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MITIGATING ARC FLASH HAZARD BASED ON PROTECTIVE DEVICES RE-COORDINATION IN DISTRIBUTION NETWORKS

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Abstract

The severity of arc fault can be reduced by reducing the fault clearing time. Protection engineers coordinate the protective devices keeping in view the bolted fault currents. To ensure the coordination between the devices sufficient discrimination margins are provided as well. The scheme works well for bolted faults but takes comparatively longer time for clearing arc faults. If the discrimination margins used by protection engineers are carefully reduced without disturbing the coordination between various devices, the arc fault clearing time can be reduced. In this paper, ETAP software has been used to model a distribution network using actual field settings for protective devices on distribution feeders, distributors and industrial units. Arc flash analysis is performed to check arc fault severity level at different system locations. Locations with extremely high arc fault energy level are identified. The protective device settings are revised with reduced discrimination margins and incorporated in protective device models in ETAP. Short circuit analysis was performed afterwards to check the protective device coordination and it was found that protection scheme works well for all fault conditions. Since the discrimination margins have been reduced, this results in reduced arc fault clearing time in distribution networks.

Keywords: Arc Fault Analysis, PPE (Personal Protective Equipment), FCT (Fault Clearing Time), FPB (Fault Protection Boundary), (PD) Protective Device, ETAP (Electrical Transients Analysis Program).

1. Introduction

An arc fault usually occurs when maintenance work is being carried out on some energized equipment. During the maintenance of energised equipment a bolted short circuit fault can be initiated by some mechanical tool, which normally gets converted into an arc fault when the cause of such fault is removed somehow. Arc resistance limits the fault current magnitude. Since Protective Devices (PD) have inverse time current characteristics, the fault clearing time increases, thus causing more damage to equipment and human life [1-9]. Usually, the protection engineers coordinate the PD's for bolted faults and not for arc faults. Thus, the protection works well for bolted faults but takes unduly long clearing time for arc faults [8, 9].

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One way to reduce the severity of arc fault is to provide dedicated protection against arc faults. However, additional capital is required to install separate PD's. Usually arc fault risk level is summarized by different standards in form of a table representing arc fault energy corresponding to the respective category and Personal Protective Equipment (PPE) required. Table I below provides a summary of arc fault categories as described by NFPA 70E 2009. As PPE category increases, it becomes difficult to continue repair work due to poor visibility and heat [10].

This work is focused on a typical distribution network having radial configuration. Time over current protection is provided to the radial feeders. The actual field settings for PD used on distribution feeders have been incorporated to check the severity of an arc fault. Since over current protective devices are used on distribution feeders, the time to clear fault increases with decrease in fault current; a typical situation faced in case of arc faults.

Table 1.Summary for Arc Fault Categories.

<table>
<tr><th>Category ID</th><th>Energy Involved (Cal/cm^2)</th><th>PPE Required</th></tr>
<tr><td>0</td><td>$0 < Cal/cm^2 < 1.2$</td><td>Non-melting or untreated natural fibre long-sleeve shirt, long pants, safety glasses, hearing protection, and leather gloves</td></tr>
<tr><td>1</td><td>$1.2 < Cal/cm^2 < 4$</td><td rowspan="2">Fire Resistant(FR) long-sleeve shirt (minimum arc rating of 4), worn over untreated cotton T-shirt with FR pants (minimum arc rating of 8) or FR coveralls (minimum arc rating of 8)</td></tr>
<tr><td>2</td><td>$4 < Cal/cm^2 < 8$</td></tr>
<tr><td>3</td><td>$8 < Cal/cm^2 < 25$</td><td rowspan="2">A total clothing system consisting of FR shirt and pants and/or FR coveralls and/or arc flash coat and pants (clothing system minimum arc rating of 4)</td></tr>
<tr><td>4</td><td>$25 < Cal/cm^2 < 40$</td></tr>
<tr><td>N/A</td><td>$Cal/cm^2 > 40$</td><td>No PPE Category Available</td></tr>
</table>

In this paper, a feasible and inexpensive solution for reducing the arc flash severity is proposed by revisiting the PD settings. This also reduces the class of protective equipment required for the safety of field staff. The main advantage of this scheme is that no capital is involved; instead existing devices in distribution networks are used to reduce arc fault category. The approach is especially valuable where safety of maintenance personnel is compromised owing to the fact that specialized devices for sensing arc faults are not installed.

