Negative Sequence Relaying Applications in Ungrounded and High Impedance Grounded Industrial Systems

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Abstract: Industrial Power systems that serve critical process loads are often served by high impedance grounded, or ungrounded, power distribution systems. These systems are intended to allow continued operation of the process loads despite a single phase-to-ground fault on the system, allowing time for maintenance personnel to find and resolve the fault without unplanned equipment shutdown. The risk associated with these systems is that a second phase-to-ground fault, on a different phase, creates a phase-to-phase fault with much higher fault currents than those associated with the initial phase-to-ground fault. These phase-to-phase faults can take a variety of paths, often through process equipment not intended for carrying fault current. The fault current is limited by the impedance of the fault path and may not be sufficient to quickly trip larger phase current-sensing circuit breakers. Where the faults occur with sufficient electrical distance between the two connections to ground, it is possible for two ground-fault trip units to see the fault and respond. When there are not ground fault trip units or both fault points occur downstream of a single ground fault trip unit, other means are necessary to ensure proper fault clearing. This paper will explore the use of negative sequence overcurrent sensing to detect these faults at levels and speeds not achievable using conventional circuit breaker technology. Potential fault conditions will be explored, with comparisons between phase overcurrent, ground overcurrent, and negative sequence sensing and the levels at which each might be able to detect and interrupt the fault current. The paper will also show that the use of negative sequence sensing makes possible the detection and interruption of these fault currents securely and at values less than maximum load currents. Finally, the paper will provide guidelines to aid in determining which systems, or where in the system, the maximum benefit can be achieved through use of negative sequence sensing.

Background

In the interest of maintaining continuous process operation, many industrial systems are operated either ungrounded or high-impedance grounded. In these systems, a single line-to-ground fault will draw currents small enough that circuit breakers or fuses used as feeder or branch circuit protection will not trip. This allows the faulted circuit to remain in service while the ground fault is located and corrective measures planned and implemented. These single faults on the system are typically detected by a shift in voltage-to-ground of each phase. The detector may be a voltage relay or may be as simple as light bulbs connected in grounded wye. Current-based detection of single ground faults in ungrounded systems is not practical while, in high impedance grounded systems, current in the grounding impedance indicates the presence of a fault but not the location. Some high-impedance grounding systems provide a means to pulse the ground current between two values, such as 5A and 10A, to aid in tracing the ground fault.

The presence of a second ground fault before the first fault is found and repaired creates a line-to-line fault through ground. The amount of ground current returning to the source remains at the low levels of a single fault; but the fault current between the two faults can, depending on fault resistance, be much higher, and is likely to flow through paths not intended to carry fault currents. Depending on the fault impedance and the rating of the downstream device(s) nearest the fault locations, the fault can persist for extended periods. While the fault persists, equipment is subject to voltage rise, heating due to the current flow, and the effects of arcing gaps and other impedance points.

Some attempts are made to use residual ground-fault sensing elements to detect these phase-to-phase faults. When the entire fault current flows through a single residual ground-fault device, the fault will not be detected as the ground-fault device will measure only the current returning to the source through ground. The remaining fault current flows out on one phase conductor and returns on another phase conductor, the sum being very close to zero. When the fault occurs between two circuits with different residual ground-fault sensing elements, the fault will be seen and will trip one or both devices provided the fault current is sufficiently large.

Negative Sequence

When using symmetrical components to analyze unbalanced system operation and fault conditions, the negative sequence is generated by unbalance. A balanced three-phase load or a bolted three-phase fault will be entirely positive sequence. Unbalanced loads or asymmetric faults will reduce the proportion of positive sequence current and will produce negative sequence currents. These unbalanced conditions will also produce zero sequence currents to the extent that load or fault current flows in some conductor other than the three-phase conductors.

In the ungrounded or high impedance systems, line-to-neutral loads are not permitted, eliminating one significant source of potential negative sequence currents in the system. The presence of phase-to-phase loads will produce a negative sequence component to the normal load currents but, in many cases, this negative sequence current will have a very low magnitude relative to the total current or to the positive sequence current.

Negative sequence currents on the secondary of transformers will be reflected in the primary currents. Where delta-wye transformers are used, the negative sequence current in the primary will be shifted 30 degrees from the secondary, but in the opposite direction to the shift of the positive sequence currents. When there are multiple step-down transformers connected to the system under consideration, the negative sequence currents from each will tend to cancel to the extent that the unbalances behind each transformer are on different phases.

Three-phase motor loads, the principal load on many systems of this type, do not produce negative sequence currents during normal operation.

These characteristics suggest that negative sequence currents may provide a means of identifying and clearing phase-to-phase faults in these systems.

Analysis – Single Faults

This is the classic line-to-line-to-ground (LLG) fault. For the Phase B to Phase C fault analyzed, the sequence diagram is as shown in Figure 1. The impedances shown as Z1c, Z2c, and Z0c are the impedances in the "common" branch of the circuit as used with the parallel faults shown in Figure 3. In this case, there are no branch currents but, to keep the notation similar, the common branch notation is shared between the diagrams.

The fault resistance is shown as Zf/2 rather than Zf to align with the fault impedance given in the study results. The study fault impedance is the total impedance between the two faulted phases while the typical derivation of the sequence network has two equal impedances, both

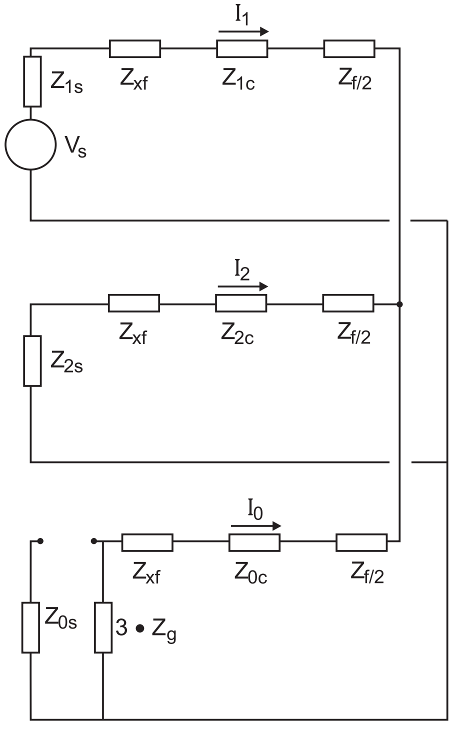


Figure 1.

labeled Zf, from each phase to the fault location. For the system considered, 3*Zg is very large compared to the other impedances. On a 1 MVA base, the 55.4 ohms of resistance necessary to limit ground faults to 5A equates to a 3*Zg of over 720 p.u., while the total positive sequence and negative sequence impedances are less than 0.1 p.u. It can be seen that essentially no current flows in the zero sequence branch and that the positive and negative sequence currents are of the same magnitude and opposite angle.

The very low current in the zero sequence branch of the network shows why ground elements cannot be used to detect second ground faults in this configuration. A ground element set to detect a LLG fault would also detect a single line-to-ground fault (SLG). Since the goal is to allow SLG faults to persist until repaired, the inability to distinguish LLG and SLG faults precludes using sensitive ground elements in this application.

The negative sequence branch of the network carries essentially the same current as the positive sequence branch. With this configuration, the positive and negative sequence currents each have a magnitude approximately equal to the faulted phase current divided by the square root of 3. The presence of this negative sequence current can be used to distinguish these faults from load for fault currents less than the maximum load current. The extent to which this can be less than maximum load current is discussed below under "Setting the Negative Sequence Elements."

Analysis – Parallel Faults

The sequence network for this fault is shown in Figure 2. This is not a common sequence network configuration, but portions of it are suggested in several of the references, particularly *Power System Protection* and *Analysis of Faulted Power Systems*.

