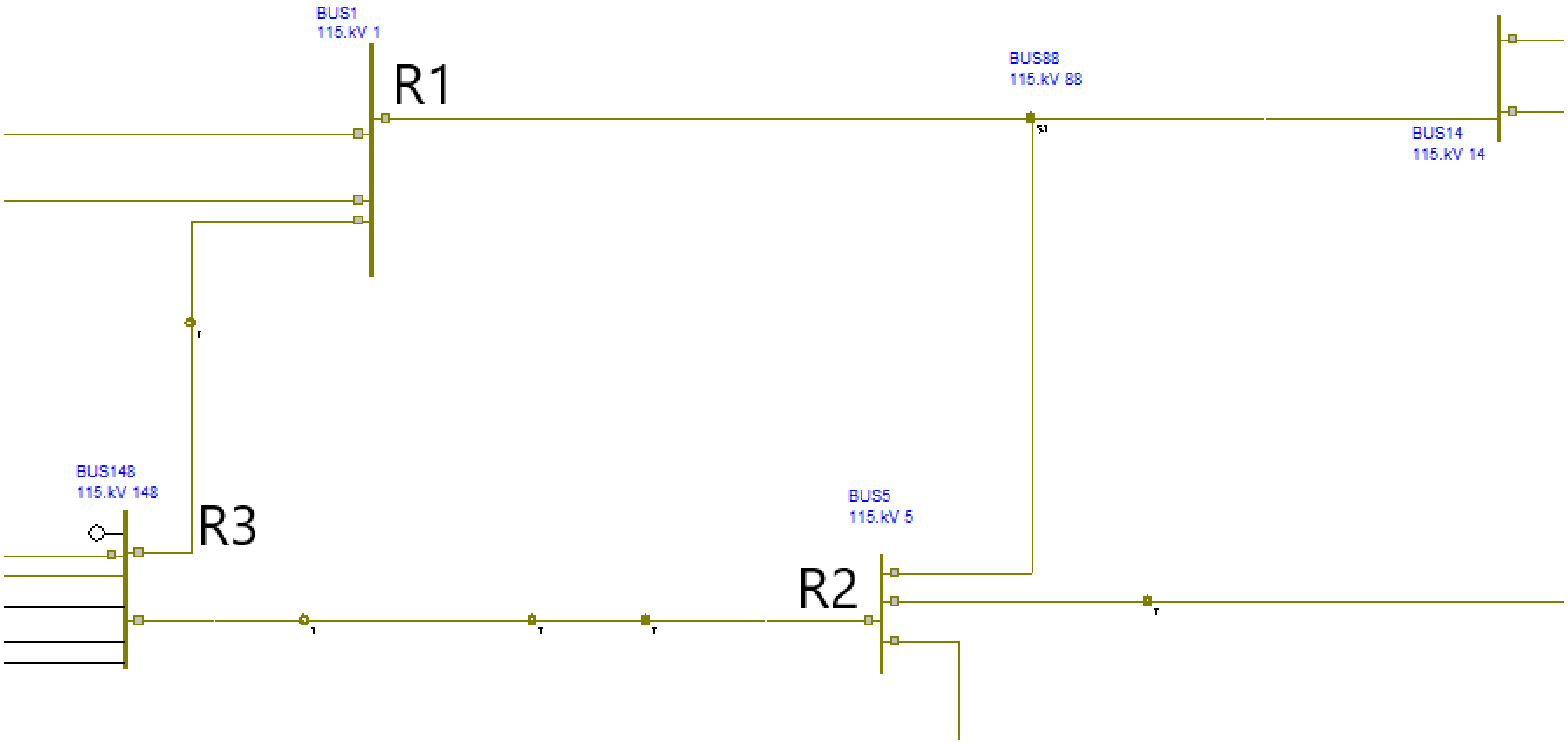
Perturbation Resolved

- R1 Z2 delay increased again to resolved violation
- Other settings changed as well
  - Solver found way to further reduce line-end response time

Relay	Element	Curve	Pickup	TMS	Reach	Delay
R1	Z1				1.8500	0.0000
	Z2				3.4200	**0.2850**
	TOC	U4	3.2749	0.5145		
	IOC		16.0000			0.1340
R2	Z1				1.7700	0.0000
	Z2				3.3600	0.5434
	TOC	U4	2.0199	0.5085		
	IOC		20.0000			0.1340
R3	Z1				0.6600	0.0000
	Z2				1.8200	0.2850
	TOC	U4	8.6338	0.5000		
	IOC		32.3800			0.1340

Solver-Suggested Settings

Infeasibility Experiment



Perturbation Resolved Cont.