2. Methods for Arc Flash Reduction

Several techniques are available to reduce the severity of arc faults. Those suggested techniques work on the principle of early detection of arc fault that ultimately results in its faster removal [11-14].A number of devices are devised for the said purpose like, installation of optical sensors is one of the options. When an arc flash occurs there is a sudden significant rise in light intensity that will not occur due to normal light sources. This sudden increase of light intensity is detected by optical sensors that give trip signal to the relays especially installed for arc flash elimination [11-14]. Another technique used for early arc fault detection and its subsequent elimination is the detection of rise in temperature and pressure when an arc fault occurs. During arc flash both of these parameters rise to a very high value within a very small period of time. Temperature and pressure sensors thus detect that an arc flash has occurred and are used to give trip signal to the relays [14-17]. Another technique that is used for fast clearing of arc faults is the conversion of arc flash fault into a bolted short circuit fault with the help of an arc quencher. It creates an intentional short circuit fault on account of detection of arc fault. This results in an increase in the fault current and the fault is cleared in a shorter time [17]. Fast current limiting fuses are also used for arc fault removal in a shorter time; however there are a number of problems associated with their use as discussed in [3,18-19]. Replacement of circuit breakers with new ones having smaller operating time is also suggested as a technique of reducing arc fault clearing time [3, 20-23]. Temporarily making the relay settings more sensitive during conduction of repair work while compromising selectivity helps in clearing the arc faults quickly [6,23].

Arc fault category can be reduced if fault clearing time is decreased; all of the above mentioned techniques work on this principle. All of these techniques include installation of some dedicated equipment for arc fault detection and its subsequent removal. This research work presents a novel method of reducing arc flash category. Reduction in fault clearing time can be achieved if the intentional delays and discrimination margins used by the protection engineers are decreased to minimal possible level using sophisticated coordination programs. Arc fault energies and hence categories are reduced by this method because arc flash incident energy and clearing times are calculated for the worst possible conditions [24-28].

3. System Modelling for Arc Fault Analysis

Simulations have been carried out using ETAP software. A Power transformer rated 31.5/40 MVA, 132/11kV is feeding the system that has a 3-phase fault level of 5.7kA at 132kV side and 15kA at 11kV bus. Six radial feeders fed by the Low Tension (LT side of power transformer are provided with time over current and instantaneous protections. Siemens 7SJ63, ABB SPAJ 140C and CDG61 Alstom relays are used with SF6 circuit breaker connected at 132kV while vacuum breakers are installed at 11kV side [28-29, 31-33].

Field settings have been used to coordinate the PD’s for conducting arc flash analysis [31]. Over load factor of 2 is assumed for radial feeders, while power transformer protection is provided with an over load factor of 20%. The time over current setting for feeders has been provided with an intentional delay of 0.3sec (average value) [1].

Table 2.Settings for 7SJ63 Overcurrent Relay

Overcurrent Element Settings				Instantaneous Element Settings		
Curve Type	Pickup Current(A)		Time Dial	Pickup Current(A)		Time Dial
	Relay Current	Primary Current		Relay Current	Primary Current	
IEC very inverse	6.14	491.2	0.2	61.4	4912	0.02

Table 2 shows the setting of very inverse type time-current characteristics curve for the relays should be used in existing field settings with discrimination margin of 0.4sec set by the utility protection engineer. The instantaneous pick up value is taken as 6 to 10 times of the time over current pick value. For earth fault element pickup current is set at 30% of nominal circuit current setting for a 7SJ63 Siemens relay [1].

4. Arc Flash Simulations and Results

4.1. Arc Fault Simulation on 11 kV Substation Bus

Arc flash faults are simulated after setting the values of PD's. Figure.2 and Appendix A show the result of arc flash analysis on substation bus. Protection scheme has been designed by considering15.33kAas a value of bolted bus fault current. Source PD (CB1) operates to clear the arc fault of 13.65kA on substation bus [31-33]. Due to higher resistance of arcing faults than the bolted, the Fault Clearing Time FCT is higher in case of the previous one. Since the fault persists for longer time more energy is involved which ultimately has resulted in higher PPE Category equal to 3 that is required to carry out live work on the bus bar at a working distance of 45cm.

