Calculating System Fault Currents in Power Systems

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Overview

Power systems are complicated networks of infrastructure which generate, transmit, distribute and consume electrical energy. Within these systems, imperfections can occur within the electrical circuits which deflect current away from its intended path to a load.Current which travels away from its designed route is known as a fault. These faults almost always have negative consequences, which can vary greatly in their severity. A small fault that is remedied quickly can simply require a fuse to be replaced or a breaker to be reset. Larger faults can result in extensive damage to ecosystems by way of wildfires and loss of life via a variety of means.

Power systems are designed to limit adverse impacts to people and our environment through many different ways. These systems are engineered and maintained to limit the opportunities for faults to occur, and in the situations when faults are still present, to mitigate any harm to the system, to people, and to the environment. However, engineering “perfect” networks to distribute energy without faults and failures can be cost prohibitive. Other factors that can cause faults are also unpredictable and are not always preventable, such as trees falling on lines or natural disasters such as hurricanes. Thus, the system must be designed to understand when a fault is occurring and take corrective action to prevent additional damage or loss of life.

Due to the large size of modern power systems, this challenge of identifying and preventing faults in the system is complex and multidimensional. While this poses an issue for calculations done by hand, creating a software package to iterate over large dimensional matrices is relatively straightforward. Thus, computer programs have been adopted to calculate necessary information from contingency cases and to aid operators in clearing or isolating faults that occur.

The program created here was designed to calculate fault currents at various buses in a large network (large for doing by hand, relatively small compared to real world applications). This information is crucial in order to correctly rate protection devices in the network and for coordinating devices together. However, this program is only concerned with the current magnitudes and not any actual details about the protection system. The network data provided for this assignment is an example of the necessary calculations needed to evaluate 4 different types of faults at various locations in the network.

Power System Infrastructure and Protection

The components of a power system must carry out two critical functions with incredibly high accuracy: allowing power to flow as intended during normal operation, and preventing power to flow through segments that are under duress. The latter must be done while limiting the impact to the rest of the system, which should be operating normally. These components are also expected to operate correctly when another piece of equipment fails.

Devices are engineered to detect any abnormalities that occur in the network and, depending on their coordination, change their operating state to clear or isolate a fault from the rest of the system. To operate only under fault conditions, these devices must be rated to the correct current ratings, which are established through fault current calculations of contingency cases.

Fault Currents

Faults are equivalent to “short circuits” and impact the system by creating a low impedance, unintentional path to other parts of the network or to ground. However, large energy networks typically operate with multiple phases of currents to allow the current to flow in a single direction and not need to return to their origin to close the circuit, which makes any fault calculations more complex.

Three-phase power systems dominate as the preferred method of distributing energy. As such, faults can occur within any combination of these phases. The most common types of faults that can occur include:

- **Three-phase:** where all three phases are short circuited to one another/ground
- **Single-line-to-ground:** where a single phase is short circuited to ground
- **Line-to-line:** where two phases are short circuited to one another
- **Double-line-to-ground:** where two phases are short circuited to ground simultaneously

Each fault type has its own set of equations that can calculate the fault current magnitude based on the components within the system. Power systems contain software which can complete all of these calculations and determine when, where and what type of faults are occurring. The program authored here aims to determine current characteristics in the system given this information about the type of fault and the location of the fault.

System Topography

The test system provided for this assignment includes six buses, seven lines, three generators, and three loads (also denoted as demands). Impedances have been provided for each line and generator sequence network. Other power flow information has also been given, including the active power output of generators, the constant power drawn from the loads, and the pre-fault voltage characteristics at each bus.

Python Program: Initial System Data

The initial step of developing our fault calculating program is to import an Excel file containing all of the system data under normal operation. Dataframes were constructed using the Python library Pandas to place the system parameters into arrays, which can be accessed throughout the program. Other useful variables are created for ease of indexing throughout the calculations in the program and for simplifying any phase to sequence conversions.

Python Program: Admittance and Impedance Matrices

Because all of our fault current calculations are completed for the sequence network equivalents to the system, an admittance matrix is created for each sequence (zero, positive, and negative). These three matrices are constructed from the data in the Excel file. For the positive and negative sequence admittance matrices, the constructing approach was the same. First, the admittances of the lines were analyzed, and the Y_bus admittance matrix was developed. Second, the generator impedances were analyzed, and the corresponding Y_g1 nda Y_g2 matrices were calculated. Luckily the system does not contain more than 3 generators so the generator admittance matrices were relatively sparse. Third, the load admittance matrix was created, in order to account for any impedances connecting a load to its corresponding bus. Finally, the sequence admittance matrices were finished by summing the bus admittance matrix, the generator admittance matrix, and the load admittance matrix together (done separately for the positive and negative sequences). Due to the topology of the system, including which generators are grounded or ungrounded, the zero sequence admittance matrix is constructed differently. Instead, the Y_bus0 matrix is constructed by iterating through the data and effectively generating the zero sequence bus admittance matrix and the zero sequence generator admittance matrix at the same time. Finally, the sum of Y_bus0 and the load admittance matrix creates the zero sequence admittance matrices.

Due to impedance values being more convenient to use in current calculations, the sequence admittance matrices are inverted to create the sequence impedance matrices. Because the current calculations carried out in the program are all in the sequence domain, the conversion to phase impedance matrices is not necessary.

Python Program: Fault Type and Calculations

The information for each fault simulated is provided by the assignment data. Each type of fault has its own function within the program which has the location of the fault bus and the location of the results bus as parameters.