- Attempting to coordinate to 0.29 seconds under normal contingencies
  - Infeasible with only TOC elements

- With distance elements, it is possible to achieve that CTI

Relay	Element	Curve	Pickup	TMS	Reach	Delay
R1	Z1				0.3100	0.0000
	Z2				2.5100	0.2900
	TOC	U4	8.1322	0.5000		
R2	Z1				0.8900	0.0000
	Z2				1.9700	0.5800
	TOC	U4	3.7427	0.5000		
R3	Z1				2.0800	0.0000
	Z2				3.9800	0.2900
	TOC	U4	3.428	0.5000		

Solution produced by the solver

Solution Analysis

- R2 Zone 2 delay
  - R2 Zone 2 overreaching R3 Zone 1?
- All TMS are as small as possible, and curves are all set to U4 (extremely inverse)
  - Solver is minimizing line end response times
  - Overcurrent element responding faster than Zone 2 element to line-end fault
  - Could cause issues with downstream relays

Relay	Element	Curve	Pickup	TMS	Reach	Delay
R1	Z1				0.3100	0.0000
	Z2				2.5100	0.2900
	TOC	U4	8.1322	0.5000		
R2	Z1				0.8900	0.0000
	Z2				1.9700	0.5800
	TOC	U4	3.7427	0.5000		
R3	Z1				2.0800	0.0000
	Z2				3.9800	0.2900
	TOC	U4	3.428	0.5000		

Solution produced by the solver

Relay	Line-End Response (seconds)
R1 TOC	0.1342
R2 TOC	0.1231
R3 TOC	0.2364

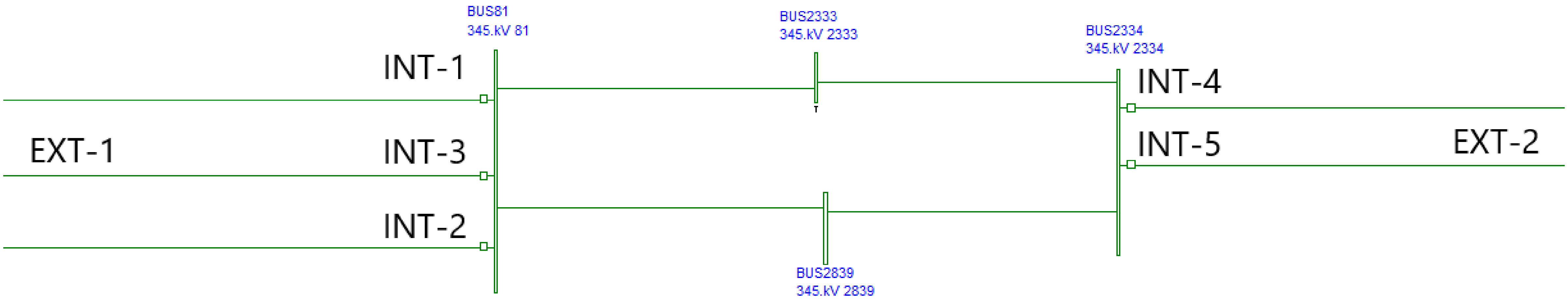
Customizable Solutions
An Optimization

- Theoretically optimal solution may not satisfy real world problem
- Case study: achieving coordination while minimizing the cost of changing the relays in field
  - Each relay has an associated “cost to change”
  - Solver set to prioritize minimizing the cost or the line-end response time

Experiment: a complex substation with two external transmission lines

- Cost of changing internal relays: 1
- Cost of changing external relays: 10

Complex substation with two external lines



Problem Parameters

- 7 overcurrent relays
  - 7 time overcurrent elements
  - 6 instantaneous elements
- TOC curve fixed for external relays
- Internal relay TOC curve can be chosen from U curves
- Solver can adjust pickup and time dial on TOC elements
- Desired CTI: 0.33 seconds

Solver run 3 times with different overall weights for the cost to change.