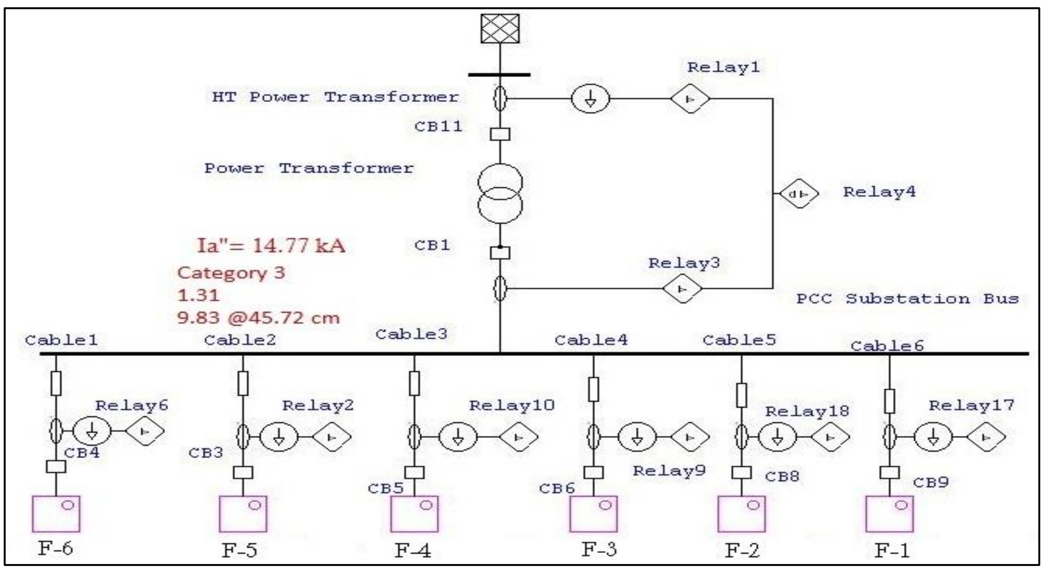

Figure2. Result of arc flash at Substation bus modelled in ETAP [33]

4.2. Arc Flash Simulation on 11kV Feeders

Similarly arc faults were have been simulated on 11 kV feeders. Category-3 faults are observed at most of the locations. The reason is the lower magnitude of arc fault currents that cause the protective devices to take large FCT. Figure.3 presents one of the six feeders namely F-5 on which arc flash faults are simulated.

Appendix B represents different feeder buses in order of increasing distance from feeding end. Appendix B summarizes the result of arc flash analysis on the feeders supplied by substation bus. It is clear that with increase of distance from the feeding end i.e. substation bus the fault clearing time increases due to decrease in arc fault current.

5. Remedial Measures

As already discussed that readjustment of PD settings can be used as an effective tool in reducing arc fault severity by decreasing the FCT, while still maintaining the device coordination. For this purpose the relay settings are revised, intentional delay is reduced

