An Automated Fault Study Application

Davis Erwin **Feliks Karchemskiy**
Pacific Gas and Electric Company

Abstract

Confronted with sustained workload increases beginning in 2001, the System Protection department within Pacific Gas and Electric Company (PG&E) developed an application to consistently and reliably compile, present, and archive fault study data for relay setting purposes. The software application has proved to be an effective mechanism in mitigating the negative consequences of an increasing workload, but there have been other notable benefits. This paper intends to describe the benefits as well as present the basic structure and categories necessary in an application of this nature. Also discussed is the expansion of work aids available for the protection engineer, new possibilities for compliance verification, and possible development of automated relay settings.

Introduction:

Fault study results are used to set relays that protect electrical assets for new construction, maintenance clearances, and periodic coordination verification. The performance of thorough and accurate fault studies is an essential responsibility of the protection engineer. The quality of the results is largely dependent on the experience of the protection engineer and the process can be time consuming and error prone. Even the most experienced protection engineer can overlook a critical system contingency and transcription errors can plague the most observant individual. The absorption of new projects presents an additional challenge, and the protection engineer must allocate the time and attention necessary to run, compile, and review the results.

Beginning in 2001, PG&E experienced a sustained workload increase due to new capital projects as well as the introduction of integrated design standards. The standards possess significant advantages, but proved burdensome due to the volume of microprocessor relay settings. In order to cope with these additional responsibilities, the group searched for new and creative processes to save time without sacrificing quality. Setting templates developed together with the automated fault study application described in this paper, helped to mitigate the challenge.

PG&E uses a commercial fault study program that has a selectable feature to automatically run contingency studies. The feature was not extensively utilized until 2001, when PG&E's system protection group developed an in-house application to compile and sort the data produced by using the feature. For a given fault study, the in-house application increased the quantity of system contingencies analyzed by an order of magnitude while dramatically decreasing the amount of time necessary to evaluate the results.

The benefits for adopting such an application are the following –

1. A consistent process that spans a wide range of system configurations and relay setting challenges.
2. A consistent process that identifies worst case contingencies for setting relays independent of protection engineer skill and experience levels.
3. Consistent table of results that is ideal for project files and archive folders used as a common platform for colleague review. Also ideal common platform for contractor based studies.
4. Cost effectiveness accrued through time savings and reduction in errors.
5. Training mechanism for new engineers
6. A "second pair of eyes" to those engineers who know their system well and prefer to manually run fault studies and calculate settings.
7. Elimination of transcription errors when using traditional processes by applying a "hands-off" approach to data collection.
8. Quick and thorough method for calculating relay settings for new projects, periodic clearances, and coordination studies.
9. Periodic compliance verification by comparing results to a relay setting database.

A review of available software on the market resulted in the conclusion there are adequate capabilities to help, at least partially, in automating the existing process of setting calculations. However since an ideal application that matched the particular needs could not be found, an in-house application was developed.

Looking forward, an application such as this is a necessary first step in a process that can automatically check relay settings stored in a database for NERC compliance reviews as well as pursuing a long term aggressive strategy of automatically setting relays.

It is not known whether other protection groups in the electric power industry have invested similar efforts into automating fault studies. We feel it is important to engage the industry with a report on a strategy that has proved successful, and welcome an open dialog on the topic.

Application Evolution

Development of this application originated from a desire to automate the ground distance setting calculations for microprocessor relays. Line ground distance reach is dependant on many variables and can vary widely depending on the electric system configuration. In the early 1990's a simple spreadsheet containing the necessary formulas was developed into which fault study results were manually inserted. The spreadsheet consisted of several rows, each to account for a particular user defined contingency. Naturally, the original idea evolved into a spreadsheet that was capable of calculating all the protective settings necessary for the microprocessor relays that PG&E began using regularly. The spreadsheet identified the worst case scenarios - minimum and maximum fault currents, minimum and maximum impedance reaches, lowest polarizing voltages, etc. The results were then incorporated into relay setting files. The next step was to make data transfer from the fault study software to the setting spreadsheet automatic.

