Impact of Harmonics on Tripping Time and Coordination of Overcurrent Relay

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Abstract: - Theoretical and experimental analyses are discussed to investigate the effects of harmonics on the operation of overcurrent relays. Theoretical approaches based on relay characteristics provided by the manufacturer are performed under non-sinusoidal operating conditions. Besides that, the experiment tests were conducted as well by employing a computer-based harmonic generator. Computed and measured tripping times are compared and suggestions on the application of overcurrent relays in harmonically polluted environments are provided. Moreover, studies on the propagation of harmonic in power distribution system and its impact on coordination of overcurrent relays is also investigated in order to form conclusions.

Key-Words: - Overcurrent relay, harmonic, tripping time, coordination, power quality.

1 Introduction

Due to the extensive application of nonlinear loads and the introduction of renewable energy devices the load current usually contains harmonic components that affect the operating characteristic of the overcurrent relay. The technical literature is filled with documents and references to harmonics in power systems [1-9], however, few have addressed the influence of these waveform distortions on protective relays [10-13].

Power system problems associated with harmonics are not new to utility and industrial systems. Waveform distortions and harmonic injections are caused by nonlinear loads and electromagnetic devices. Electrical loads in industrial, commercial, and residential sectors of power system are typically a combination of linear and nonlinear loads. Any device with a nonlinear characteristic may be responsible for injecting harmonic currents and voltages into the electrical system. With the advancement of solid-state switching technology and higher energy efficiency achieved from power-electronic driven loads, the numbers of nonlinear loads are rapidly increasing. Examples of linear loads are incandescent lamps, motors, heaters, conventional ovens, and air conditioning; whereas nonlinear/power electronic loads include fluorescent lamps, adjustable speed drives, converters, computers, and other electronic home appliances, such as television sets, video players, etc.

Other sources of harmonics in power system are arc furnaces, saturated transformers, arcing faults, thyristor switching loads, transformer energization and capacitor bank switching. While nonlinear loads are considered as sources of harmonics, linear loads act as damping elements to harmonic propagation and affect the resonance frequency of the distribution system.

The effects of non-sinusoidal voltages and currents on the performance of underfrequency and overcurrent relays were experimentally studied by Fuller, et al. [10]. It was found that for harmonic voltage and current amplitudes, under frequency relays and the time delay operation of overcurrent relays show a marked deterioration in their performance; however, the instantaneous operating characteristics of overcurrent relays are hardly affected.

Girgis, et al. [11] studied the effects of voltage and current harmonics on the operation of four types of solid-state relays (SSR's). Their experimental results indicate that voltage harmonic distortion may cause a delay in the turn-on time of more than a cycle. In some cases, complete failure to turn on or off may occur.

Reference [12] addresses the effect of harmonics on the operation of directional distance (OHM unit) relay. Their experimental results show that the relay may report a wrong fault location in the presence of the harmonic distortion. The relay is frequency

sensitive up to 20 kHz, the highest testing frequency, and it is a phase sensitive when voltage and current are distorted. A number of relays were tested and each responded differently to harmonic distortions.
Elmore, et al. [13] describe the theoretical expectations of harmonic influence and present laboratory confirmation of the results. The results indicate that the influence of mixed frequency harmonics (with magnitude decreasing with order) on the steady state behavior of the protective relays studied is minor and insignificant; however, a distinct change in relay operation is reported for single harmonic injections.
In this paper, two analytical approaches are carried out. First approach is based on relay characteristics provided by the manufacturer to investigate the performance of overcurrent relays under non-sinusoidal operating conditions. Tripping times are computed and compared with measurements for current waveform distortions containing low order harmonics with different THD levels. The second approach is experimental analysis performed under same condition as that of first method. Theoretical and experimental analyses of this paper indicate that waveform distortion of load current will alter the tripping time of overcurrent relays and do impact on coordination between relays. Suggestions on the application of overcurrent relays in harmonically polluted environments are provided.