The impedances Z1c, Z2c, and Z0c in the network are the common portion, between the transformer (Zxf) and the point the two branches split. The impedances Z1a, Z2a, and Z0a are in one branch to the fault while impedances Z1b, Z2b, and Z0b are in the other branch. For the purposes of this analysis, it is assumed that half of the total fault impedance, Zf, is on each side of ground. Given the magnitude of 3*Zg relative to the rest of the impedances in the system, the distribution of the total fault impedance between the phases and "ground" has little effect on the results.

The diagram shows the sequence network for two simultaneous SLG faults. The phase-shifting transformers are a result of the symmetry change in creating a SLG fault in a phase other than Phase A. In this case, branch 'a' has a fault on Phase B, while branch 'b' has a fault on Phase C. If one of the faults were on Phase A, all three of the transformers for that portion of the network would be 1:1 with no phase shifting.

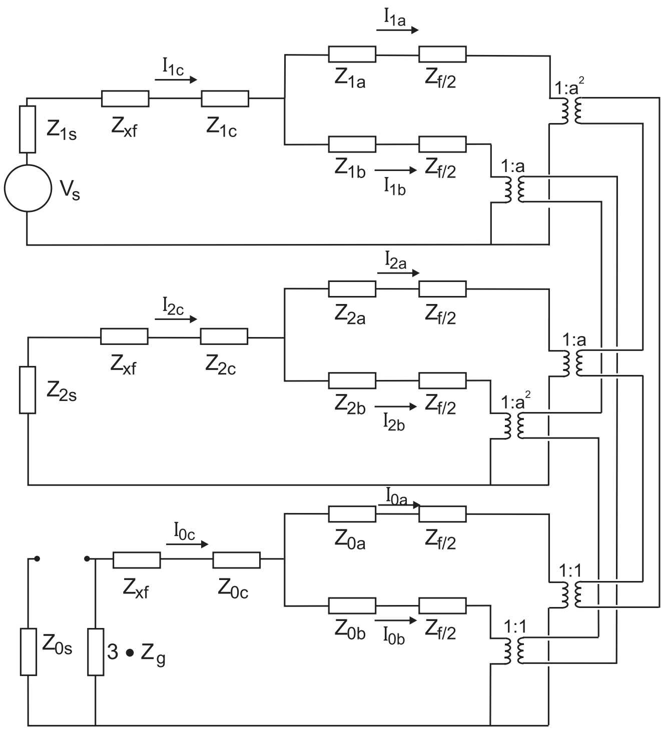


Figure 2.

If the 3*Zg impedance is considered to be infinite, it can be seen that the zero sequence currents in the two branches would be equal in magnitude and 180 degrees apart in phase. With the zero sequence currents in the branches of equal magnitude, it becomes evident that the negative and positive sequence currents in the two branches are also of the same magnitude as the zero sequence currents. In the case under consideration, the amount of current in the common portion of the zero sequence circuit is very small compared to the zero sequence current in the two branches, and the currents in the branches are very nearly 180 degrees out of phase.

The phase shifting in the positive and negative sequence networks cause the two branch currents to be 60 degrees out of phase with each other. The result of this is that the current in the common portion of the network has a magnitude $\sqrt{3}$ times larger than currents in the branches, with the phase angle in the common portion 30 degrees from the two branches.

If the impedances in the branches are combined and placed in the common portion of the network, this network will give the same results as the simpler network of Figure 2.

For a fault represented by the network of Figure 3, breakers or relays on the branches will see positive, negative, and zero sequence currents, each with a magnitude equal to 1/3 of the fault current. Breakers or relays on the common portion of the network will see only positive and negative sequence currents, and these currents will each have a magnitude equal to the fault current divided $\sqrt{3}$.

The Study System

The results presented in this paper are based on a simple system, Figure 3, designed to allow testing various fault locations on feeders of many common sizes. The system starts with a source supplying 5500 Amperes of fault current at 12.47kV to a 2500kVA transformer with an impedance of 5.75%. On the 480V side of the transformer, the neutral is grounded through a resistor to limit phase-to-ground fault currents to 5A. A main switchboard is connected to the transformer through 50 feet of 9 parallel sets of 500 kcmil copper cables. At the service switchboard, the three-phase fault current available is 36,854A.

The internal feeders are all 50 feet in length; the 200A, 400A, and 800A feeders are made of one, two, and four sets of 3/0 copper conductors in parallel. The 1600A feeders are five sets of 500 kcmil copper in parallel.

The breakers at the service switchboard are ANSI rated Low Voltage Power Circuit Breakers. Beyond that board, the 800A

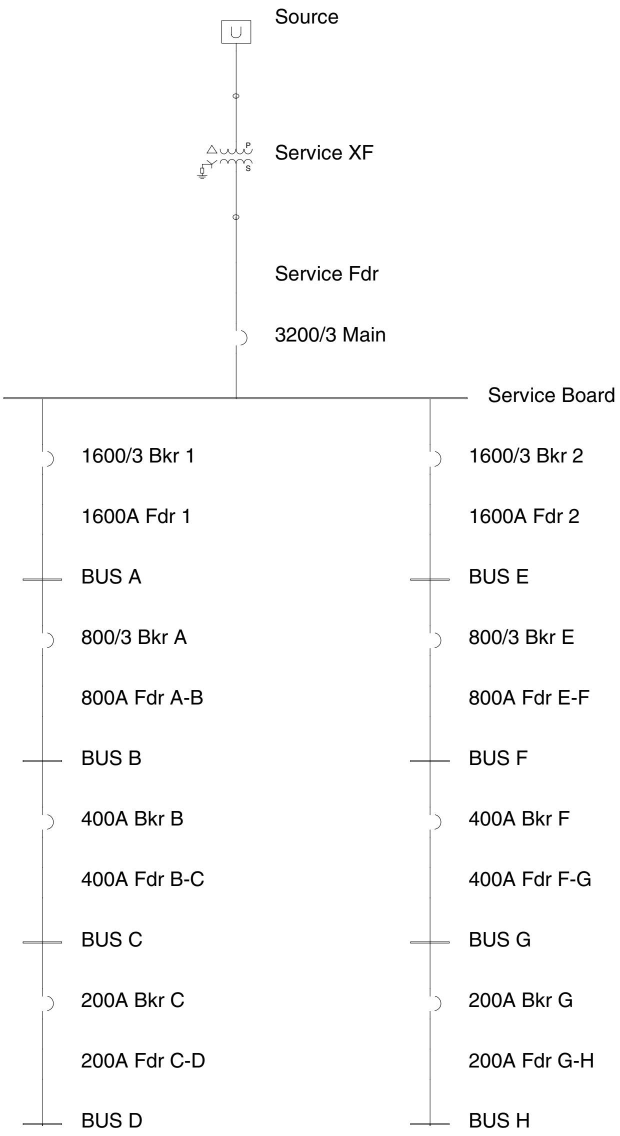


Figure 3.

breakers are equipped with solid-state trip units and ground fault sensing. The 400A and 200A breakers have thermal-magnetic trips. The system uses circuit breakers from two of the major manufacturers, although this appears to have a limited effect on the results.

The breaker phase and ground settings were selectively coordinated to the extent possible; some overlap in the instantaneous region of the phase settings is unavoidable.

Negative sequence trip elements are those of one line of relays. The negative sequence lines on the trip curves are the relay sense and operate times; an additional 0.12 seconds was added to each for breaker operating time.

Coordination curves are shown in Figures 4 through 9 at the end of the paper.

