A Cost Benefit Analysis of Faster Transmission System Protection Schemes and Ground Grid Design

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***Abstract*— This paper analyzes how reducing tripping times affects the capital cost of a transmission station's ground grid. A range of trip times are examined to demonstrate the increased cost of a slower tripping scheme and its relationship with substation ground grid design. This relationship is used to determine the potential savings when utilizing faster protection schemes on modern relays.**

Keywords—grounding; trip time; cost; ground grid; transmission; substation;

I. INTRODUCTION

Cost is often the most important factor aside from functionality when designing a transmission station. While large ticket items such as breakers and transformers comprise a large portion of a project's budget, other less obvious costs such as relay selection can impact the overall price of a station's installation. More complex forms of transmission protection such as distance elements require both more expensive relays and potential installation of new measurement or communication equipment.

Example trip times were gathered using various applications of protection systems for three differential substation configurations. These scenarios ranged from utilizing overcurrent protection to differential relaying. To demonstrate the price comparison of purchasing a faster breaker, these trip times were additional analyzed using 3 and 5 cycle breakers. This analysis looks at different applications of protection schemes but can be generalized to adjusting breaker failure trip time delays and the chosen coordination time intervals used to determine distance and overcurrent trip times.

The effects of reducing a station's worst fault trip time on the price tag are analyzed though comparisons of the ground grid needed to keep the station safe from touch and step potentials. The robustness of a ground grid is largely subject to the amount of time ground fault current can persist.

The challenge of quantifying potential savings or additional costs comes from the wide range of situations. Situations presented in this paper are a simplification of real world scenarios to aid in understanding the trend a budget may take because of engineering decisions. The scope of this paper only considers the impact of fault current on ground grid design costs and assumes faster clearing times are not required for stability purposes.

II. EXAMPLE SYSTEM AND TRIP TIMES

Tripping times were developed using the example systems developed at different voltage levels and various topologies. Substation B in Fig. 1 has a 200ft by 200ft foot print with two line terminals, a single radial bus configuration and a distribution transformer.

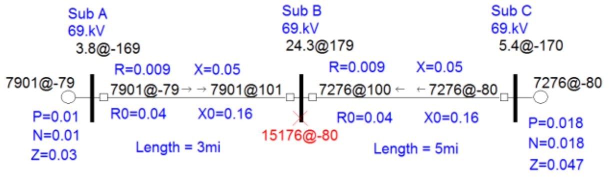

Fig. 1. Two Terminal 69kV Substation

Substation B in Fig. 2 has a 200ft by 200ft foot print with three line terminals, a local auto-transformer and a local generation tie. The 138kV and 69kV buses have a radial configuration.

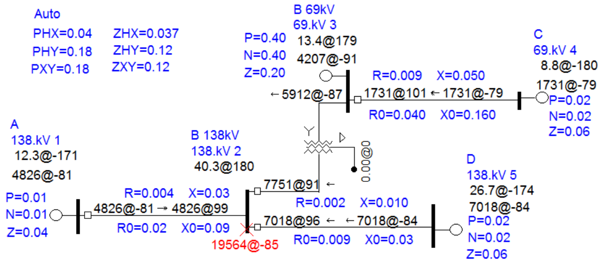

Fig. 2. Three Terminal 138/69kV Substation

Substation B in Fig. 3 has a 400ft by 400ft foot print with six line terminals and two generator step-up transformers. The 230kV bus is a double breaker configuration.

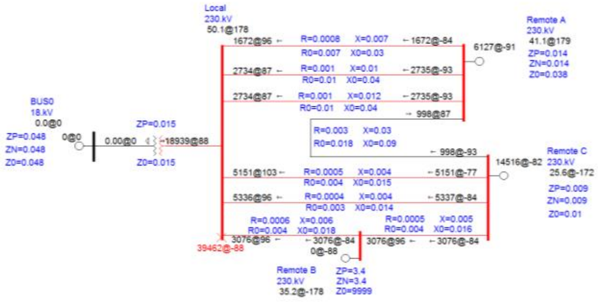

Fig. 3. Six Terminal 230kV Substation

A. *Line Relaying Performance*

The following protection schemes are used in the analysis. The total cost of installation will be estimated as $100,000 for the relay panel plus the additional relaying costs indicated below.