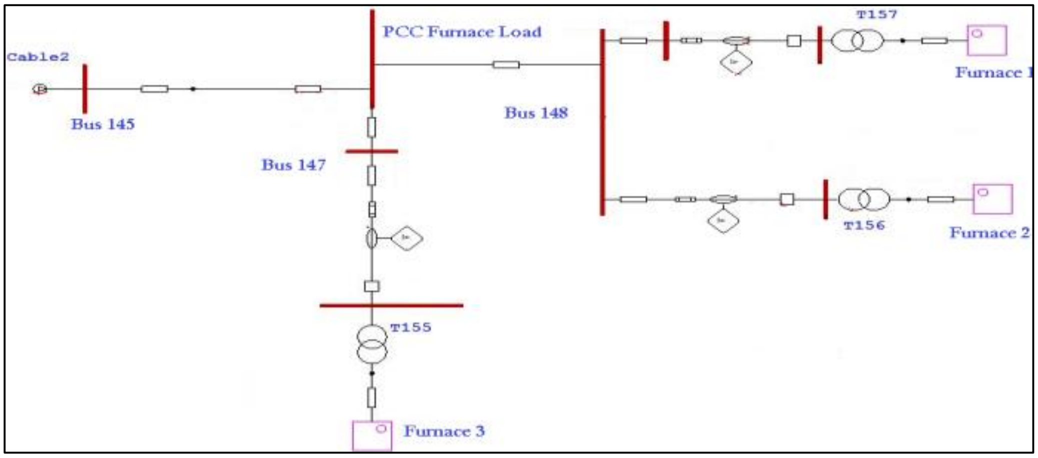

Figure. 3. Single line diagram of F-5 feeder.

to 0.2sec and discrimination margin to 0.35sec. The subsections below illustrate the revised settings for feeder relays, power transformer LT and HT relay. Both the phase element and earth fault element settings have been revised, Appendices C and D represents the calculations for phase element and earth elements respectively.

6. Simulations with Revised Settings

New device settings have been incorporated in the relay models. Short circuit analysis carried out on the system showed proper coordination for all fault conditions between the devices despite the fact that intentional delays and discrimination margins have been reduced. Figure.4 provides Time Current Characteristics (TCC) for relays with new settings. It is clear from the figure that the coordination between the relays has not been disturbed. Arc fault simulations are repeated with new device settings.

6.1. *Arc Fault Simulation on 11kV Substation bus*

Appendix E provides a summary of the improvement achieved with proposed new settings on Substation bus. The PPE category drops to 2 with incident energy reduces to 7.93 Cal/cm^2.

6.2.*Arc Flash Simulation on 11kV Feeders*

Arc flash simulation with new proposed settings shows significant improvement as the PPE category drops to ‘0’ and ‘1’ in most of the cases. The incident energy involved in arc fault decreases significantly due to reduction in FCT as mentioned in Appendix F. All the buses have nominal voltage rating of 11 kV. Thus, the protective devices are perfectly coordinated despite of reducing delays and discrimination margins as shown in Figure.4. The system under study consists of around 1100 buses. Figure.5 shows the effectiveness of the method in reducing hazard risk level on different buses.

About 60% of the buses exhibit two level reductions in hazard risk level, i.e. from category4 to 2 or 3 to 1 etc. Approximately 15% of the buses show a three level reduction in hazard risk level. Same goes for one level reduction. Arc flash category has not increased on any of the buses as the result of revised relay settings. While at some of the buses arc fault category remains unchanged.