2 Theoretical calculation of tripping time from relay characteristic

2.1 RMS and THD of the non-sinusoidal load current

It is imperative to size the overcurrent device to true rms as measured by a true rms meter. Average sensing, rms equivalent meters do not correctly respond to harmonic current. Harmonic-rich currents will have higher effective rms as compared to non-distorted sinusoidal waveforms.

The rms value of a pure sinusoidal waveform $(\mathrm{I_{rms}} = \mathrm{I_{1rms}})$ is defined as:

$$I_{1rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_{1\max}{}^2 \sin^2(\omega t)dt} = \frac{I_{1\max}^2}{2} \qquad (1)$$

The rms value of a non-sinusoidal current waveform $(\mathrm{I_{ns-rms}})$ is defined as:

$$I_{ns-rms}^2 = \frac{1}{2\pi}\int_0^{2\pi} i^2(t)dt = \frac{1}{2\pi}\int_0^{2\pi}[I_{1\max}\sin(\omega t+\varphi_1) + I_{2\max}\sin(2\omega t+\varphi_2) + ... + I_{n\max}\sin(n\omega t+\varphi_n)]^2 dt$$

$$= \frac{I_{1\max}^2}{2} + \frac{I_{2\max}^2}{2} + ... + \frac{I_{n\max}^2}{2}$$

Simplifying the above equation results in

$$\mathrm{I_{ns-rms}} = \sqrt{\mathrm{I_{1rms}^2 + I_{2rms}^2 + ... + I_{nrms}^2}} \qquad (2)$$

The total harmonic distortion of load current is defined as:

$$\mathrm{THD_I} = \frac{\mathrm{I_h}}{\mathrm{I_{1rms}}} \times 100\% \qquad (3)$$

where $I_h = \sqrt{I_{2rms}^2 + I_{3rms}^2 + ... + I_{nrms}^2}$

2.2 The standard characteristic of relay

A solid state overcurrent relay type MCGG of Alstom T&D Protection & Control Ltd [14] is used. Operating time characteristics of the relay are provided by manufacturer as follow:

- Standard Inverse Characteristic (SI)

$$t_{si} = \frac{0.14}{[I^{0.02} - 1]} \quad [\text{sec}] \qquad (4)$$

- Very Inverse Characteristic (VI)

$$t_{vi} = \frac{13.5}{[I - 1]} \quad [\text{sec}] \qquad (5)$$

- Extremely Inverse Characteristic (EI)

$$t_{ei} = \frac{80}{[I^2 - 1]} \quad [\text{sec}] \qquad (6)$$

where: $\mathrm{t_{si}}$, $\mathrm{t_{vi}}$ and $\mathrm{t_{ei}}$ are the tripping times based on the standard inverse, very inverse and extremely inverse characteristics, respectively.
$I = I_{input} / I_{pickup}$ with $\mathrm{I_{pickup}}$ is setting value of relay.

2.3 Estimated tripping time from standard characteristics

To investigate the impact of waveform distortion on the tripping time of the relay, a single-phase rectifier load current with the following harmonic spectrum is assumed:

- The fundamental component of the distorted load current is varied from 1.20 to 4.4 times of the pickup current.
- For 10% of Total Harmonic Distortion ($\mathrm{THD_I}$), amplitudes of fundamental, third, fifth and seventh harmonics current components are set to 100%, 9.03%, 3.92% and 3.04%, respectively.
- For higher $\mathrm{THD_I}$ levels (e.g., 20% and 30%), the fundamental component of the load current is maintained while the magnitudes of harmonic distortions are proportionally increased.

- Three characteristic of relay are tested: Standard Inverse; Very Inverse and Extremely Inverse.
- Higher harmonic orders can be included, however, they are assumed to be negligible in this investigation.