No cost: w = 0

Relay	Original Curve	New Curve	Original Pickup	New Pickup	Original TMS	New TMS	Relay Trip Time
Internal-1	SEL U4	SEL U4	0.5500	0.5500	10.5000	0.5000	0.0325
	SEL U4	SEL U4	0.5500	0.5500	12.0000	0.5000	0.0325
Internal-2	SEL U1	SEL U4	1.8000	1.0000	3.2000	0.5000	0.0208
Internal-3	SEL U3	SEL U4	1.5000	1.0000	3.3000	0.5000	0.0250
Internal-4	SEL U1	SEL U4	0.9000	0.9000	3.3000	0.5000	0.0147
	SEL U1	SEL U4	0.9000	0.9000	3.3000	0.5000	0.0147
Internal-5	SEL U2	SEL U4	0.5000	0.5000	3.6000	0.5000	0.0216
External-1	SEL U3	SEL U3	0.5000	2.8254	6.4000	0.5000	0.1391
External-2	SEL U3	SEL U3	0.5000	3.5496	3.5000	0.5000	0.2772

Cost only: w = 1

Relay	Original Curve	New Curve	Original Pickup	New Pickup	Original TMS	New TMS	Relay Trip Time
Internal-1	SEL U4	SEL U4	0.5500	0.5500	10.5000	0.5000	0.0325
	SEL U4	SEL U4	0.5500	0.5500	12.0000	12.0000	0.7803
Internal-2	SEL U1	SEL U5	1.8000	1.0000	3.2000	0.5000	0.0418
Internal-3	SEL U3	SEL U5	1.5000	2.5657	3.3000	0.5000	0.0609
Internal-4	SEL U1	SEL U1	0.9000	0.9000	3.3000	0.5000	0.0827
	SEL U1	SEL U1	0.9000	0.9000	3.3000	3.3000	0.5458
Internal-5	SEL U2	SEL U5	0.5000	4.4243	3.6000	0.5000	0.1395
External-1	SEL U3	SEL U3	0.5000	3.5859	6.4000	0.5000	0.1989
External-2	SEL U3	SEL U3	0.5000	0.5000	3.5000	3.5000	0.3656

Mixed results: w = 0.2

Relay	Original Curve	New Curve	Original Pickup	New Pickup	Original TMS	New TMS	Relay Trip Time
Internal-1	SEL U4	SEL U4	0.5500	0.5500	10.5000	0.5000	0.0325
	SEL U4	SEL U4	0.5500	1.0349	12.0000	0.5000	0.0855
Internal-2	SEL U1	SEL U4	1.8000	1.0000	3.2000	0.5000	0.0208
Internal-3	SEL U3	SEL U4	1.5000	1.0000	3.3000	0.5000	0.0250
Internal-4	SEL U1	SEL U4	0.9000	0.9000	3.3000	0.5000	0.0147
	SEL U1	SEL U4	0.9000	0.9000	3.3000	0.5000	0.0147
Internal-5	SEL U2	SEL U4	0.5000	0.5000	3.6000	0.5000	0.0216
External-1	SEL U3	SEL U3	0.5000	2.8254	6.4000	0.5000	0.1391
External-2	**SEL U3**	**SEL U3**	**0.5000**	**0.5000**	**3.5000**	**3.5000**	**0.3656**

No Cost vs Cost: Analysis

- Response time only: All relays changed
- Cost only: 3 aren’t changed
- Mixed: 1 external relay isn’t changed