In 2001, the data transfer mechanism that imports the fault study data file was written within Excel™ using Microsoft Visual Basic™. Over the intervening years, the application's programming has changed to incorporate user recommended improvements as well as adjusting for new version releases of our fault study program. The most recent import engine, (Version 4), utilizes an intermediate "script" file that organizes the output data into a CSV (comma separated variable) format. This latest improvement eliminated the need to update the spreadsheet programming for each new fault study application release.

We have also incorporated the same functional application within MathCAD™ but it has not found wide use due to a previous limitation in importing, storing, and manipulating text data within matrices. This limitation is found in pre-version 14 releases. As a result, this paper will concentrate only on the spreadsheet version of the automated solution. The following sections will describe the process steps for using the application.

Automated Application Process Steps

There are five main process steps involved with the automated fault study method using PG&E's application. Figure 9 graphically displays the necessary steps, and each step will be briefly described next.

Step 1 - Run Fault Studies

The first step of any process involving setting relays is to run fault studies. Using PG&E's fault study application, the engineer is capable of independently selecting contingencies and running a fault study as well as utilizing a program feature that automatically runs faults for each "Outage" in the vicinity of the relay terminal (See Figure 1).

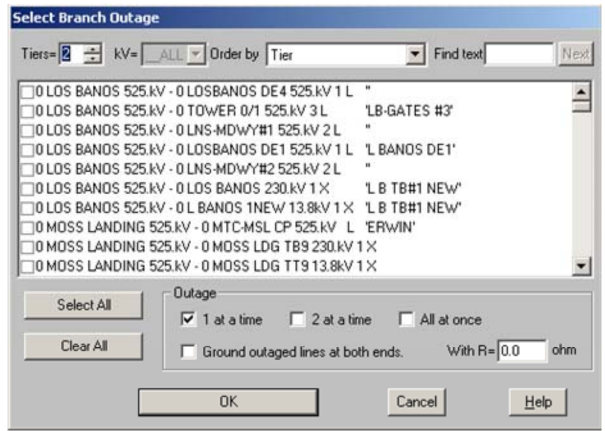


Figure 1 – Menu of Contingencies (Aspen™ - OneLiner™ Automatic Feature)

With the idea of setting protective relay elements in mind, it is important that the most severe credible contingencies are analyzed. There have been occasions that the automatic feature captures a contingency that the engineer overlooked. This can happen when analysis is being performed in an unfamiliar area of the system, or project time constraints limit the engineer's attention, etc. As a result, it is recommended that the automatic outage feature be used at least as a backup to the manual method.

The fault study program automatically removes a piece of equipment from service and then runs a study and stores the results. The program progresses by placing the last equipment outage back in service, removes the next component from service, and then runs the next fault. This process continues until all of the selected outages have been completed. The fault study application will "store" each successive result into a buffer. The buffer contains the data of the most recent fault as well as all those previously ran. Once the multi-fault study has been run, the buffer contents need to be exported to a file (Step 2). The buffered results can be cleared by the user at any desired time and a new analysis can begin.

Often there are credible double contingencies or varying operational set-ups that require another fault study. For example, there may be a generator near the relaying terminal that is out of service for long periods of time and the study results need to include the generator in and out of service. Perhaps there are series capacitors near the relaying terminal and the study results should include the series capacitors in-service and bypassed. If credible double contingencies such as these are to be studied, the modifications to the system need to be applied, the buffer cleared, another fault study ran, and results exported to a different file.

Step 2 - Export Fault Study Data

As described in the previous section, once an engineer has completed the desired fault study scenarios for a given system configuration, the results are exported from the program buffer into an ASCII file. The exported file must be of a format that can be imported into a data analysis tool such as Excel™, MathCAD™, MATLAB™, etc. A "script" file was written that is imbedded within the fault study application that exports the buffered results in a CSV format.