The Study

Results of the study calculations are shown in Table 1. Faults of increasing resistance were created at each load bus and between load busses of the same rating of the different branches. For each fault resistance, phase currents and sequence currents were calculated using a MathCAD sheet created for the purpose; these values were checked against results from a commercial fault-calculation software package. With these values available, breaker trip times were calculated for tripping based on phase, ground, and negative sequence values. For many fault resistances, it was found that one or more of the elements would not cause a breaker to trip.

When the entire fault happens downstream of a single ground unit, the residual current seen by the ground unit is limited by the grounding impedance, and the ground unit will not trip for these faults. This will be discussed further, under “Single Faults.”

When the two fault locations are downstream of different ground units, there is residual current seen by the ground unit. The magnitude of this residual current is not limited by the grounding impedance but is limited by the circuit and fault impedances.

As the fault resistance increases, fault currents decrease and eventually are low enough that protective elements will no longer pick up. The clearing times listed in the data include clearing times in seconds, N/A where the listed element would never trip, and >nnn when the element would pick up but the clearing time is over 1000 seconds or tripping depends on where in the tolerance band the specific breaker falls.

With tripping times available, energy dissipated in the fault path is calculated. For tripping times of “N/A” or >nnn, a clearing time of 1000 seconds was chosen arbitrarily on the assumption that someone would eventually notice the problem and turn off enough circuits to clear one of the phase-to-ground faults. The energy dissipated in each fault, if cleared by the phase, ground, or negative sequence elements, are listed and the lowest value shown. Based on these energy levels, a best element is selected.

The final column looks at those cases where the negative sequence element is the best element and compares the energy dissipated prior to the negative sequence element clearing the fault with the energy dissipated if the second best element clears the fault.

Results

Refer to Table 1. As anticipated, ground elements in the common portion of the system do not see, and will not clear, these LLG faults. A somewhat unexpected result was that when there are ground elements in the branches, those ground elements are often the most effective element in clearing the fault. The results for tests 54-60 and 80-81 show the ground element clearing these faults faster than either the phase or negative sequence elements; however, in these cases the ground element is one or more breakers upstream from the fault location. This is indicated in the Table by the highlighted area.

For bolted faults, phase elements operating in their instantaneous region will provide faster fault clearing than either negative sequence or ground elements (see tests 16, 23, 30, 37, 45, 53, 61, 69, and 77). Tests 1, 6, and 11 provide similar results with a phase element in its short time region.

Where a ground element is not available or will not see the fault, and where the fault resistance is high enough that the phase elements do not trip in the fastest portion of their trip characteristics, the negative sequence elements can be seen to reduce significantly the amount of energy released during fault events. In most cases, the energy released in the fault is less than 1% of that released were the negative sequence element not present. In many cases, the energy released is less than 0.1% of that otherwise released.

Considerations in Applying Negative Sequence Elements

It is important to establish the normal level of negative sequence current in the system to be protected. If the entire load is connected between two phases, with no load on the third phase, the negative sequence current would be the maximum load current divided by $\sqrt{3}$. Setting the negative sequence pickup at this level will ensure that the negative sequence element will not pick up for any load condition, but it may be set much higher than need be. For a system where 75% or more of the load is 3-phase motor load, it may be possible to set the negative sequence elements at 25% of maximum load, the setting used in this study.

A negative sequence element can overreach a downstream phase sensing element. To check for possible overreach, the negative sequence element should be plotted at $\sqrt{3}$ times its actual current and compared to the phase element. For example, to check a negative sequence element with a 100A pickup (I2) against a downstream 125A breaker (phase current), plot the negative sequence element as though it had a 173A pickup (100A * $\sqrt{3}$). Because this overreach does not occur on balanced load, it may be decided to allow overreach for increased sensitivity similar to the way ground elements typically overreach downstream phase elements.

Because these faults are through a path not designed to carry fault currents, there is a possibility of arcing during the fault condition. If a 50T type of element is used, there is the possibility of the timing resetting during the arcing condition if the current drops sufficiently. Using a 51 element and selecting an integrating (or electromechanical) reset characteristic will allow the element to resume timing following intermittent interruptions. Selecting the flattest curve available in the relay will allow relatively uniform timings for higher currents while maintaining coordination at lower current levels. The curves used in this study are a short-time inverse curve family based on the IAC-55 relay curves and a definite time curve family based on the CO-6 relay. These two curve families are similar with the CO-6 type curves fitting above the IAC-55 type curves. The lower two curves are the IAC-55 curves and the upper two curves are the CO-6 curves.

It is also possible that an existing system that has never had negative sequence sensing will have bad power factor correction capacitors or starter contactors that do not make or break uniformly. One system was found to have several problems creating undesired negative sequence currents in excess of 50% of load. Once these problems were tracked down and repaired, the negative sequence current on the system was reduced to less than 10% of maximum load current.

Application at Higher Voltages

While this study is based on a 480V system, the findings are applicable at higher voltages. Medium-voltage industrial systems with relays would have different curves for phase and ground elements, but the general relationships remain. In general, relay ground elements can be set lower than the ground elements of 480V breakers, but relay ground elements are also unable to detect these faults when both faulted phases are downstream of the ground element.

Conclusions

Phase protection is effective for bolted faults and faults with very low resistance but can be very slow for faults with more than minimal resistance; sufficient resistance and a phase element will not clear the fault.

Ground protection can be effective if the ground element sees only part of the fault. Ground elements are blind to LLG faults on these systems when the entire fault is downstream of the ground element.

Negative sequence elements can detect LLG faults on ungrounded or high-impedance grounded systems whether seeing part of the fault or the entire fault. If the negative sequence element sees the entire fault it will respond if the fault current exceeds $\sqrt{3}$ times pickup. If the negative sequence element sees only one branch of the fault it will respond if the fault current exceeds 3 times the pickup.