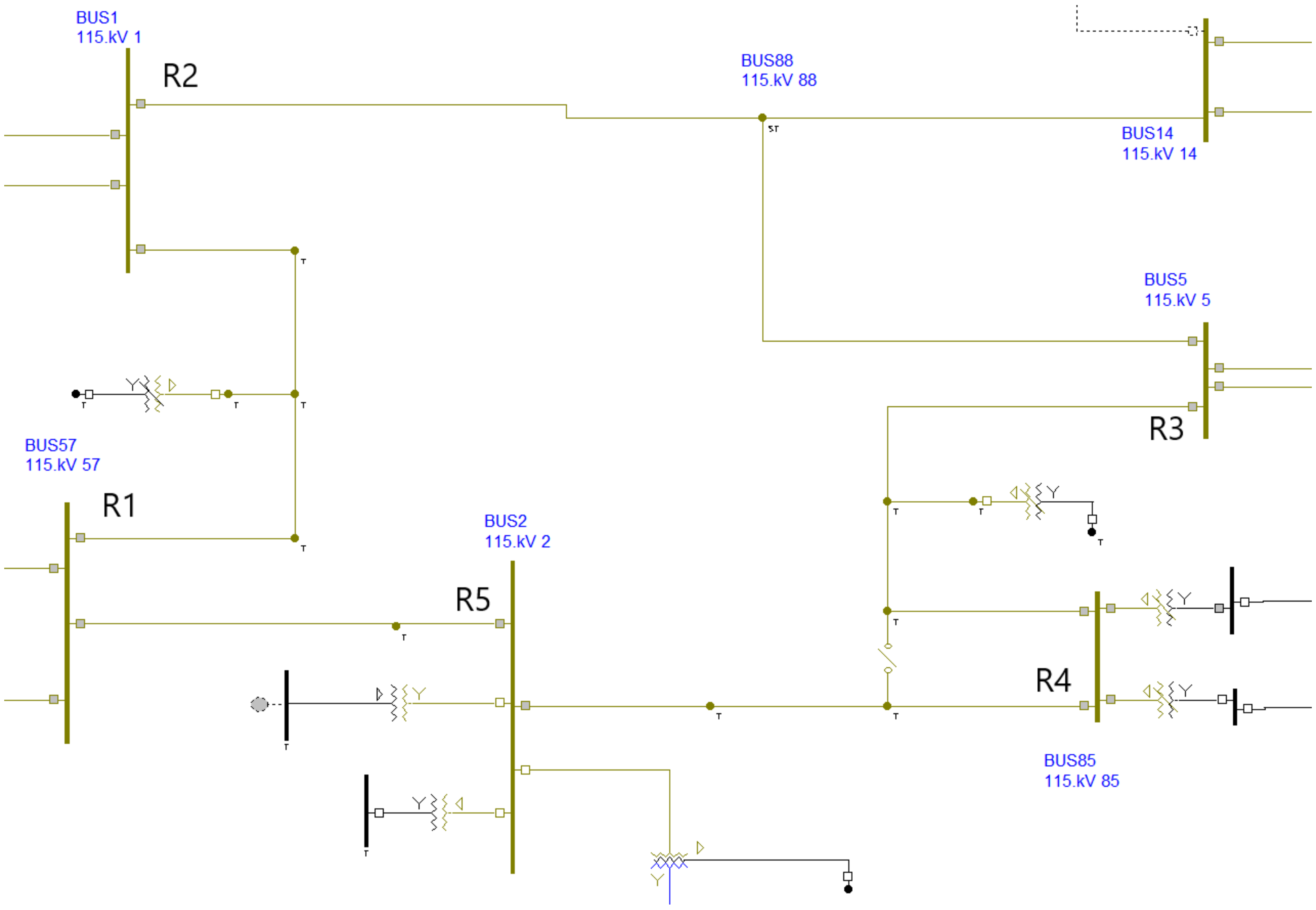
- Successfully customized solution
    - Solution better tailored to each utility’s needs

Contingencies and Constraint Relaxation

- Many utilities focus on coordinating under normal conditions
- Coordinating under contingencies is more difficult and time-consuming – sometimes just impossible
- **Constraint relaxation**: choose to allow CTI violations if they are above a certain threshold

Case Study – coordinating 5 terminals to 0.33 seconds under N-1 contingencies**.**

5 Bus System


BUS1
115.kV 1
R2
BUS88
115.kV 88
BUS14
115.kV 14
BUS5
115.kV 5
R3
BUS57
115.kV 57
R1
BUS2
115.kV 2
R5
R4
BUS85
115.kV 85

Problem Parameters

- Looking at TOC elements only
- Solver to choose from U curves
- Contingencies taken: remotes, transformers

- Solver can’t find a solution

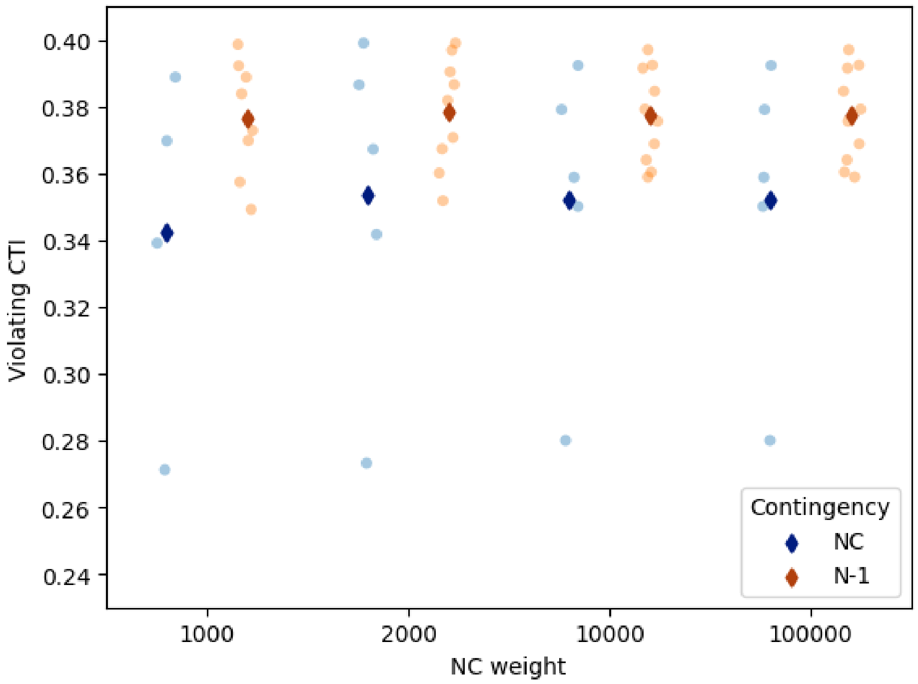
Results when using constraint relaxation