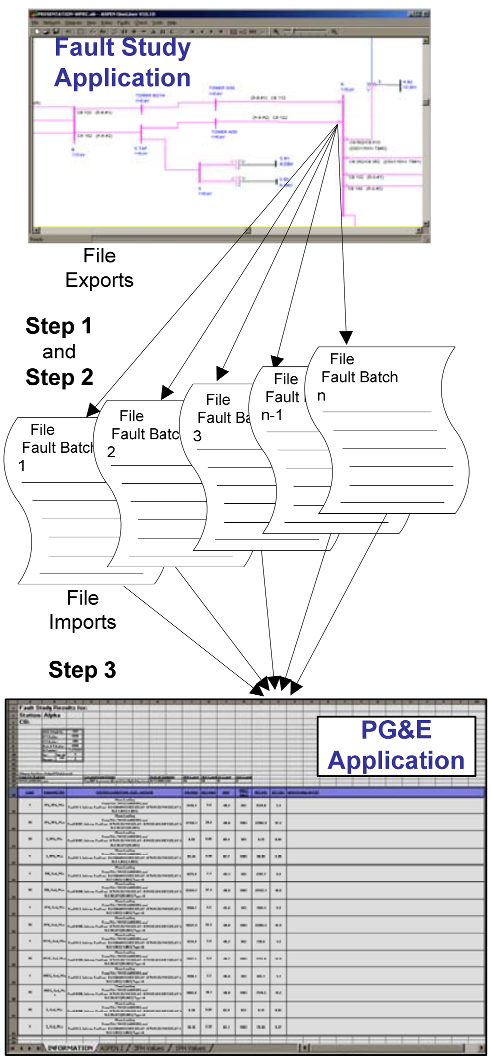


Figure 2 – Import and Export Process

Each file displayed in Figure 2 contain the results of a fault study for a given system configuration. Each file contains multiple fault study results; especially if the "automatic" feature is utilized.

Step 3 - Import Fault Study Data File(s)

Once all of the fault studies for every desired system configuration have been run and the appropriate data files have been created, the file information will be imported into PG&E's application.

For each file that is imported, the user will be requested to input text that defines the system configuration for that file (See Figure 3). The user text will be concatenate to each outage contained within the file. This text will be critical in distinguishing the different contingencies that will later be evaluated.

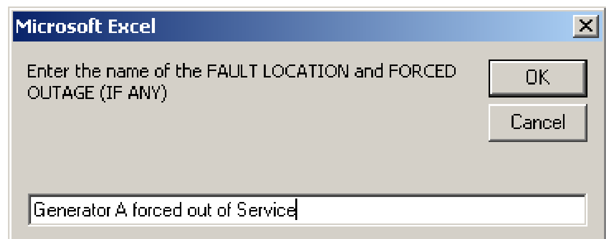


Figure 3 – Import and Export Process

The data from each file will be parsed into four different Excel sheets within the same workbook – "3PH Values" containing the relaying terminal electrical values for a three phase fault, "1PH Values" containing the values for the single line to ground faults, "LL Values" for Line to Line fault data, and "LL-G Values" for Line-Line-Ground fault data values.