Tripping times of the relay computed from the standard characteristics provided by the manufacturer (Eq.4; Eq.5; Eq.6) are computed and shown in Table 1, Table 2, Table 3 for three levels of THD load current (THD_I =10%, 20% and 30%).
Note that tripping times shown in those tables denote deviation of tripping time in percentage.

3 Experimental measurements

A single-phase testing system for measuring the effects of (individual and/or mixed) harmonic currents on the performance and tripping time of protective relays has been developed (Fig.1& Fig.2). A computer based waveform generator, an amplifier and corresponding software and interface circuits are used to test a solid state over-current relay of type MCGG manufactured by Alstom T&D Protection & Control Ltd. Individual harmonics currents and any combinations of up to four harmonic components with desired orders, magnitudes and phase shifts can be injected and the corresponding tripping times could be measured. Experimental are performed for:

- Sinusoidal currents, and
- Distorted currents with low order harmonics.

The results of first test are used to determine the standard characteristic of the relay as provided by the manufacturer. The second test is to determine the effect of harmonics on characteristic of relay and to measure the deviations of tripping times.
Figure 1 and figure 2 shows the experimental setup consisting of:
Waveform Generator: The computer based waveform generator uses software to generate non-sinusoidal signals with the desired harmonic magnitudes and harmonic phase angles. The signal is transferred through sound card of the computer.
Software Specifications and Features: DaqGen is the software signal generator [15] that allows any Windows-supported sound card to become a continuous real-time signal generator. Output signal has independent controls for wave type, frequency, level, and combination of modulators.
Power Amplifier: Normally, the output signal of sound card is weak and not sufficient for testing purposes. To amplify the signal to the desired level, a power amplifier was built which can generate a current up to 4A. A 20W Amplifier Module Kit (K5116) manufactured by Altronic Company, Australia is used.

Resistor: A variable resistor of maximum 10Ω is used to limit the output current of amplifier.

Relay: Experiments are performed for an Alstom single phase overcurrent relay type MCGG (I_n = 1A). This relay uses solid state techniques, each measuring board utilizing a micro-computer as a basic circuit element. The current measurement, whether perform on a single phase or poly phase input, is performed via an analogue to digital converter. Main features of the relay are:

- Choice of 4 inverse time curves and 3 definite time ranges by switched selection.
- Wide setting range of 0.05xIn to 2.4xIn in step of 0.05xIn.
- Time multiplier range from 0.05 to 1 on all seven characteristics.
- Accurately follows time curves to BS 142 and IEC60255

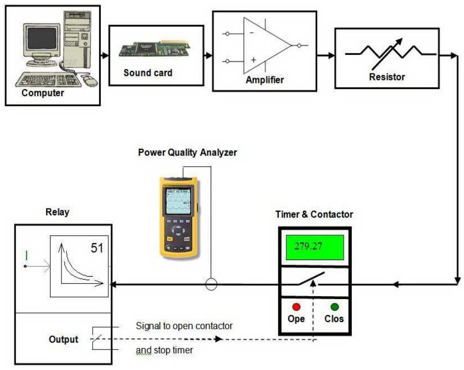

Fig.1 Principle diagram of experiment

Fig.2 Photo of experiment setup

Digital Timer: This digital timer is a combination of a timer and an internal 3-phase contactor. Resolution of timer is 10ms.

Power Quality Analyzer FLUKE 43: Power quality analyzer is mainly used to capture waveforms of injected current and measure total harmonic distortion (THD_I).

Using the experimental set up of Figure 2; tripping times of the relay are measured for distorted currents with THD levels of 10%, 20% and 30%, as specified in Section II. The fundamental component is varied from 1.20 to 4.4 times of the pickup current. Table 4, Table 5 and Table 6 shows the measured deviation of tripping time in percentage.

4 Harmonic propagation and its impact on coordination of relays

4.1 Power distribution system simulation for harmonic power flow calculation

As a result of above studies, harmonics do effect on the tripping time of over current relays, but the question now is that if those relays are installed in power system then how the coordination between relays are affected?