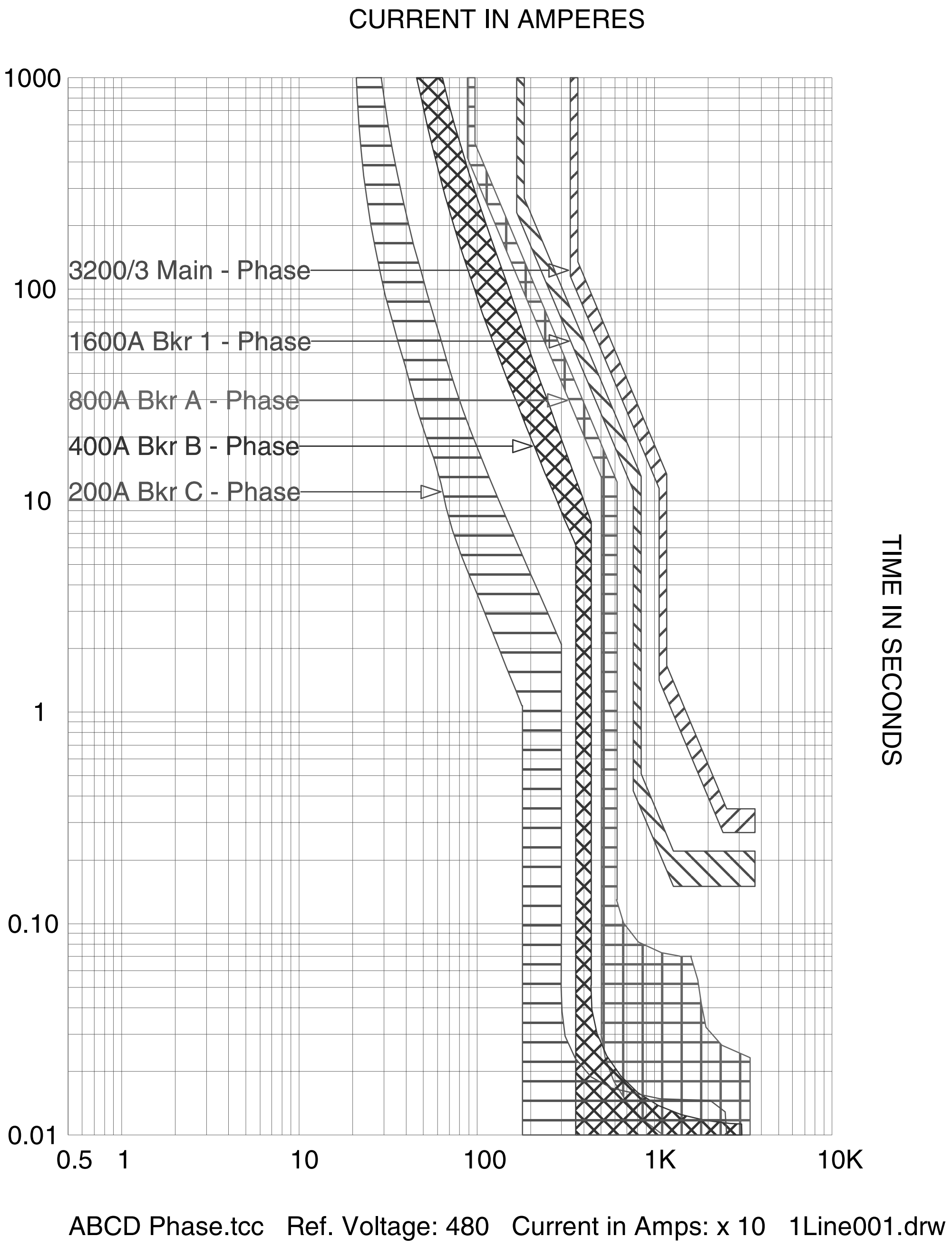
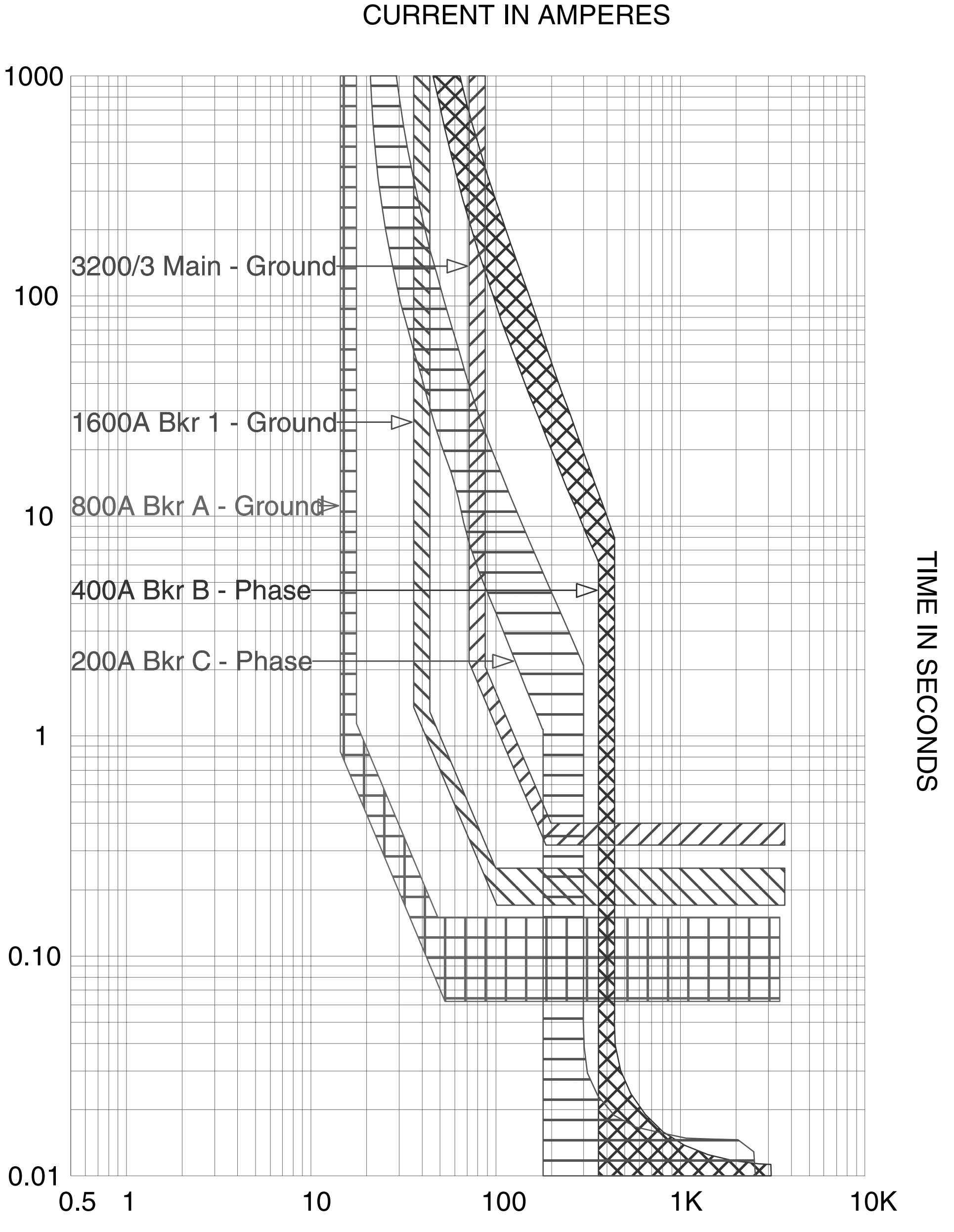

CURRENT IN AMPERES
1000
100
10
1
0.10
0.01
0.5
1
10
100
1K
10K
TIME IN SECONDS
3200/3 Main - Phase
1600A Bkr 1 - Phase
800A Bkr A - Phase
400A Bkr B - Phase
200A Bkr C - Phase
ABCD Phase.tcc Ref. Voltage: 480 Current in Amps: x 10 1Line001.drw

Figure 4.