Option 1: Overcurrent, $2000

- Primary and backup relaying implementing overcurrent protection
- Breaker failure to trip protection
- Single DC source

Option 2: Distance, $10,000 + $45,000 / position for non-radial bus configurations

- Primary and backup relaying implementing distance protection
- Breaker failure to trip protection
- Single DC source

Option 3: DCB with second DC source, $35,000 + $20,000/position

- Primary and backup relaying implementing DCB protection
- Wave trap installation
- Breaker failure to trip protection
- Redundant DC sources

Option 4: Line current differential, $2500 + $10,000 per transmission line mile

- Primary and backup relaying implementing differential protection
- Fiber optic communication installation
- Breaker failure to trip protection
- Redundant DC sources

B. *Bus Differential Relaying Performance*

Option 1: Current summation, $2,000

- Primary and backup relaying implementing current summation protection
- Single DC source

Option 2: Low impedance differential, $12,000

- Primary and backup relaying implementing low impedance differential protection
- Single DC source

Option 3: Low impedance differential with second DC source, $20,000 / position

- Primary and backup relaying implementing low impedance differential protection
- Redundant DC sources

C. *Transformer Relaying Performance*

Option 1: Overcurrent, $2,000

- Primary and backup relaying implementing current summation protection
- Single DC source

Option 2: Current Differential, $13,000

- Primary and backup relaying implementing low impedance differential protection
- Single DC source

Option 3: Current Differential, $20,000 / position

- Primary and backup relaying implementing low impedance differential protection
- Redundant DC sources

D. *Worst Case Fault Clearing Time Calculation*

Fig. 4 shows the worst case fault clearing time for relay applications with a single DC source is the time remote end relaying takes to clear the local bus fault. This assumes that the local DC source is inoperative and no local breaker operations occur.

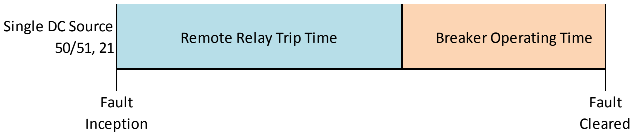

Fig. 4. Single DC Source Worst Clearing Time

Fig. 5 shows the worst-case fault clearing time for relay applications with a single DC source and a DCB scheme installed is the local relay trip time with a breaker failure to trip event that requires a transfer trip.

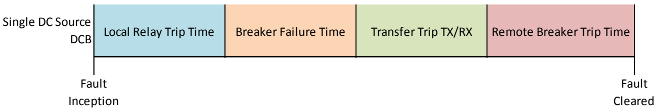

Fig. 5. Single DC Source Worst Clearing Time and DCB

Fig. 6 shows the worst-case fault clearing time for relay applications with redundant DC sources with differential protection is the relay trip time with a breaker failure to trip event.

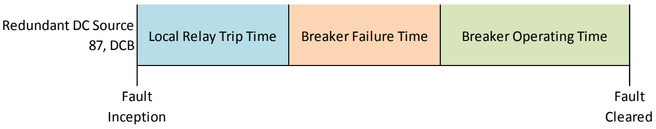

Fig. 6. Redundant DC Source Worst Clearing Time with Line Differential

TABLE I. FAULT CLEARING TIMES SUMMARY IN CYCLES

System	Option 1	Option 2	Option 3	Option 4
69kV (15,000A) 3~ Breaker	35.7~ (595ms)	23.0~ (383ms)	17.0~ (283ms)	13.5~ (225ms)
5~ Breaker	37.7~ (628ms)	25.0~ (417ms)	23.0~ (383ms)	18.5~ (308ms)
138kV (20,000A) 3~ Breaker	80.2~ (1337ms)	23.0~ (383ms)	17.0~ (283ms)	13.5~ (225ms)
5~ Breaker	82.2~ (1370ms)	25.0~ (417ms)	23.0~ (383ms)	18.5~ (308ms)
230kV (40,000A) 3~ Breaker	23.0~ (383ms)	23.0~ (383ms)	17.0~ (283ms)	13.5~ (225ms)
5~ Breaker	25.0~ (417ms)	25.0~ (417ms)	23.0~ (383ms)	18.5~ (308ms)

Fig. 7 shows the worst-case fault clearing time for relay applications with redundant DC sources with differential protection is the relay trip time with a breaker failure to trip event.

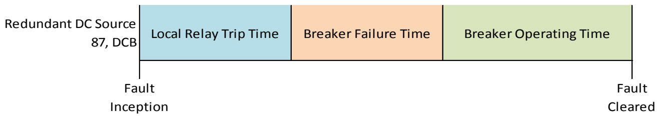

Fig. 7. Redundant DC Sources Worst Clearing Time with Line Differential

The fault clearing times by option and system are summarized in the Table I with trip times given in cycles (milliseconds).

E. Incremental Costs of Installing Faster Relaying

The cost analysis of this section uses recent construction data dated 2017 to arrive at estimates for equipment installation. The fiber installation cost was estimated at $10,000 per transmission line mile. This estimate is approximated from the costs database maintained by the U.S Department of Transportation Office of the Assistant Secretary for Research and Technology [2].

Table II summarizes the various chosen relaying sets used for line, bus, and transformer protection. The transformer and bus relaying must be upgraded along with the line relaying to maintain faster clearing times for bus faults.