- If solver must violate a CTI constraint, the CTI must still be at least 0.17 seconds
- Identifying difficult area
  - Every CTI constraint involving R3 and one of its backups is violated
  - All the violations for R4 use R3 as the backup time
- Showing the need for heterogenous protection
  - Except for R2, every relay has a violation under N-0 for a close-in fault
  - Could call for instantaneous or distance elements

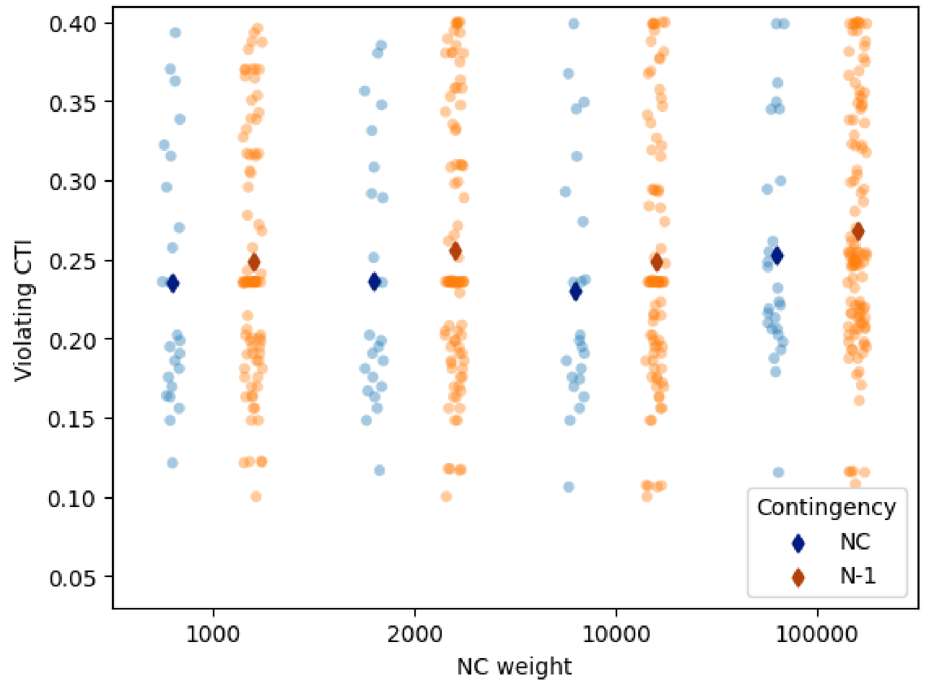
Relay	CTI Constraints	Violated Constraints	Lowest CTI
R1	48	7	0.1733
R2	144	4	0.2548
R3	144	48	0.1700
R4	60	36	0.1700
R5	60	6	0.1700

On a Larger Scale

3 Terminal System



12 Terminal System



The solver is given a weight that represents the penalty for violating a normal condition CTI constraint.

Future Work

- **Time overcurrent elements**
  - Response times are sometimes too short
  - Is there a need to let the solver change the curve?
- **Distance elements**
  - To avoid zone 2 delays being set to 0.000, need to take downstream relays into account
- **Instantaneous elements**
  - Let solver change the pickup
- **Check for non-linearity**
  - Some of these new features may have introduced non-linearity
- **Support larger studies**
- **Increase customization**
  - To support a variety of philosophies

Conclusion

- Solver has come a long way from when we first implemented it.
- The DOE SBIR Grant allowed us to make much progress and run many experiments.
- Autotuning-assisted coordination studies are a viable advancement coming soon to system protection.

Questions?

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