CURRENT IN AMPERES
TIME IN SECONDS
1000
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0.10
0.01
0.5
1
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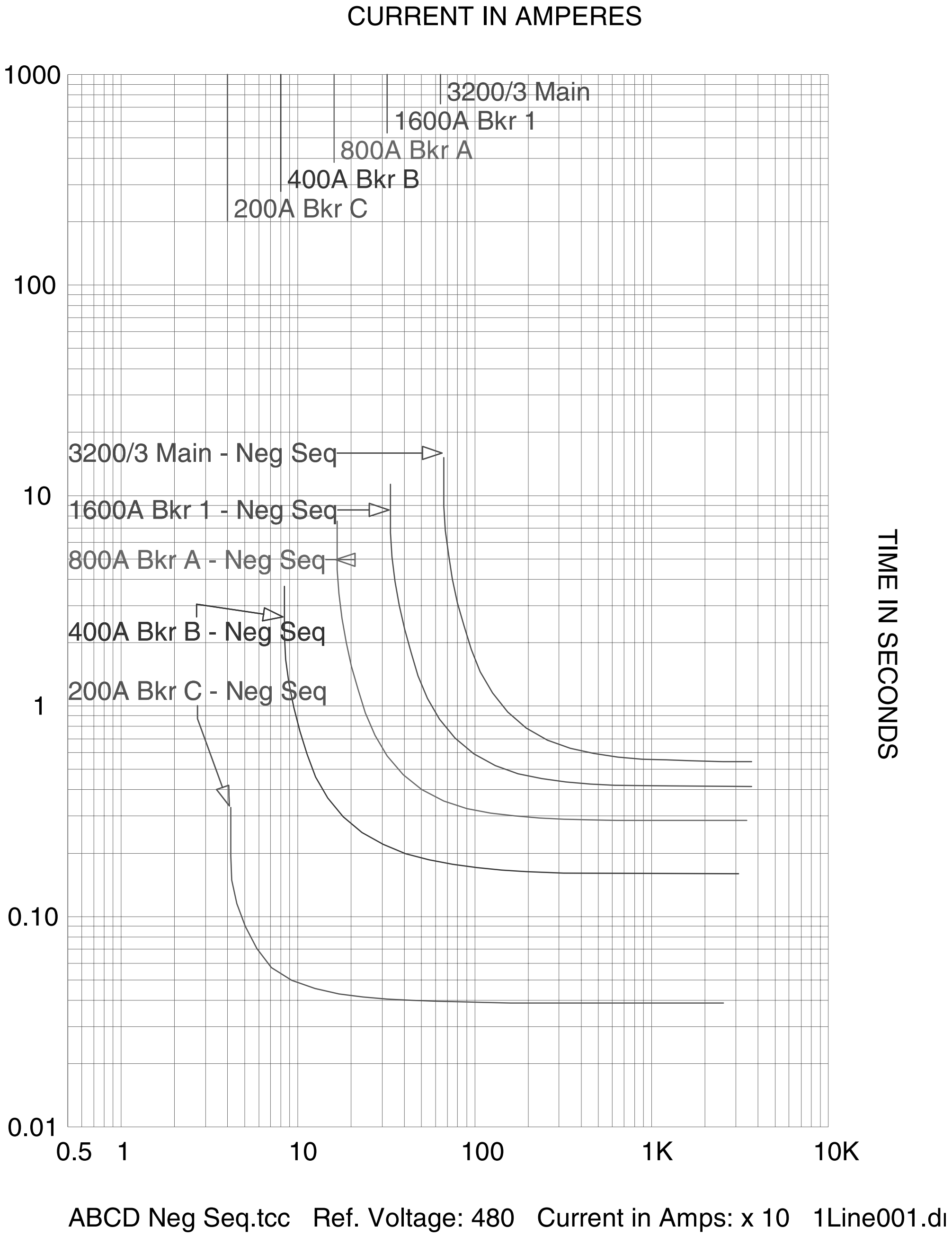
1K
10K
3200/3 Main - Ground
1600A Bkr 1 - Ground
800A Bkr A - Ground
400A Bkr B - Phase
200A Bkr C - Phase
ABCD Ground.tcc Ref. Voltage: 480 Current in Amps: x 10 1Line001.drv

Figure 5.


CURRENT IN AMPERES
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TIME IN SECONDS
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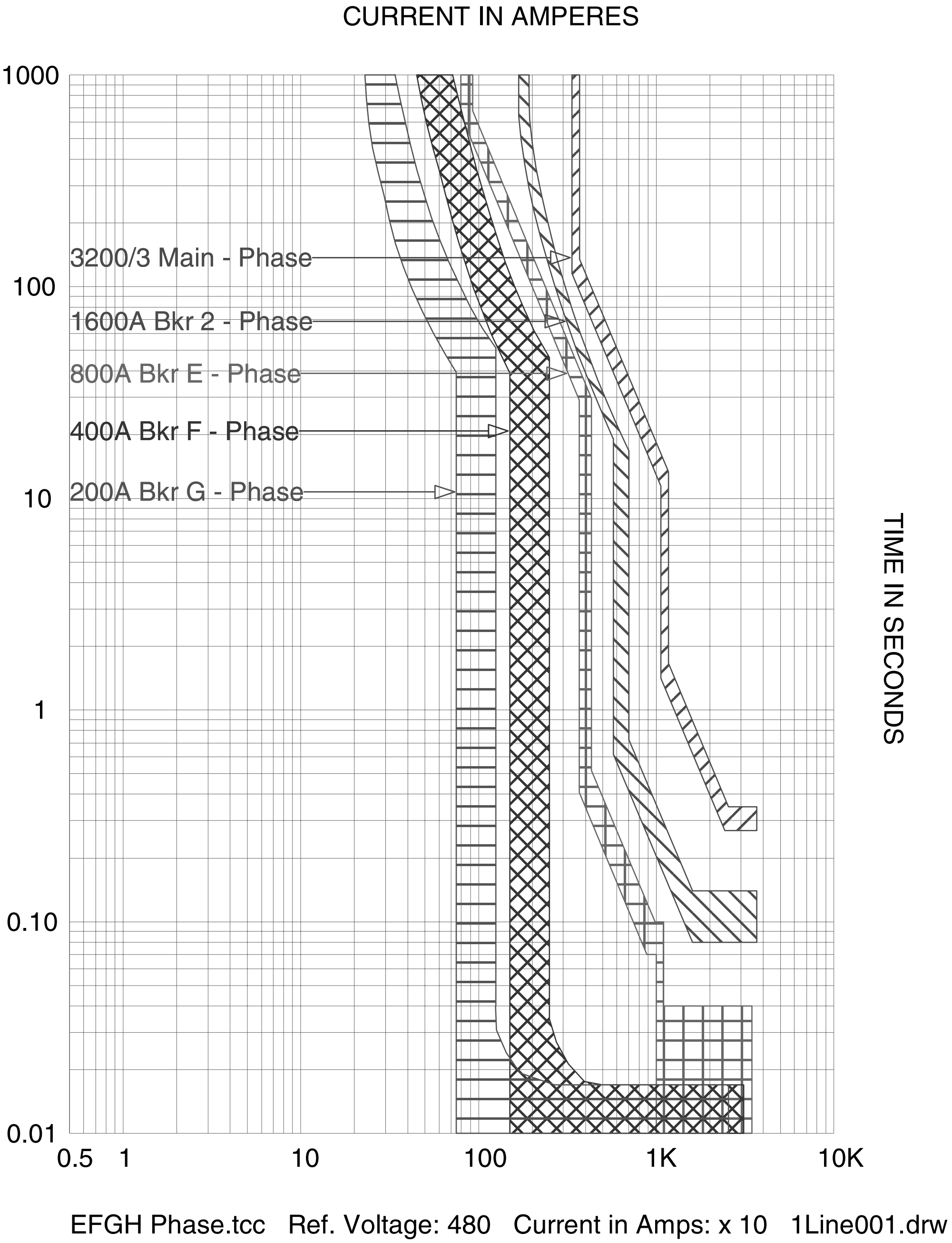
1600A Bkr 1
800A Bkr A
400A Bkr B
200A Bkr C
3200/3 Main - Neg Seq
1600A Bkr 1 - Neg Seq
800A Bkr A - Neg Seq
400A Bkr B - Neg Seq
200A Bkr C - Neg Seq
ABCD Neg Seq.tcc Ref. Voltage: 480 Current in Amps: x 10 1Line001.dı

Figure 6.