To illustrate effect of harmonics on the coordination of relays, a test case is simulated. The test case consists of 13-bus and is representative of a medium-sized industrial plant, actually this test case bases on a standard IEEE 13-bus industrial distribution system for harmonics modeling and simulation [16]. The plant is fed from a utility supply at 69 kV and the local plant distribution system operates at 13.8 kV. The system is shown in figure 3 and described by the data in Table 7, 8 & 9. Due to the balanced nature of this test case, only positive sequence data is provided. Capacitance of the short overhead line and all cables are neglected.

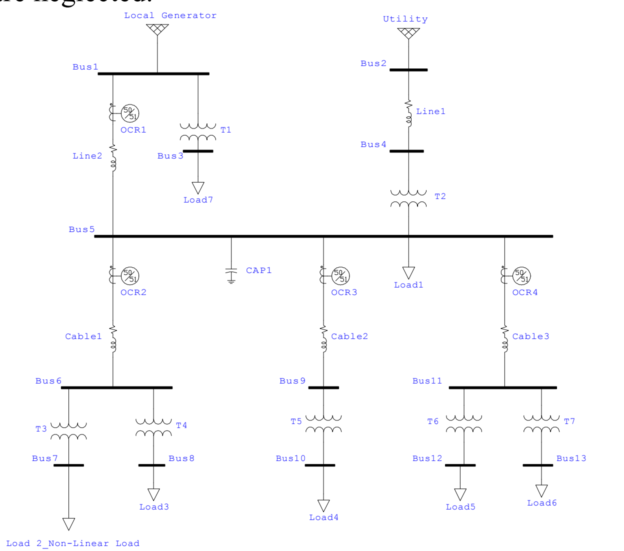

Fig.3 IEEE 13-bus industrial distribution system

Simulation software named ETAP (Electrical Transient Analyzer Program) [17] is utilized in order to run harmonic power flow for the test case. Practically, overcurrent relays are widely used to protect feeder and load in distribution power system, so in this test case overcurrent relays (OCRs) are utilized and connected to Line 2, Cable 1, Cable 2 and Cable 3. Load 2 is assigned as a non-linear load and actually it is an adjustable speed drive. This non-linear load will be moved around between different locations to picture that how much harmonics can occur at relay connected points. For harmonic study purpose, the adjustable speed drive (non–linear load) will be modeled as a six pulse current source conforming to typical IEEE six-pulse current source model.

4.2 Result of harmonic power flow analysis

To generally clarify the propagation of harmonics in the investigated grid, three possible test configurations are simulated:

- Non-linear load is connected to local load bus 7
- Non-linear load is switched to local load bus 10
- Non-linear load is switched to infeed bus 5

Results of harmonic power flow analysis and THD_I at relay connected points are shown in Fig.4, Fig.5, Fig.6:

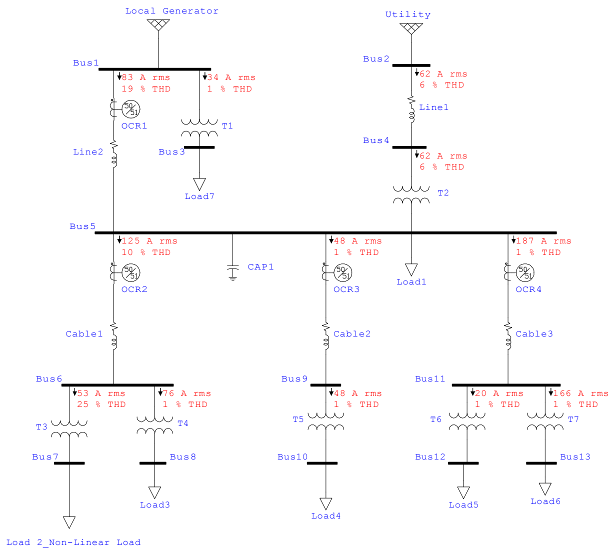

Fig.4 Harmonic power flow result when non- linear load is connected to bus 7

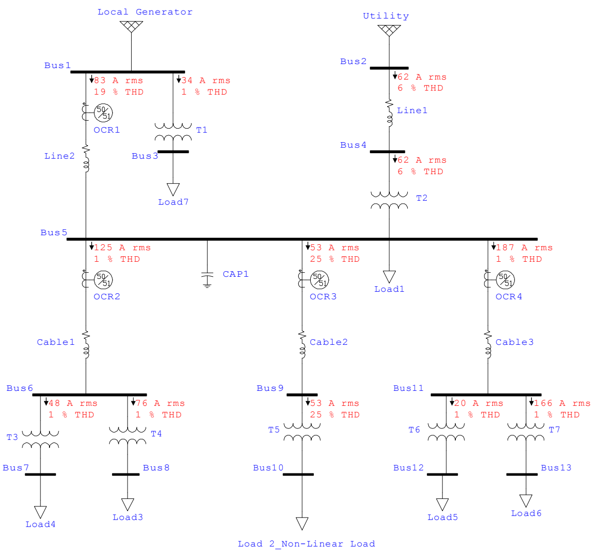

Fig.5 Harmonic power flow result when non- linear load is connected to bus 10

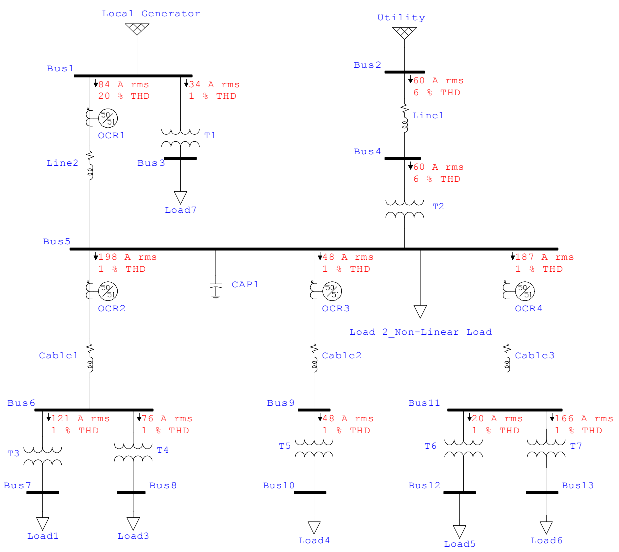

Fig.6 Harmonic power flow result when non- linear load is connected to infeed bus 5

This simulation shows a large deviation of THD_I at relay connected points around grid and value of THD_I at a specific point depends significantly on configuration of system.

4.3 Effect of harmonics on coordination of overcurrent relays

In order to ensure proper operation of protection system, overcurrent relays must be carefully coordinated. As a result, in this investigated grid, operation of relay OCR1 located at up stream feeder must coordinate with that of other relays (OCR2, OCR3 and OCR4) located downstream or at load side. In other word, there must be a margin time between tripping time of OCR1 and any that of downstream relays as shown below:

$$t_{\text{tripping of OCR1}}=\max\{t_{\text{tripping of OCR2}};\ t_{\text{tripping of OCR3}};\ t_{\text{tripping of OCR4}}\}+\Delta t \qquad (7)$$

where Δt is margin time (if calculated for faulty conditions then generally the value of Δt can be taken around 0.3s to 0.6s)

Based on harmonic power flow analysis, it can be seen that at OCR1 connected point the value of THD_I is about 19%, but at downstream relay connected points (OCR2 or OCR3 or OCR4) these values, at the worst case, may go down to around 1%. Referred to above studies on impact of THD_I on tripping time of relay, it can be concluded that:

- With THDI of 19% then OCR1 would trip faster than expected up to 45% in the worst case (Table 6)
- With THDI of about 1% then downstream relays such as OCR2 or OCR3 or OCR4 would almost trip properly as expected.