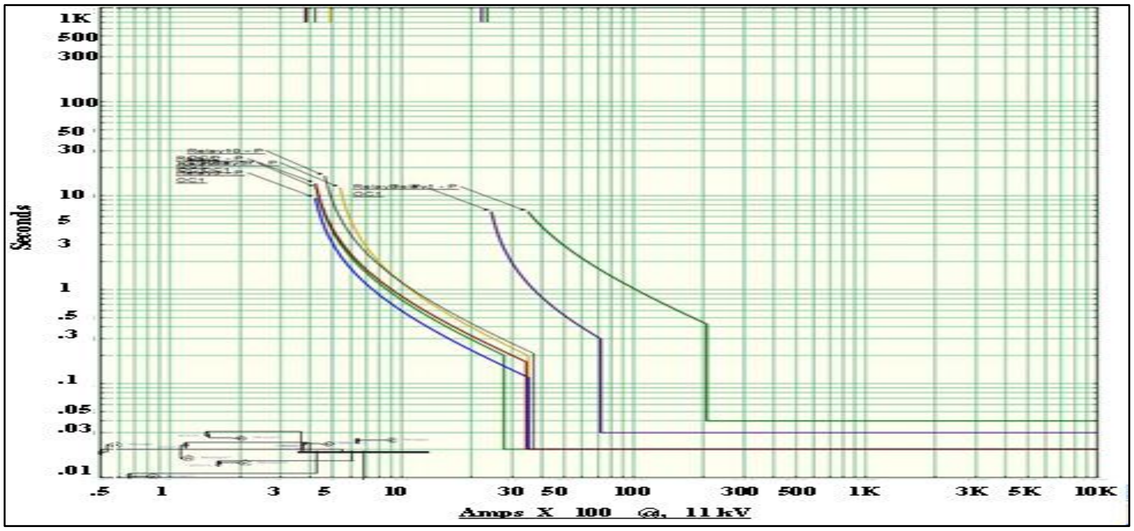

Figure. 4 TCC curves for relays with proposed settings shows proper coordination

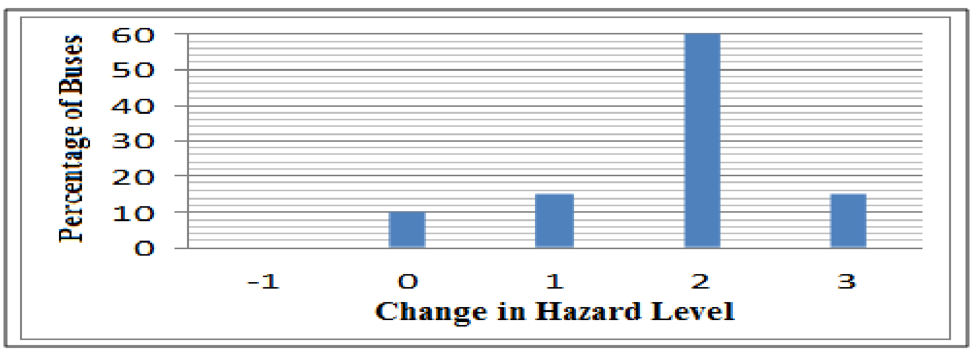

Figure. 5. Change in arc flash category on system buses as result of revised relay settings.

7. Conclusions and Recommendations

Simulation results show that with the help of reducing intentional delays in time over current elements and discrimination margins between devices, arc fault clearing time has been reduced significantly e.g. on substation bus from 0.226sec with old settings to 0.182sec using revised settings (Detailed results shown in Appendices E and F). Smaller fault clearing time has resulted in decreasing the energy involved in arc fault; once again considering the substation bus from 9.828Cal/cm^2 to 7.931Cal/cm^2 at a working distance of 45.72cm. Due to the lower magnitude of the energy involved, fault protection boundary has decreased from 1.308m to 1.175m and risk level has also been significantly reduced from category 3 to 2 for the same substation bus. Low category

clothing is inexpensive and it is easier to carry out repair work with it. A major advantage of this technique is that no capital cost is involved. However time investment is required on part of utility protection engineers. Thus this research work extends the application of existing protective devices from safety of equipment to the area of personnel safety. This practice can be adopted worldwide. Apparently a disadvantage of this approach is that the number of interruptions will increase for the consumers; however the increased human life safety limits this apparent disadvantage.
Providing safety equipment and education to field staff is mandatory to avoid any mishap while working on energized circuits.

Some important recommendations are given below:

- Utility protection engineers are suggested to revisit the PD settings as shown in this study to reduce the arc fault severity and subsequently the clothing category required for field staff safety.
- It is recommended that utility should provide the field staff with proper PPE.
- Arc flash analysis results at various locations must be displayed on equipment at prominent places to inform the maintenance staff about the hazard risk level.

8. Appendices

A. Simulation Result on Substation Bus.

I_{Load}(A)	$I_{F,Bus}$ (kA)	Source PD	$I_{Arcing,Bus}$ (kA)	Source PD I_{Arcing} (kA)	$T_{F,Clearing}$ (sec)	Incident Energy (Cal/cm^2)	PB (m)	Category (NFPA70E 2009)	Working Distance (cm)
1600	15.33	CB1	14.77	13.65	0.226	9.828	1.308	3PPE Cat	45.72

B. Simulation Results on Feeders

Feeder ID	Bus ID	$I_{F,Arcing}$ (kA)	$T_{F,Clearing}$ (Sec)	Incident Energy(Cal/cm^2)	FPB (m)	Risk Level
F-1	Bus 140	3.43	0.57	9.534	1.29	3
	Bus 141	3.385	0.69	9.541	1.29	3
F-2	Bus 113	3.748	0.49	9.482	1.29	3
	Bus 115	3.418	0.65	9.528	1.29	3
F-3	Bus 71	3.623	0.56	9.502	1.29	3
	Bus 77	3.43	0.65	9.534	1.29	3
F-4	Bus 32	3.53	0.59	9.517	1.29	3
	Bus 38	3.514	0.6005	9.519	1.29	3
F-5	Bus145	14.335	0.066	1.794	0.56	1
	PCC Furnace Load	3.312	0.438	9.479	1.28	3
	Bus147	2.916	0.505	10.311	1.34	3
	Bus148	2.856	0.518	10.348	1.34	3