CURRENT IN AMPERES
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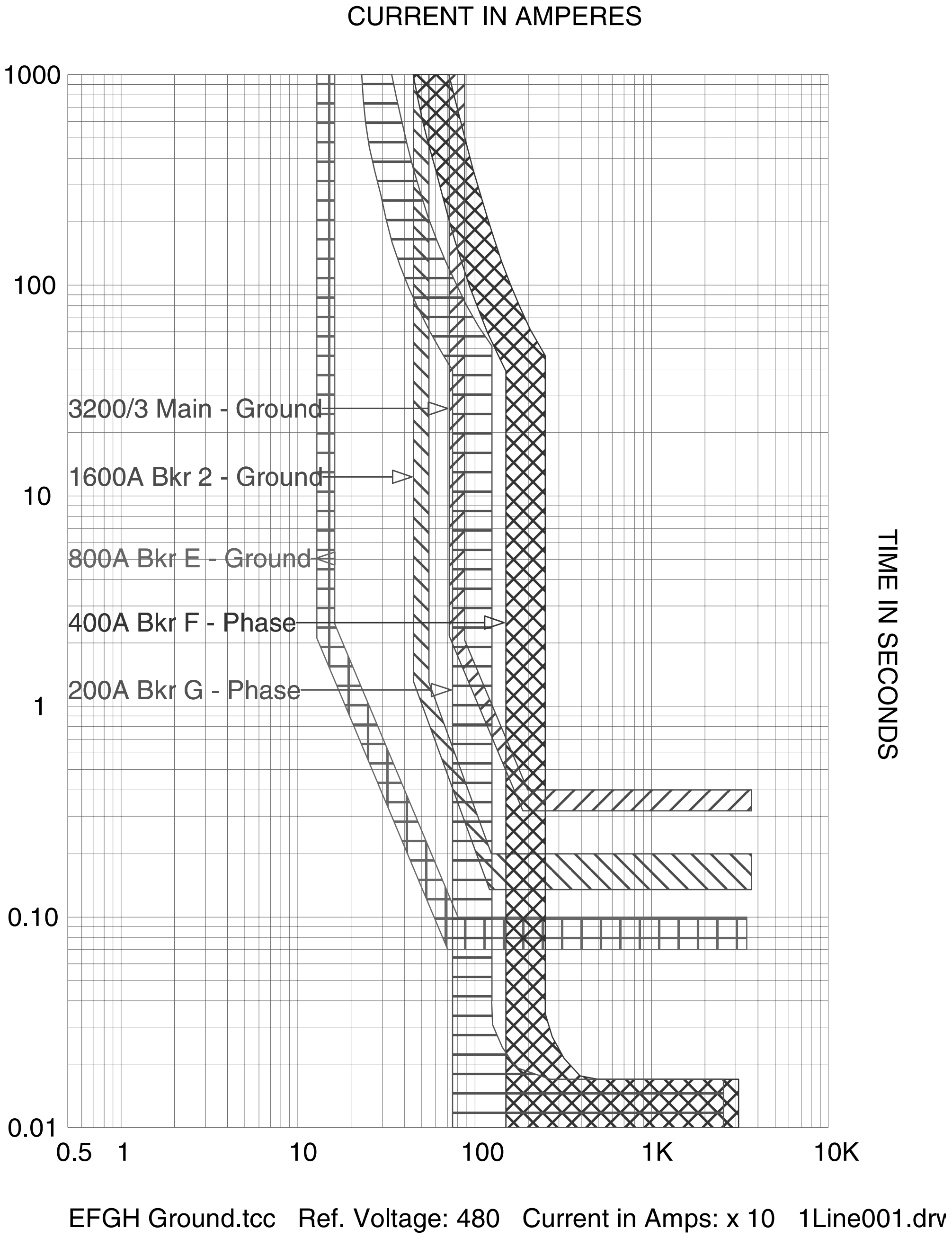
1K
10K
TIME IN SECONDS
3200/3 Main - Phase
1600A Bkr 2 - Phase
800A Bkr E - Phase
400A Bkr F - Phase
200A Bkr G - Phase
EFGH Phase.tcc Ref. Voltage: 480 Current in Amps: x 10 1Line001.drw

Figure 7.


CURRENT IN AMPERES
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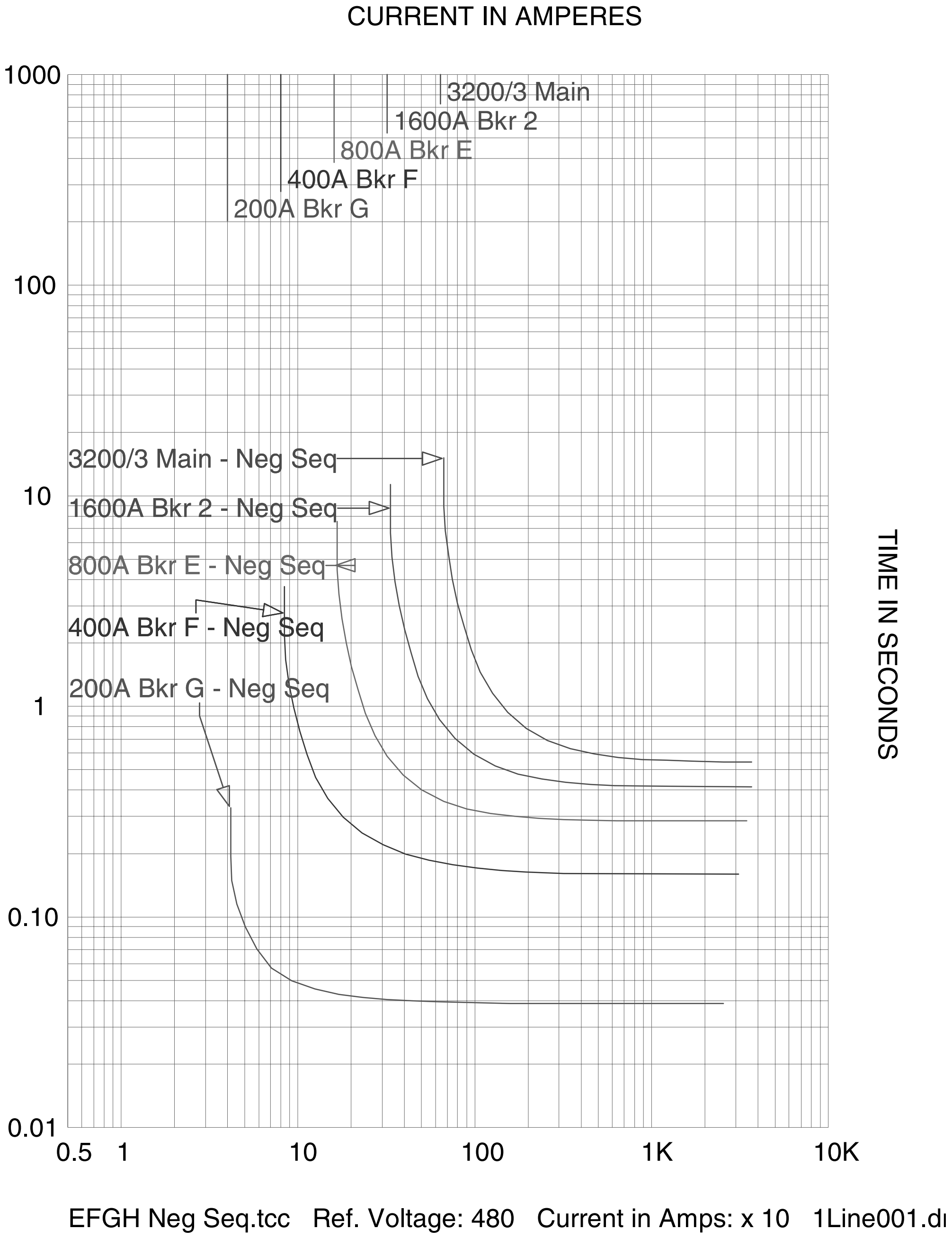
10K
TIME IN SECONDS
3200/3 Main - Ground
1600A Bkr 2 - Ground
800A Bkr E - Ground
400A Bkr F - Phase
200A Bkr G - Phase
EFGH Ground.tcc   Ref. Voltage: 480   Current in Amps: x 10   1Line001.drv

Figure 8.


CURRENT IN AMPERES
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3200/3 Main
1600A Bkr 2
800A Bkr E
400A Bkr F
200A Bkr G
3200/3 Main - Neg Seq
1600A Bkr 2 - Neg Seq
800A Bkr E - Neg Seq
400A Bkr F - Neg Seq
200A Bkr G - Neg Seq
TIME IN SECONDS
EFGH Neg Seq.tcc Ref. Voltage: 480 Current in Amps: x 10 1Line001.dı

Figure 9.