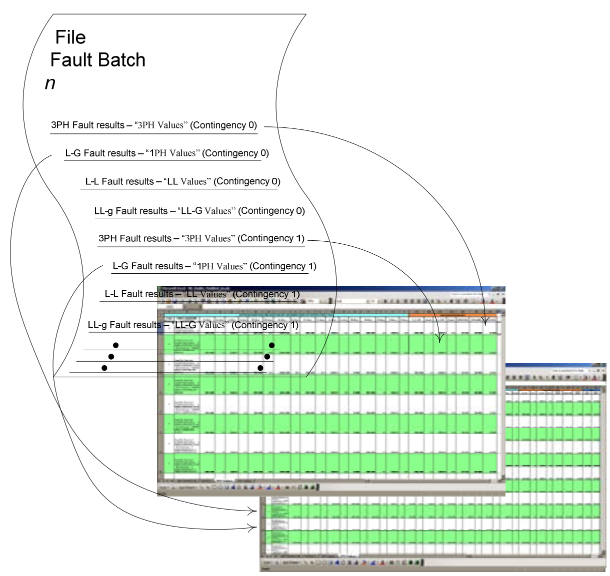


Figure 4 – Import File Format

Figure 4 visually depicts the parsing of the input file data for the Three Phase faults as well as Single Line to Ground fault entries (Line to Line and Line to Line to Ground faults intentionally omitted). If the contents of the import files do not contain specific fault types, then the application will not create the associated sheets.

A typical row of data will contain the necessary voltage and current data for the terminal of interest as well as a text description of the imported data file name, accompanying user input data (Figure 3), and contingency description. Figure 5 displays typical row entries contained within a fault data sheet.

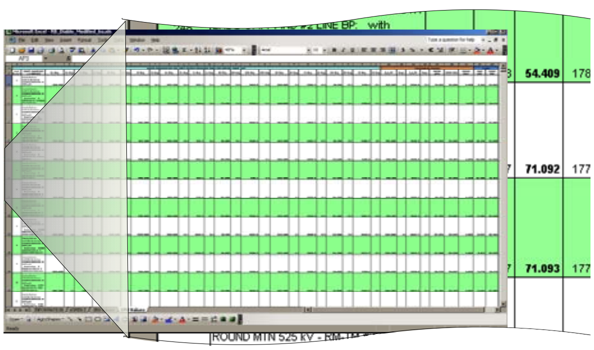


Figure 5 – Row Data Contingency Description

If more than one data file is imported, each consecutive imported file contents will be placed into the appropriate spreadsheet and appended to the preceding file contents. Once all files have been imported, each sheet will then contain all of the desired faults.

Step 4 - Review Min & Max Data for Legitimacy

Once all of the fault studies for every desired system configuration have been imported into PG&E's application, a review of the contents is necessary. For this specific purpose, a Minimum and Maximum Summary chart is automatically constructed at the bottom of each spreadsheet (displayed in Figures 6 and 7). The summary data lists the row number that contains the Minimum or Maximum fault data contents as well as the description of the contingency. If the contingency is not one that is considered valid or otherwise is not desired to be used, then the row simply deleted from the spreadsheet and the cell equations will automatically reshuffle and update to show the new resulting Minimum or Maximum.

At this point, the Minimum and Maximum data for a given contingency should be verified to be those expected. Experienced protection engineers will have a sense of their system and expect certain contingencies to produce the Minimum or Maximum values. However it is not unusual that an unexpected contingency will yield the minimum or maximum value and the expected contingency data should be compared to the resultant spreadsheet worst case scenario.

RESULTS OF ALL FAULTS ON THIS SHEET

FAULT LOCATION and OUTAGE	Va Mag	Va Ang	Ia Mag	Ia Ang	V0 Mag
Max Fault Case:	814	4377	3226	407	4380
MAXIMUM	223.900	1.4	3692.0	-89.4	43.000
MINIMUM	175.600	0.8	2490.6	-91.4	12.300
Min Fault Case:	3662	9	4397	4142	3905
Total Cases Considered:	4610				
# of Cases 3V0 < 5 Volts:	0				
# of Cases V2 < 2.5 Volts:	0				