Now the problem is formulated as the upper stream relay (OCR1) would do tripping with shorter time (shorten up to 45% as expected) while other downstream relays would properly perform tripping. As a result, this time deviation of 45% might easily exceed margin time Δt in most cases, in other word upper stream relay OCR1 may trip in prior to other relays and this violates coordination requirement between relays (Eq.7)

5 Conclusion

Theoretical and experimental analyses of this paper have shown the influence of harmonic on solid state overcurrent relays. A representative relay was tested using sinusoidal and distorted currents containing low order harmonics. Main conclusions are:

- Waveform distortion does affect the performance of protective relays and may cause them to operate improperly. In most cases, the waveform distortion of the load current has little effect on the fault current. However, for overloaded conditions (or for low magnitude faults) the current may contain substantial harmonics and distortion can become a significant factor.
- Based on test results, it can be generally concluded that the effect of harmonic currents would lead to a shortened operation time of the solid-state relays; relay performs differently when THDI waveform distortion varies. Moreover, relay may even respond differently when different characteristics are investigated.
- The higher the THDI, the greater the variation of tripping time that can be seen. Significant deviations can occur with 20% or greater THD in current

waveform at all three (Standard Inverse, Very Inverse and Extremely Inverse) characteristics of relay.

- Harmonics mostly show significant effects on tripping time at overload current ranges (1.2 to 2 times of pickup current); in case of fault conditions, those effects are theoretically negligible.
- It is likely to be impossible to generalize the behavior of any relay response to harmonics without actual tests, as the actual test results show larger deviations than that of theoretical calculation.
- In harmonic-polluted environment as such industrial factories, the proper coordination of relay may be violated. This may cause nuisance problems and sometime shutdown power supply unexpectedly.
- Finally, impact of harmonics on the coordination of relays should be carefully investigated because this impact depends greatly on configuration of grid, setting time and relay's utilized characteristic as well.

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Appendix:

Table 1: Computed tripping times (in percentage) for standard inverse characteristic*

I_{in}/I_{pick}	Standard Inverse Characteristic		
	THD_I 10%	THD_I 20%	THD_I 30%
1.2	-2.82	-10.26	-20.04
1.4	-1.54	-5.84	-11.96
1.6	-1.08	-4.25	-8.84
1.8	-0.93	-3.46	-7.26
2	-0.80	-2.99	-6.18
2.4	-0.63	-2.40	-5.04
2.8	-0.59	-2.08	-4.31
3.2	-0.50	-1.85	-3.87
3.6	-0.56	-1.67	-3.52
4.0	-0.40	-1.41	-3.21
4.4	-0.22	-1.29	-3.01

Table 2: Computed tripping times (in percentage) for very inverse characteristic*

I_{in}/I_{pick}	Very Inverse Characteristic		
	THD_I 10%	THD_I 20%	THD_I 30%
1.2	-3.08	-11.20	-21.88
1.4	-1.81	-6.84	-14.04
1.6	-1.38	-5.29	-11.07
1.8	-1.18	-4.56	-9.54
2	-1.04	-4.00	-8.52
2.4	-0.83	-3.42	-7.37
2.8	-0.80	-3.20	-6.80
3.2	-0.81	-3.09	-6.35
3.6	-0.77	-2.70	-5.97
4.0	-0.67	-2.67	-5.78
4.4	-0.76	-2.52	-5.79

Table 3: Computed tripping times (in percentage) for extremely inverse characteristic*

I_{in}/I_{pick}	Extremely Very Inverse Characteristic		
	THD_I 10%	THD_I 20%	THD_I 30%
1.2	-3.36	-12.20	-23.82
1.4	-2.11	-7.97	-16.32
1.6	-1.72	-6.51	-13.55
1.8	-1.51	-5.77	-12.13
2	-1.42	-5.36	-11.32
2.4	-1.31	-4.88	-10.35
2.8	-1.20	-4.70	-9.91
3.2	-1.15	-4.50	-9.58
3.6	-1.20	-4.48	-9.42
4.0	-1.13	-4.32	-9.19
4.4	-1.15	-4.36	-9.17