Test	Faulted Bus		Fault	Fault Amps		Sequence Amps			3I0	Clearing Time (sec)					Energy Released (kJoules)			Lowest	Best	Neg Seq
Number	B Phase	C Phase	Ohms	B Phase	C Phase	Pos	Neg	Zero		B Phase	C Phase	B Ground	C Ground	Neg. Seq.	Phase	Ground	Neg. Seq.	Energy	Element	% Energy
1	Bus A	Bus A	0.001	29436	29433	16994	16994	0.83	2.49	0.22	0.22	N/A	N/A	0.54	191	866390	468	191	Phase	
2	Bus A	Bus A	0.25	1892	1892	1093	1092	0.83	2.49	260	260	N/A	N/A	0.68	232678	894916	609	609	Neg Seq	0.26%
3	Bus A	Bus A	0.33	1439	1439	831	830	0.83	2.49	N/A	N/A	N/A	N/A	0.79	683338	683338	540	540	Neg Seq	0.08%
4	Bus A	Bus A	0.5	953	953	551	550	0.83	2.49	N/A	N/A	N/A	N/A	1.17	454105	454105	531	531	Neg Seq	0.12%
5	Bus A	Bus A	0.75	637	637	368	367	0.83	2.49	N/A	N/A	N/A	N/A	3.37	304327	304327	1026	1026	Neg Seq	0.34%
6	Bus E	Bus E	0.001	29436	29433	16994	16994	0.83	2.49	0.14	0.14	N/A	N/A	0.54	121	866390	468	121	Phase	
7	Bus E	Bus E	0.25	1892	1892	1093	1092	0.83	2.49	>300	>300	N/A	N/A	0.68	894916	894916	609	609	Neg Seq	0.07%
8	Bus E	Bus E	0.33	1439	1439	831	830	0.83	2.49	N/A	N/A	N/A	N/A	0.79	683338	683338	540	540	Neg Seq	0.08%
9	Bus E	Bus E	0.5	953	953	551	550	0.83	2.49	N/A	N/A	N/A	N/A	1.17	454105	454105	531	531	Neg Seq	0.12%
10	Bus E	Bus E	0.75	637	637	368	367	0.83	2.49	N/A	N/A	N/A	N/A	3.37	304327	304327	1026	1026	Neg Seq	0.34%
11	Bus A	Bus E	0.001	28476	28474	9492	9492	9492	28476	0.22	0.14	0.25	0.2	0.54	114	162	438	114	Phase	
12	Bus A	Bus E	0.25	1888	1888	629	629	629	1887	260	>300	0.25	0.2	0.99	231695	178	882	178	Ground	
13	Bus A	Bus E	0.33	1437	1437	479	479	479	1437	N/A	N/A	0.25	0.2	1.48	681440	136	1009	136	Ground	
14	Bus A	Bus E	0.5	953	952	318	318	318	954	N/A	N/A	0.25	0.2	N/A	453628	91	453628	91	Ground	
15	Bus A	Bus E	0.75	637	637	212	212	212	636	N/A	N/A	N/A	N/A	N/A	304327	304327	304327	304327	None	
16	Bus B	Bus B	0.001	26442	26440	15266	15265	0.83	2.49	0.026	0.026	N/A	N/A	0.41	18	699126	287	18	Phase	
17	Bus B	Bus B	0.25	1876	1876	1084	1083	0.83	2.49	133	133	N/A	N/A	0.44	117019	879844	387	387	Neg Seq	0.33%
18	Bus B	Bus B	0.33	1430	1430	826	825	0.83	2.49	225	225	N/A	N/A	0.45	151834	674817	304	304	Neg Seq	0.20%
19	Bus B	Bus B	0.5	950	949	549	548	0.83	2.49	>353	>353	N/A	N/A	0.51	450775	450775	230	230	Neg Seq	0.05%
20	Bus B	Bus B	0.75	635	635	367	366	0.83	2.49	N/A	N/A	N/A	N/A	0.62	302419	302419	187	187	Neg Seq	0.06%
21	Bus B	Bus B	1	477	477	276	275	0.83	2.49	N/A	N/A	N/A	N/A	0.83	227529	227529	189	189	Neg Seq	0.08%
22	Bus B	Bus B	1.25	382	382	221	220	0.83	2.49	N/A	N/A	N/A	N/A	1.26	182405	182405	230	230	Neg Seq	0.13%
23	Bus F	Bus F	0.001	26442	26440	15266	15265	0.83	2.49	0.04	0.04	N/A	N/A	0.41	28	699126	287	28	Phase	
24	Bus F	Bus F	0.25	1876	1876	1084	1083	0.83	2.49	161	161	N/A	N/A	0.44	141655	879844	387	387	Neg Seq	0.27%
25	Bus F	Bus F	0.33	1430	1430	826	825	0.83	2.49	276	276	N/A	N/A	0.45	186249	674817	304	304	Neg Seq	0.16%
26	Bus F	Bus F	0.5	950	949	549	548	0.83	2.49	644	644	N/A	N/A	0.51	290299	450775	230	230	Neg Seq	0.08%
27	Bus F	Bus F	0.75	635	635	367	366	0.83	2.49	N/A	N/A	N/A	N/A	0.62	302419	302419	187	187	Neg Seq	0.06%
28	Bus F	Bus F	1	477	477	276	275	0.83	2.49	N/A	N/A	N/A	N/A	0.83	227529	227529	189	189	Neg Seq	0.08%
29	Bus F	Bus F	1.25	382	382	221	220	0.83	2.49	N/A	N/A	N/A	N/A	1.26	182405	182405	230	230	Neg Seq	0.13%
30	Bus B	Bus F	0.001	24163	24161	8054	8054	8054	24162	0.026	0.04	0.15	0.1	0.41	15	58	239	15	Phase	
31	Bus B	Bus F	0.25	1862	1862	621	621	621	1863	133	165	0.15	0.1	0.49	115279	87	425	87	Ground	
32	Bus B	Bus F	0.33	1422	1422	474	474	474	1422	230	285	0.15	0.1	0.54	153476	67	360	67	Ground	
33	Bus B	Bus F	0.5	946	946	315	315	315	945	>360	650	0.15	0.1	0.7	290848	45	313	45	Ground	
34	Bus B	Bus F	0.75	634	634	211	211	211	633	N/A	N/A	0.15	0.16	1.43	301467	45	431	45	Ground	
35	Bus B	Bus F	1	477	477	159	159	159	477	N/A	N/A	0.16	0.28	N/A	227529	36	227529	36	Ground	
36	Bus B	Bus F	1.25	382	382	127	127	127	381	N/A	N/A	0.25	0.45	N/A	182405	46	182405	46	Ground	
37	Bus C	Bus C	0.001	21644	21662	12507	12507	0.83	2.49	0.011	0.011	N/A	N/A	0.28	5	468852	131	5	Phase	
38	Bus C	Bus C	0.25	1846	1846	1066	1065	0.83	2.49	61.7	61.7	N/A	N/A	0.29	52564	851929	247	247	Neg Seq	0.47%
39	Bus C	Bus C	0.33	1412	1412	816	815	0.83	2.49	118	118	N/A	N/A	0.3	77636	657936	197	197	Neg Seq	0.25%
40	Bus C	Bus C	0.5	942	942	544	543	0.83	2.49	317	317	N/A	N/A	0.31	140647	443682	138	138	Neg Seq	0.10%
41	Bus C	Bus C	0.75	632	632	365	364	0.83	2.49	>320	>320	N/A	N/A	0.33	299568	299568	99	99	Neg Seq	0.03%
42	Bus C	Bus C	1	476	475	275	274	0.83	2.49	>885	>885	N/A	N/A	0.35	226100	226100	79	79	Neg Seq	0.03%
43	Bus C	Bus C	1.25	381	381	220	220	0.83	2.49	N/A	N/A	N/A	N/A	0.38	181451	181451	69	69	Neg Seq	0.04%
44	Bus C	Bus C	1.5	318	318	184	183	0.83	2.49	N/A	N/A	N/A	N/A	0.41	151686	151686	62	62	Neg Seq	0.04%
45	Bus G	Bus G	0.001	21644	21662	12507	21507	0.83	2.49	0.017	0.017	N/A	N/A	0.28	8	468852	131	8	Phase	
46	Bus G	Bus G	0.25	1846	1846	1066	1065	0.83	2.49	74	74	N/A	N/A	0.29	63043	851929	247	247	Neg Seq	0.39%
47	Bus G	Bus G	0.33	1412	1412	816	815	0.83	2.49	130	130	N/A	N/A	0.3	85532	657936	197	197	Neg Seq	0.23%
48	Bus G	Bus G	0.5	942	942	544	543	0.83	2.49	390	390	N/A	N/A	0.31	173036	443682	138	138	Neg Seq	0.08%
49	Bus G	Bus G	0.75	632	632	365	364	0.83	2.49	>295	>295	N/A	N/A	0.33	299568	299568	99	99	Neg Seq	0.03%
50	Bus G	Bus G	1	476	475	275	274	0.83	2.49	>746	>746	N/A	N/A	0.35	226100	226100	79	79	Neg Seq	0.03%
51	Bus G	Bus G	1.25	381	381	220	220	0.83	2.49	N/A	N/A	N/A	N/A	0.38	181451	181451	69	69	Neg Seq	0.04%
52	Bus G	Bus G	1.5	318	318	184	183	0.83	2.49	N/A	N/A	N/A	N/A	0.41	151686	151686	62	62	Neg Seq	0.04%