The relaying upgrade costs are calculated using (1). The calculated base costs in Table III assume all equipment to support the installation of overcurrent relaying on all terminals. This includes current transformers on all breaker positions and a single DC supply. Breaker control and breaker failure to trip relaying is assumed in the standard configuration.

$$\text{Total Cost} = \text{Relaying} + \text{Metering} + \text{Comm. Eq.} + \text{DC Supply} \quad (1)$$

TABLE II. RELAY SYSTEMS USED FOR ANALYSIS

Relay Systems	Line	Transformer	Bus
Set A	Option 1	Option 1	Option 1
Set B	Option 2	Option 2	Option 2
Set C	Option 3	Option 3	Option 3
Set D	Option 4	Option 3	Option 3

TABLE III. RELAY SYSTEM BASE COSTS

System	Relay Set A	Relay Set B	Relay Set C	Relay Set D
69kV (15,000A)	$8,000	$96,000	$181,000	$386,000
138kV (20,000A)	$12,000	$165,000	$280,000	$787,500
230kV (40,000A)	$18,000	$381,000	$598,000	$1,813,000

III. GROUND GRID ANALYSIS

A. Design Criteria

Before analysis of a grid may begin, various information must be gathered about the substation in question. As the models used are not based off a real station, this information had to be estimated using IEEE standards [1], typical industry practice, and engineering judgment.

- Current injected into ground is completely remote current. Only a single fault source near the middle of the station is modeled.
- X/R = 20
- 4/0 conductor size is utilized as per typical industry practice. This was verified to be sufficient for all situations used.

- 4 inches of 3,000 Ohm-meter crushed rock is used on the surface. Crushed rock extends to the extents of the tested area.
- The grid is at a depth of 2 feet.
- Ground rods are 10 feet in length and 5/8 inches in diameter.
- The outside of the modeled grid is assumed to be the minimum required area free of step and touch potentials.
- The soil is of a uniform resistivity.

Design of a ground grid does not follow the same path each time. In the interest of reaching consistent conclusions, each grid was made safe using the following process.

1. A square grid is modeled using an even spacing of conductors throughout. Ground rods are placed around outside border at conductor intersections as needed.
2. Minimal conductors are added around corners to mitigate voltage potential issues there.
3. A conductor is placed in an empty grid spacing where there is a voltage potential issue.
4. If enough voltage potential issues exist when the trip time is increased, the entire grid is redrawn with a denser spacing.

B. Incremental Grid Cost

The cost of implementation of a grounding grid comes from three main areas: engineering, material, and installation. Engineering costs will be ignored in this analysis as it represents a relatively small portion of the overall cost. Recent construction data from 2017 was used to estimate the combined cost of material and labor to build a ground grid at $50 per foot. This includes the price of horizontal conductors at a typical depth as well as ground rods. It is important to note that this cost can vary greatly with copper prices, installation methods, and owner specific requirements.

A soil resistivity of 75 Ohm-Meters was used to test each of the fault current values from Table I. The base cost of a ground grid is found by making a grid safe at the design current and the fastest tripping time. This is used as a starting point to gauge the incremental cost of increasing the tripping times in each of the scenarios in Table II. The initial price of the ground grid provides little use, as the designs are simply a representation of real world grids. Useful information is extracted by calculating the cost differential between iterations of clearing time increases or soil model variations. Every set of clearing times corresponding with the fault current level in Table I is used to acquire said incremental costs.

To provide more data and reduce the number of variables, the 69kV/15kA set of trip times was tested using the same method with two additional soil models. No two stations will have the same soil characteristics. A station with poor soil conditions will require higher design and installation costs due to the decreased benefit of addition ground conductors. Soil models are rarely uniform, and this can play a role in overall cost.

IV. DATA ANALYSIS

Tables IV through VI show the incremental cost increase between iterations of fault clearing time. Table VII displays the cost impacts of clearing times at two additional soil models. There is a clear jump in conductors needed between each of the fault current ratings. As discussed previously, this is not valuable information and is only a result of system loading and total grid area.