Figure 6 – Sheet Simple Summary Min & Max

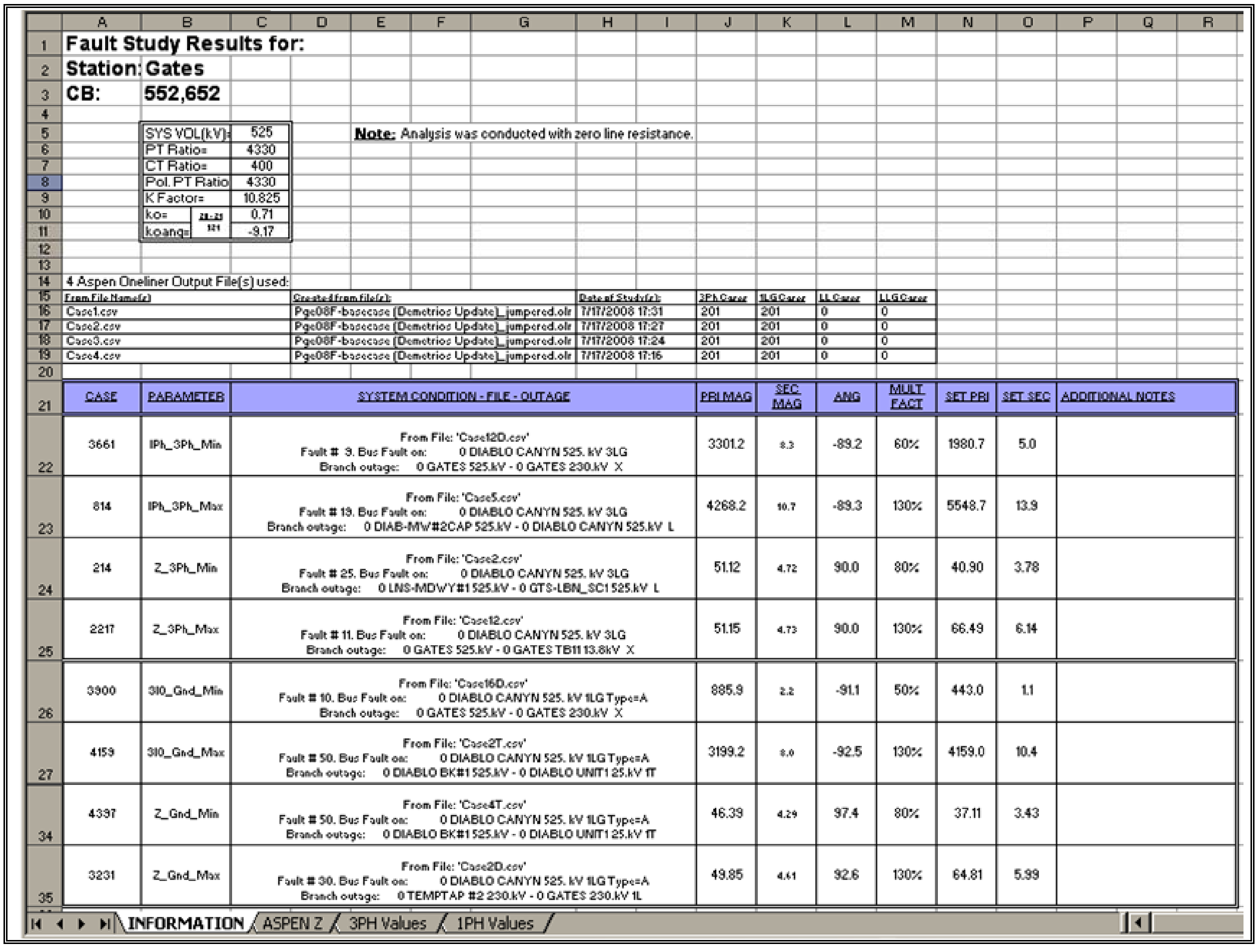
	CASE	PARAMETER	SYSTEM CONDITION - OUTAGE	PRI MAG	SEC MAG
4627					
4628	3900	3I0_min	From File: 'Case16D.csv' Fault # 10. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 GATES 525.kV - 0 GATES 230.kV X	885.9	2.215
4629	4159	3I0_max	From File: 'Case2T.csv' Fault # 50. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 DIABLO BK#1 525.kV - 0 DIABLO UNIT1 25.kV 1T	3199.2	7.998
4630	4397	IPhase_Min	From File: 'Case4T.csv' Fault # 50. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 DIABLO BK#1 525.kV - 0 DIABLO UNIT1 25.kV 1T	2490.6	6.227
4635	3245	INEG_Max	From File: 'Case2D.csv' Fault # 58. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 DB-MD2 R C 525.kV - 0 MIDWAY 525.kV L	1762.4	4.406
4636	4397	ZG_min	From File: 'Case4T.csv' Fault # 50. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 DIABLO BK#1 525.kV - 0 DIABLO UNIT1 25.kV 1T	46.39	4.29
4637	3231	ZG_max	From File: 'Case2D.csv' Fault # 30. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 TEMPTAP #2 230.kV - 0 GATES 230.kV 1L	49.85	4.61