C. Summary of Revised Feeder Relay Settings (Phase Element)

Feeder ID	Relay ID	I_{nom} (A)	CTR	I_{Pickup} (A)	Selected I_{Pickup} (A)	I_{inst} (A)	Available I_{inst} (A)	PSM	Required t_{op} (sec)	Calculated TSM	Selected TSM
F-2	Siemens Relay	211	80	5.275	5.28	46.25	46.25	8.76	0.2	0.115	0.12
F-3	Siemens Relay	194	80	4.85	4.85	34.375	34.38	7.087	0.2	0.09	0.09

F-4	Alstom Relay	212	80	5.3	4.8	45.625	45.75	9.505	0.2	0.126	0.13
F-5	Alstom Relay	360	80	8.1	8	43.1325	44	5.5	0.2	0.066	0.07
F-6	ABB Relay	237	80	5.905	5.9	51.65	52	8.754	0.2	0.115	0.12

D. Summary of Revised Feeder Relay Settings (Earth Element)

Feeder	Relay ID	I_{nom} (A)	CTR	I_{Pickup} (A)	Selected I_{Pickup} (A)	I_{inst} (A)	Available I_{inst} (A)	PSM	Required t_{op} (sec)	Calculated TSM	Selected TSM
F-2	Siemens Relay	211	80	0.79	0.79	44.06	44.06	55.77	0.2	0.8114	0.81
F-3	Siemens Relay	194	80	0.73	0.73	32.63	32.63	44.69	0.2	0.65	0.65
F-4	Alstom Relay	212	80	0.8	1	40	40	40	0.2	0.5877	0.59
F-5	Alstom Relay	360	80	1.35	1.5	33.25	33.25	22	0.2	0.311	0.31
F-6	ABB Relay	237	80	0.9	0.9	49.4	49.4	54.9	0.2	0.8	0.8

E. Simulation Results Summary for Substation Bus

	$I_{F,Arc}$ (kA)	Working Distance(cm)	$T_{F,Clearing}$(sec)	Energy involved (Cal/cm^2)	FPB (m)	Category
I_{Field}settings	14.77	45.72	0.226	9.828	1.308	3
$I_{Revised}$ settings	14.77	45.72	0.182	7.931	1.175	2

F. Comparison of Arc Flash parameters at Selected Buses on Feeders

Feeder ID	Bus ID	$I_{F,Arc}$ (kA)	$T_{F,Clearing}$(Sec)		Incident Energy (Cal/cm^2)		FPB (m)		Hazard/Risk Level	
			Old Settings	Revised Settings	Old Settings	Revised Settings	Old Settings	Revised Settings	Old Settings	Revised Settings
F-1	Bus140	3.43	0.57	0.266	9.534	1.541	1.29	0.52	3	1
	Bus141	3.385	0.69	0.2694	9.541	1.539	1.29	0.52	3	1
F-2	Bus113	3.748	0.49	0.072	9.482	0.459	1.29	0.28	3	0
	Bus115	3.418	0.65	0.267	9.528	1.54	1.29	0.52	3	1
F-3	Bus71	3.623	0.56	0.25	9.502	1.553	1.29	0.52	3	1
	Bus77	3.43	0.65	0.26	9.534	1.541	1.29	0.52	3	1
F-4	Bus32	3.53	0.59	0.258	9.517	1.547	1.29	0.52	3	1
	Bus38	3.514	0.60	0.26	9.519	1.546	1.29	0.52	3	1
F-5	PCC Furnace Load	3.312	0.438	0.276	9.479	1.542	1.28	0.518	3	1
	Bus147	2.916	0.505	0.316	10.311	1.639	1.34	0.534	3	1
	Bus148	2.856	0.518	0.323	10.348	1.639	1.34	0.534	3	1

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