Table 1.

Test Number	Faulted Bus		Fault Ohms	Fault Amps		Sequence Amps			3I0	Clearing Time (sec)					Energy Released (kJoules)			Lowest Energy	Best Element	Neg Seq % Energy
	B Phase	C Phase		B Phase	C Phase	Pos	Neg	Zero		B Phase	C Phase	B Ground	C Ground	Neg. Seq.	Phase	Ground	Neg. Seq.			
53	Bus C	Bus G	0.001	18022	18019	6007	6007	6007	18021	0.012	0.017	0.15	0.1	0.28	4	32	91	4	Phase	
54	Bus C	Bus G	0.25	1812	1812	604	604	604	1812	62.8	77	0.15	0.1	0.3	51549	82	246	82	Ground	
55	Bus C	Bus G	0.33	1393	1392	464	464	464	1392	123	133	0.15	0.1	0.31	78706	64	198	64	Ground	
56	Bus C	Bus G	0.5	933	933	311	311	311	933	322	419	0.15	0.1	0.34	140149	44	148	44	Ground	
57	Bus C	Bus G	0.75	628	628	209	209	209	627	>320	>295	0.15	0.16	0.39	295788	44	115	44	Ground	
58	Bus C	Bus G	1	473	473	158	158	158	474	>320	>746	0.15	0.29	0.46	223729	34	103	34	Ground	
59	Bus C	Bus G	1.25	380	380	127	127	127	381	N/A	N/A	0.25	0.44	0.57	180500	45	103	45	Ground	
60	Bus C	Bus G	1.5	317	317	106	106	106	318	N/A	N/A	0.35	0.63	0.83	150734	53	125	53	Ground	
61	Bus D	Bus D	0.001	15572	15570	8890	8890	0.83	2.49	0.018	0.018	N/A	N/A	0.159	4	242456	39	4	Phase	
62	Bus D	Bus D	0.25	1788	1788	1033	1032	0.83	2.49	5.6	5.6	N/A	N/A	0.159	4476	799236	127	127	Neg Seq	2.84%
63	Bus D	Bus D	0.33	1379	1379	796	796	0.83	2.49	9.4	9.4	N/A	N/A	0.159	5899	627542	100	100	Neg Seq	1.70%
64	Bus D	Bus D	0.5	927	927	536	535	0.83	2.49	21.2	21.2	N/A	N/A	0.16	9109	429665	69	69	Neg Seq	0.76%
65	Bus D	Bus D	0.75	625	625	361	361	0.83	2.49	57	57	N/A	N/A	0.16	16699	292969	47	47	Neg Seq	0.28%
66	Bus D	Bus D	1	472	472	273	272	0.83	2.49	130	130	N/A	N/A	0.161	28962	222784	36	36	Neg Seq	0.12%
67	Bus D	Bus D	1.25	379	379	219	218	0.83	2.49	268	268	N/A	N/A	0.162	48120	179551	29	29	Neg Seq	0.06%
68	Bus D	Bus D	1.5	316	316	183	182	0.83	2.49	594	594	N/A	N/A	0.162	88972	149784	24	24	Neg Seq	0.03%
69	Bus H	Bus H	0.001	15572	15570	8890	8890	0.83	2.49	0.017	0.017	N/A	N/A	0.159	4	242456	39	4	Phase	
70	Bus H	Bus H	0.25	1788	1788	1033	1032	0.83	2.49	0.019	0.019	N/A	N/A	0.159	15	799236	127	15	Phase	
71	Bus H	Bus H	0.33	1379	1379	796	796	0.83	2.49	0.027	0.027	N/A	N/A	0.159	17	627542	100	17	Phase	
72	Bus H	Bus H	0.5	927	927	536	535	0.83	2.49	76	76	N/A	N/A	0.16	32655	429665	69	69	Neg Seq	0.21%
73	Bus H	Bus H	0.75	625	625	361	361	0.83	2.49	154	154	N/A	N/A	0.16	45117	292969	47	47	Neg Seq	0.10%
74	Bus H	Bus H	1	472	472	273	272	0.83	2.49	307	307	N/A	N/A	0.161	68395	222784	36	36	Neg Seq	0.05%
75	Bus H	Bus H	1.25	379	379	219	218	0.83	2.49	633	633	N/A	N/A	0.162	113656	179551	29	29	Neg Seq	0.03%
76	Bus H	Bus H	1.5	316	316	183	182	0.83	2.49	>200	>200	N/A	N/A	0.162	149784	149784	24	24	Neg Seq	0.02%
77	Bus D	Bus H	0.001	11593	11591	3864	3864	3864	11592	0.015	0.017	0.15	0.1	0.159	2	13	21	2	Phase	
78	Bus D	Bus H	0.25	1718	1718	573	573	573	1719	6.1	0.019	0.15	0.1	0.16	14	74	118	14	Phase	
79	Bus D	Bus H	0.33	1337	1337	446	446	446	1338	10.3	0.028	0.15	0.1	0.16	17	59	94	17	Phase	
80	Bus D	Bus H	0.5	908	908	303	303	303	909	22.1	79	0.15	0.1	0.161	9110	41	66	41	Ground	
81	Bus D	Bus H	0.75	617	617	206	206	206	618	60	160	0.15	0.17	0.162	17131	43	46	43	Ground	
82	Bus D	Bus H	1	467	467	156	156	156	468	134	332	0.16	0.29	0.164	29224	35	36	35	Ground	
83	Bus D	Bus H	1.25	376	376	125	125	125	375	291	667	0.26	0.45	0.166	51426	46	29	29	Neg Seq	63.04%
84	Bus D	Bus H	1.5	314	314	105	105	105	315	605	>210	0.35	0.66	0.168	89476	52	25	25	Neg Seq	48.08%

Table 1, (cont.)

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