INFORMATION / ASPEN Z / 3PH Values / 1PH Values

Figure 7 – Sheet Summary Min & Max

Step 5 - Review Min & Max Data for Settings

After a complete review of the Minimum and Maximum data has been completed for each import spreadsheet and the appropriate rows have been eliminated from the analysis, the user will then proceed to the "INFORMATION" sheet to view a summary of fault data contained on all individual spreadsheets. The "INFORMATION" sheet also allows the user to input the CT and PT ratio as well as other important information. The "INFORMATION" sheet will give a complete review of the Minimum and Maximum data for all multi-phase and ground faults. It will also automatically list the import file names, base cases from which they were derived and total quantity of the cases considered (See Figure 8 for an example). The data on the "INFORMATION" sheet can be used to set the relay protection elements.



Fault Study Results for:
Station: Gates
CB: 552,652

SYS VOL(kV)=	525
PT Ratio=	4330
CT Ratio=	400
Pol. PT Ratio	4330
K Factor=	10.825
ko=	0.71
koang=	-9.17

Note: Analysis was conducted with zero line resistance.

4 Aspen Oneliner Output File(s) used:

From File Name(s)	Created from file(s):	Date of Study(s):	3Ph Cases	1LG Cases	LL Cases	LLG Cases
Case1.csv	Pge08F-basecase (Demetrios Update)_jumpered.olr	7/17/2008 17:31	201	201	0	0
Case2.csv	Pge08F-basecase (Demetrios Update)_jumpered.olr	7/17/2008 17:27	201	201	0	0
Case3.csv	Pge08F-basecase (Demetrios Update)_jumpered.olr	7/17/2008 17:24	201	201	0	0
Case4.csv	Pge08F-basecase (Demetrios Update)_jumpered.olr	7/17/2008 17:16	201	201	0	0