Table 4: Measured tripping time (in percentage) for standard inverse characteristic*

I_{in}/I_{pick}	Standard Inverse Characteristic		
	THD_I 10%	THD_I 20%	THD_I 30%
1.2	-20.40	-34.76	-41.82
1.4	-17.52	-24.73	-27.99
1.6	-11.95	-21.38	-28.62
1.8	-10.94	-20.21	-21.39
2	-11.57	-15.69	-20.49
2.4	-6.25	-9.43	-11.79
2.8	-6.49	-11.33	-13.12
3.2	-5.41	-10.33	-12.88
3.6	-4.75	-9.51	-12.32
4.0	-4.34	-8.68	-10.19
4.4	-4.08	-7.76	-10.00

Table 5: Measured tripping time (in percentage) for very inverse characteristic*

I_{in}/I_{pick}	Very Inverse Characteristic		
	THD_I 10%	THD_I 20%	THD_I 30%
1.2	-24.97	-39.26	-47.25
1.4	-25.82	-34.67	-38.14
1.6	-13.91	-25.84	-34.50
1.8	-14.02	-24.94	-24.94
2	-12.44	-19.84	-26.50
2.4	-9.03	-13.92	-17.40
2.8	-10.90	-18.01	-20.02
3.2	-8.81	-16.72	-20.60
3.6	-9.58	-17.07	-20.91
4.0	-8.98	-14.77	-16.57
4.4	-6.88	-13.99	-19.95

Table 6: Measured tripping time (in percentage) for extremely inverse characteristic*

I_{in}/I_{pick}	Extremely Very Inverse Characteristic		
	THD_I 10%	THD_I 20%	THD_I 30%
1.2	-29.86	-45.32	-47.69
1.4	-21.40	-29.72	-38.14
1.6	-19.69	-32.94	-43.04
1.8	-16.81	-30.61	-34.19
2	-17.52	-28.86	-42.63
2.4	-11.53	-20.00	-25.26
2.8	-13.75	-24.85	-28.90
3.2	-12.40	-24.39	-29.92
3.6	-12.02	-23.38	-30.25
4.0	-14.66	-25.00	-29.17
4.4	-10.16	-21.71	-28.29

*Note: minus sign (-) denotes that tripping time is shortened.

Table 7: Per-unit line and cable data (base value 13.8kV, 10MVA)

From	To	R	X
Bus 2	Bus 4	0.00139	0.00296
Bus 5	Bus 1	0.00122	0.00243
Bus 5	Bus 6	0.00075	0.00063
Bus 5	Bus 9	0.00157	0.00131
Bus 5	Bus 11	0.00109	0.00091

Table 8: Transformer data

From	To	Voltage	kVA	%R	%X
Bus 4	Bus 5	69:13.8	15000	0.4698	7.9862
Bus 1	Bus 3	13.8:0.48	1500	0.9593	5.6694
Bus 6	Bus 7	13.8:0.48	1250	0.7398	4.4388
Bus 6	Bus 8	13.8:4.16	1725	0.7442	5.9537
Bus 9	Bus 10	13.8:0.48	1500	0.8743	5.6831
Bus 11	Bus 12	13.8:0.48	1500	0.8363	5.4360
Bus 11	Bus 13	13.8:2.4	3750	0.4568	5.4810

Table 9: Generation and load data

Bus	P_{gen} kW	Q_{gen} kvar	P_{load} kW	Q_{load} kvar
Bus 1	2000	1910	-	-
Bus 3	-	-	600	530
Bus 5	-	-	2240	2000
Bus 7	-	-	1150	290
Bus 8			1310	1130
Bus 10	-	-	810	800
Bus 12	-	-	370	330
Bus 13	-	-	2800	2500