Each fault type function calculates its respective currents through each phase at the fault bus and determines the resulting currents through each phase of each component connected to the results bus. Components include transmission lines, transformers, generators, and shunt elements, where present.

Due to the fact that each fault type is given, it is trivial to calculate the fault current at the fault bus using known equations in the sequence domain. Then, converting this fault current to the phase domain gives the expected fault current flowing through each line in the physical system during this scenario.

Calculating the current flowing through each connection to the results bus is more complex than calculating the fault current and requires more steps. First, the fault-on voltage at the results bus is calculated in each sequence network (E_0, E_1, E_2). Then, the fault-on voltage is calculated at the bus on the other end of the component connected to the results bus. For example, for the results bus being bus 2 in the system, the connecting fault-on voltage would be calculated at bus 3 if there was a line connecting buses 2 and 3. Finally, the current through the connecting component can be calculated because the impedance of the component is given and the voltage drop across the component is now known. Iterating through each line and generator connected to the results bus is necessary to complete all the necessary calculations. Components such as transformers and shunt elements are excluded from these calculations for the results bus because they are not present in the power system provided.

Python Program: Results

The assignment data included four contingency cases which detailed a fault type at a specific bus in the network, as well as the results bus to analyze for this scenario. In each case, the fault current is calculated from the sequence components and is converted to the phase domain. Additionally, the current flowing through each component connected to the results bus is calculated from sequence component values and is also converted to the phase domain. These results are output directly from the functions and are printed in Python for use in debugging and verifying results. The complete results for the assignment data are included in Appendix A.

Testing

Due to the size of the power system detailed in the assignment data, verifying our results by hand would not be feasible. Instead, a smaller test case was developed that only included 2 buses, 1 generator, and 1 line. This case lacked the complexity of the larger power system but the currents within the system were easily calculated by hand for each type of fault at each bus.

Using this example data, various program results and quantities were able to be verified for each type of fault. These quantities included the admittance and impedance matrices for each sequence network, the fault current magnitude at the faulted bus, the results bus voltage magnitude, and the voltage magnitude at another bus connected to the results bus by a line/generator. While time constraints did not permit the verification of the current flowing through each component connected to the results bus, the other quantities used to calculate this current were deemed correct, so this current was assumed to be correct as well.

Further testing would be required to increase the robustness of the program results. In particular, designing a slightly larger example test case would be necessary to better verify accuracy. Creating a test case with more buses, lines, and generators than the test case developed here would ensure every special case is handled correctly in the program simultaneously. Additionally, explicitly calculating the current through each component connected to the results bus by hand would be useful for increasing confidence in the results of the program.

Conclusions

This program was developed for simulating fault scenarios in a power system and yields results for calculating the fault current at the faulted bus and the desired currents through components connected to other buses throughout the network. Upon inspection, all magnitudes and phase angles for the fault current for each type of fault are reasonable and resemble the expected values. Affirmation of these calculations was determined by constructing a simple test case power system and calculating the current results for all four types of faults by hand. Since all results calculated by hand for this test case matched computed results from the program, the program is believed to be accurate for these values. Future work includes further verifying the results of the program by developing a more complex power system and solving for all desired quantities by hand again.

Appendix A: Simulation Results

Table 1.1: 3-Phase Fault at Bus 1 with Results at Bus 2

	Phase A Current (pu)	Phase B Current (pu)	Phase C Current (pu)
Fault Current	72.95 < -89.72°	72.95 < 150.28°	72.95 < 30.28°
Line Current (2 to 1)	51.57 < -89.46°	51.57 < 150.54°	51.57 < 30.54°
Line Current (2 to 5)	18.39 < -100.77°	18.39 < 139.23°	18.39 < 19.23°
Generator 2 Current	15.39 < 89.36°	15.39 < -30.64°	15.39 < -150.64°

Table 1.2: Single-Line-to-Ground Fault (Phase A) at Bus 2 with Results at Bus 6

	Phase A Current (pu)	Phase B Current (pu)	Phase C Current (pu)
Fault Current	9.44 < -89.97°	0.00 < 0.00°	0.00 < 0.00°
Line Current (6 to 3)	146.81 < 89.32°	70.21 < 72.09°	63.21 < 100.23°
Line Current (6 to 5)	2.71 < -82.48°	0.57 < -35.65°	0.41 < -118.34°

Table 1.3: Line-to-Line Fault (Phase B to Phase C) at Bus 4 with Results at Bus 1

	Phase A Current (pu)	Phase B Current (pu)	Phase C Current (pu)
Fault	0.00 < 0.00°	20.53 < -176.71°	20.53 < 3.29°
Line Current (1 to 4)	2.97 <93.00°	21.16 < -172.69°	21.14 < -0.73°
Line Current (1 to 2)	32.32 < 94.24°	26.06 < -138.43°	26.49 < -34.31°
Generator 1 Current	7.81 <89.79°	3.92 < -88.29°	3.90 < -92.15°

Table 1.4: Double-Line-to-Ground Fault (Phases B and C) at Bus 5 with Results at Bus 4

	Phase A Current (pu)	Phase B Current (pu)	Phase C Current (pu)
Fault	0.00 < 0.00°	20.31 < 178.46°	20.37 < 8.21°
Line Current (4 to 1)	9.95 < 93.64°	92.52 < -2.13°	92.48 < -172.13°
Line Current (4 to 3)	59.95 < -86.75°	84.15 < -14.60°	84.92 < -157.87°
Line Current (4 to 5)	0.19 < 100.97°	8.42 < -178.74°	8.35 < 10.04°