CASE	PARAMETER	SYSTEM CONDITION - FILE - OUTAGE	PRI MAG	SEC MAG	ANG	MULT FACT	SET PRI	SET SEC	ADDITIONAL NOTES
3661	IPh_3Ph_Min	From File: 'Case12D.csv' Fault # 9. Bus Fault on: 0 DIABLO CANYN 525. kV 3LG Branch outage: 0 GATES 525.kV - 0 GATES 230.kV X	3301.2	8.3	-89.2	60%	1980.7	5.0	
814	IPh_3Ph_Max	From File: 'Case5.csv' Fault # 19. Bus Fault on: 0 DIABLO CANYN 525. kV 3LG Branch outage: 0 DIAB-MW#2CAP 525.kV - 0 DIABLO CANYN 525.kV L	4268.2	10.7	-89.3	130%	5548.7	13.9	
214	Z_3Ph_Min	From File: 'Case2.csv' Fault # 25. Bus Fault on: 0 DIABLO CANYN 525. kV 3LG Branch outage: 0 LNS-MDWY#1 525.kV - 0 GTS-LBN_SC1 525.kV L	51.12	4.72	90.0	80%	40.90	3.78	
2217	Z_3Ph_Max	From File: 'Case12.csv' Fault # 11. Bus Fault on: 0 DIABLO CANYN 525. kV 3LG Branch outage: 0 GATES 525.kV - 0 GATES TB11 13.8kV X	51.15	4.73	90.0	130%	66.49	6.14	
3900	3I0_Gnd_Min	From File: 'Case16D.csv' Fault # 10. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 GATES 525.kV - 0 GATES 230.kV X	885.9	2.2	-91.1	50%	443.0	1.1	
4159	3I0_Gnd_Max	From File: 'Case2T.csv' Fault # 50. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 DIABLO BK#1 525.kV - 0 DIABLO UNIT1 25.kV 1T	3199.2	8.0	-92.5	130%	4159.0	10.4	
4397	Z_Gnd_Min	From File: 'Case4T.csv' Fault # 50. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 DIABLO BK#1 525.kV - 0 DIABLO UNIT1 25.kV 1T	46.39	4.29	97.4	80%	37.11	3.43	
3231	Z_Gnd_Max	From File: 'Case2D.csv' Fault # 30. Bus Fault on: 0 DIABLO CANYN 525. kV 1LG Type=A Branch outage: 0 TEMPTAP #2 230.kV - 0 GATES 230.kV 1L	49.85	4.61	92.6	130%	64.81	5.99	

INFORMATION / ASPEN Z / 3PH Values / 1PH Values

Figure 8 – "INFORMATION" sheet: Overall Min Max Summary and other Important Information

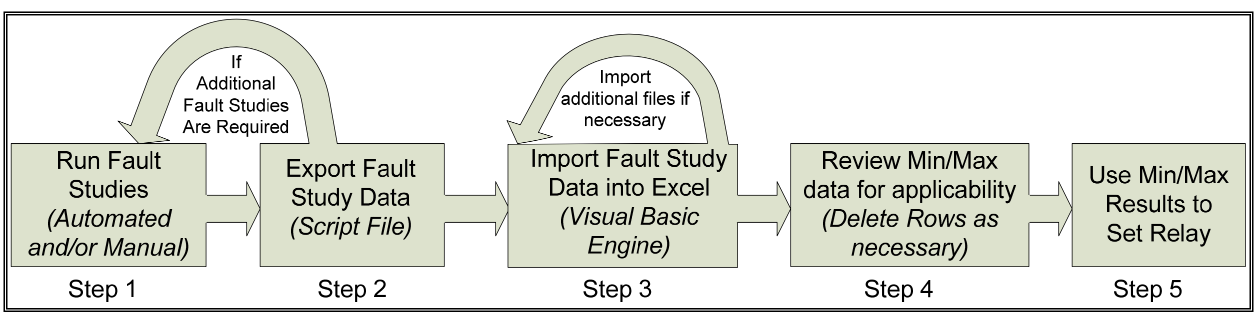


Figure 9 – Process Steps for Using PG&E's Automated Fault Study Application

PG&E Application Benefits and Notes

The process and associated application have benefits that are implicit in the descriptions above. The most notable benefit is the absence of manual transcription of fault data. The process automatically transfers all the necessary data from the fault study program to the workbook spreadsheets. The possibilities of transcription errors are eliminated and the process is much faster than traditional methods. The application and process has resulted in a marked increase in productivity.

The fault study data is also presented in a consistent manner and is ideal for project folders and archival retention. The "INFORMATION" page contains much of the information needed to show an auditor the terminal worst case scenarios, the base cases from which they were taken, and the quantity of cases evaluated, etc.