An interesting trend appears out of the data when looking at an individual clearing time across all three simulated currents. As an example, the percent increase of cost between

TABLE IV. Ground Grid Design costs at 15kA

Clearing Time (cycles)	Conductor Required (feet)	Total Cost at $50 per foot	Incremental Cost Increase	Total Cost Increase From Fastest Clearing Time	Percent Increase From Fastest Clearing Time
13.5	4,538	$226,900			
17	4,853	$242,650	$15,750	$15,750	6.94%
18.5	4,853	$242,650	$0	$15,750	6.94%
23	5,298	$264,900	$22,250	$38,000	16.75%
25	5,298	$264,900	$0	$38,000	16.75%
35.7	5,620	$281,000	$16,100	$54,100	23.84%
37.7	5,719	$285,950	$4,950	$59,050	26.02%

TABLE V. GROUND GRID DESIGN COSTS AT 20KA

Clearing Time (cycles)	Conductor Required (feet)	Total Cost at $50 per foot	Incremental Cost Increase	Total Cost Increase From Fastest Clearing Time	Percent Increase From Fastest Clearing Time
13.5	5,433	$271,650			
17	5,611	$280,550	$8,900	$8,900	3.28%
18.5	5,789	$289,450	$8,900	$17,800	6.55%
23	6,233	$311,650	$22,200	$40,000	14.72%
25	6,391	$319,550	$7,900	$47,900	17.63%
80.2	9,260	$463,000	$57,050	$191,350	70.44%
82.2	9,260	$463,000	$57,050	$191,350	70.44%

TABLE VI. GROUND GRID DESIGN COSTS AT 40KA

Clearing Time (cycles)	Conductor Required (feet)	Total Cost at $50 per foot	Incremental Cost Increase	Total Cost Increase From Fastest Clearing Time	Percent Increase From Fastest Clearing Time
13.5	12,794	$639,700			
17	12,917	$645,850	$6,150	$6,150	0.96%
18.5	13,645	$682,250	$36,400	$42,550	6.65%
23	14,476	$723,800	$41,550	$84,100	13.15%
25	14,642	$732,100	$8,300	$92,400	14.44%

TABLE VII. GROUND GRID DESIGN COSTS WITH DIFFERENT SOIL RESISTIVITY

	Soil Model					
	Total Cost			Cost Increase over 13.5 cycles		
Clearing Time (cycles)	25 ohm-m	75 ohm-m	225 ohm-m	25 ohm-m	75 ohm-m	225 ohm-m
13.5	$113,800	$226,890	$497,000			
17	$113,800	$242,650	$503,000	$0	$15,760	$6,000
23	$125,800	$264,900	$532,000	$12,000	$38,010	$35,000
35.7	$145,800	$281,000	$587,000	$32,000	$54,110	$90,000

17 and 13.5 cycles decreases as the fault current is raised. This is generally true across all the data, and implies the benefit of a faster tripping time may not have as large of an impact at higher fault currents. However, while holding the tripping time constant, the incremental cost appears to generally show a positive correlation with respect to the fault current level. Because the owner of the station would primarily care about the dollar savings on the final price tag, the percent increase is significantly less important than the dollar amount differences.

It is worth noting that on the 15kA data set, the jump from 17 to 18.5 cycles and from 23 to 25 cycles required no additional copper. This is due to the safety margin that is built into the initial faster clearing time ground grid which could not be reduced without causing an unsafe condition. This results from the non-continuous nature of increasing or decreasing grid spacing since the substation area is held constant

The data also shows that most of the substations and scenarios explored in this paper are best optimized with a simple step distance relay scheme. Decreasing trip times beyond to sub 20 cycle clearing times does allow some money to be saved in the ground grid but this amount is much less than the cost of faster relaying.

The soil model variation also shows that substations with lower fault current availability and located in soil with low resistivity can be safely protected by simple overcurrent schemes. The 25ohm-m soil model shows that upgrading the relaying scheme from Set A to Set B (at a cost of $88,000) only saves $20,000 in ground grid costs. This indicates that a more cost-effective solution could be implemented if the trip time is not limited by another power system constraint.

V. ADDITIONAL CONSIDERATIONS

As grounding grids can be considered an upfront cost in the installation of a station, it is straight forward to analyze the effects of fault clearing times. Situations involving important loads may force unconventional relaying schemes to avoid disruptions in service. However, there are most likely additional consequences of changes to clearing times.

Longer lasting through fault currents are anticipated to reduce the life of a transformer due to mechanical damage, but this is difficult to quantify due to transformer lifespans lasting potentially decades. Further research and data collection is required to investigate this suspicion.

VI. CONCLUSION

This paper examines the interplay between the costs of system protection and the costs of a substation ground grid. Generally, this paper has found that there can be some benefit to deciding which relay scheme is used based on results from a soil testing analysis. When clearing time is not dictated by other concerns, this paper indicates that slower and cheaper relaying schemes could be used to protect substations with lower fault currents or better soil conditions while faster and more expensive relaying schemes could be used to protect substations with higher fault currents in poor soil to reduce the cost of the substation ground grid. This indicates that some preliminary analysis and soil resistivity investigation could save money if performed before the final relay protection scheme is determined. Additional money could be saved by investigating protection time delay margins used on protection schemes such as breaker failure, overcurrent, and distance relaying for smaller substations that are likely to be built in areas with high soil resistivity with large fault currents.

VII. BIBLIOGRAPHY

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