The resulting matrices of information can be used as a training tool for new engineers. The impacts of single contingency strong source removal from behind and in front of the relaying terminal can be easily seen using sensitivity plots of the column data. On occasions, the data has been used in a statistical manner for sensitivity analysis for ground distance elements. Also, an unfamiliar area of the system can be quickly learned. It has been our experience that some results are surprising even to seasoned engineers. A cautionary note that is worth mentioning - the resulting data is only as accurate as the components modeled in the fault study program.

This application was developed by protection engineers, for protection engineers and only contains those features that are desired and proven to be useful. In the seven years that the program has been released, it has not been used as a management tool to increase production or used with the idea that it can somehow replace the protection engineer. This application and associated process is a tool to facilitate protection work. To date, it is not mandatory that protection engineers use the tool - use is strictly voluntary.

Future vision:

As it was mentioned in the introduction, at the beginning of this decade, PG&E System Protection experienced a significant workload increase caused by two major factors. The first one was the pursuit of a major electrical infrastructure upgrade; the second was the utilization of the newly developed MPAC (Modular Protection and Control) approach. While the MPAC approach brought an overall productivity increase for capital projects, it resulted in a very significant workload increase for protection engineers. This increase was a reflection of relay replacements on multiple terminals under compressed schedule, shifting workload from auxiliary device wiring to logical programming, and the necessity to study multiple contingencies during transition from the relays in the old control buildings to the MPAC relays. This trend is expanding and continuing today.

The process and application described in this paper proved to be a useful tool under these conditions, but it represents only a step toward a new horizon. The benefits of this and similar applications are not just to increase the productivity of protection engineers to meet the challenge of the increased amount of work, or to improve quality of settings.

Further development of similar tools for protection engineers will help to meet NERC requirements for data collection, retention and verification. One solution to this challenge might link study tools, relay setting templates and databases. To allow maximum flexibility, these elements of the future automated system could be designed for use as stand alone applications as well as parts of complete process suite. It should be noted that software already available on the market offers enough power and flexibility to make it happen. Compiling all the necessary documentation in proper order to meet NERC requirements will provide insight on the process steps necessary to accomplish the automation task.

Naturally the process described in this paper can be expanded to include these features but it will take time and expertise. The most logical next step would include an automated data transfer from the relay setting calculation spreadsheet to a relay setting file. Many challenges must be addressed if a fully automated relay setting process is to be realized. These challenges include overcoming both warranted and unwarranted skepticism from engineers and management alike. One manner of overcoming such skepticism is successful demonstration and vetting of each process component. The next step will require close cooperation with relay manufacturers and effective version control over their software.

PG&E's experience in the creation of similar tools showed that the development process is most effective when the tools are produced by protection engineers for protection engineers. This approach results in significant reduction in the task description phase of the development, enhances the communication between developer and user, and improves the overall quality of the final product. In order to make new software tools user friendly, special attention should be paid to achieving optimal function distribution between protection engineer and computer as well as effective human-machine interfaces.

The goals of development of automated study and setting calculation tools are not limited to those listed above (productivity, setting quality, documentation, verification and analysis). These tools together with continuous technology improvement will help to build an important element of effective and highly flexible adaptive protection systems of the future.

References and Further Reading:

1. Lawrence C. Gross, JR.; Practical Challenges and Solutions for Protection Engineering; Western Protective Relaying Conference; October, 2003.

2. Edgar R. Terlau, II; Experiences With The Application And Setting of Ground Distance Relaying; Western Protective Relaying Conference; October, 1990.

Biographies:

Davis Erwin received his BSEE and MSEE in 1997 and 1998 respectively from New Mexico State University. Davis is a registered professional engineer in California and has been with PG&E system protection since 1999 primarily supporting 500kV system projects and Special Protection Schemes.

Feliks Karchemskiy received his MSEE with Honors from Kiev Polytechnic Institute, Ukraine, in 1978. He has more than 30 years (17 with PG&E) of diversified engineering experience in high voltage cable engineering, substation engineering, power quality and system protection. He is currently Supervising Protection Engineer responsible for Central Area in PG&E system.