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Wide-Area Protection Settings Evaluation and Visualization Tool

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SUMMARY

With greater variability in grid operations, commissioning/de-commissioning of conventional and variable generation sources, addition of new equipment to power grids and more widespread use of numerical protection relays it is becoming more challenging to ensure protection relays remain coordinated. Protection relays are configured based on the known grid at the time of the study, but with this greater grid variability and changes the relays may be required to operate in a grid which differs significantly from that for which they were original configured.

To tackle this challenge a Protection Settings Evaluation Tool (PSET) has been developed in collaboration between the Electric Power Research Institute (EPRI), FirstEnergy Corporation, and a number of other transmission and distribution grid utilities to simulate and assess protection performance across large grid areas. The purpose of the tool is to automatically simulate and assess protection system coordination and performance across transmission and distribution grids in order to identify possible misoperations, miscoordinations, slowly cleared faults or uncleared faults. In addition to performing one-off studies the tool is equipped to track and trend relay performance over time, so as soon as some grid change gives rise to relays losing coordination or creating conditions for a relay to misoperate the issue can be identified by the tool and mitigation measures planned. The work documented in this paper concerns the research performed to develop the functionality, performance, and visualization aspects of the tool.

KEYWORDS

Protection, Protection Performance Monitoring, Misoperations, Miscoordinations

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Introduction

The number of protection relays, protection functions and overall relay complexity have all grown significantly since the advent of microprocessor protection relays in the 1990s. In tandem with this increase in both number and complexity of protection relays, transmission and distribution grids are experiencing greater changes through the de-commissioning of conventional generators and commissioning of new generators and energy sources.

When relay settings are calculated a limited set of system conditions are considered as part of the analysis. Within a few years, the grid may have changed significantly from that for which the relay was originally designed, set and configured. To tackle this protection relay settings may be re-evaluated on some fixed schedule of some years. Between maintenance cycles there is scope for relays to lose coordination and be at risk of misoperating in response to certain short circuits. This can be seen in NERC statistics, where protection misoperations are found to occur in approximately 10% of system disturbances and of those misoperations 31% are due to protection settings, logic or design issues [1]. It is the misoperations due to protection settings which the work documented in this paper intends to tackle.

As part of the ongoing research programme in grid protection, the Electric Power Research Institute (EPRI) have developed the Protection Settings and Evaluation Tool (PSET). PSET performs automated protection analysis to identify potential misoperations, miscoordinations, and uncleared faults. PSET has been designed to run in conjunction with ASPEN OneLiner [2,3] and Electrocon CAPE [4,5] power system simulation packages. It functions by sequentially simulating multiple fault types across multiple locations along each transmission line in a selected grid area, voltage level or across an entire grid. The grid is studied under various operating conditions including intact network, N-1 line or generator outage contingencies, and circuit breaker failure network case. Each protection relay tripping in response to each fault is automatically assessed to identify any misoperations, miscoordination, uncleared faults or near-misses.

The results are compiled into XML output file where they may be reviewed in a web-browser, spreadsheet or database. Customized MS Excel spreadsheet and MS Access database have been developed to permit the analysis and comparison of multiple results files representing protection performance snapshots in time. For instance, if the tool is run once a month the results from this month may be compared with last month and the tool will automatically filter the results to flag any changes in protection performance. This ensures that if changes to the power grid result in relays which may misoperate in response to grid short circuits they can be quickly identified and the potential misoperations mitigated. It also ensures that the user need not model every single relay on their system to gain value from the tool – it will monitor the performance of those relays which are modelled and if any deterioration in performance is detected it will be flagged, while uncleared faults on lines which do not have protection modelled can be hidden from view.

Simulation Method

When the user runs the tool they are presented with a dialog box with options for selecting which area of the grid to study, which faults to consider, and metrics against which each protection relay's performance will be evaluated. Figure 1 presents the dialog box from the version of the tool for ASPEN OneLiner. The study region can be selected based on a grid voltage level, grid area, grid zone, or the user may elect to select a particular busbar and all lines within the given number of busbars will be studied. As such, the user may focus the study on a targeted region of a network or more broadly analyze protection across a wider grid.

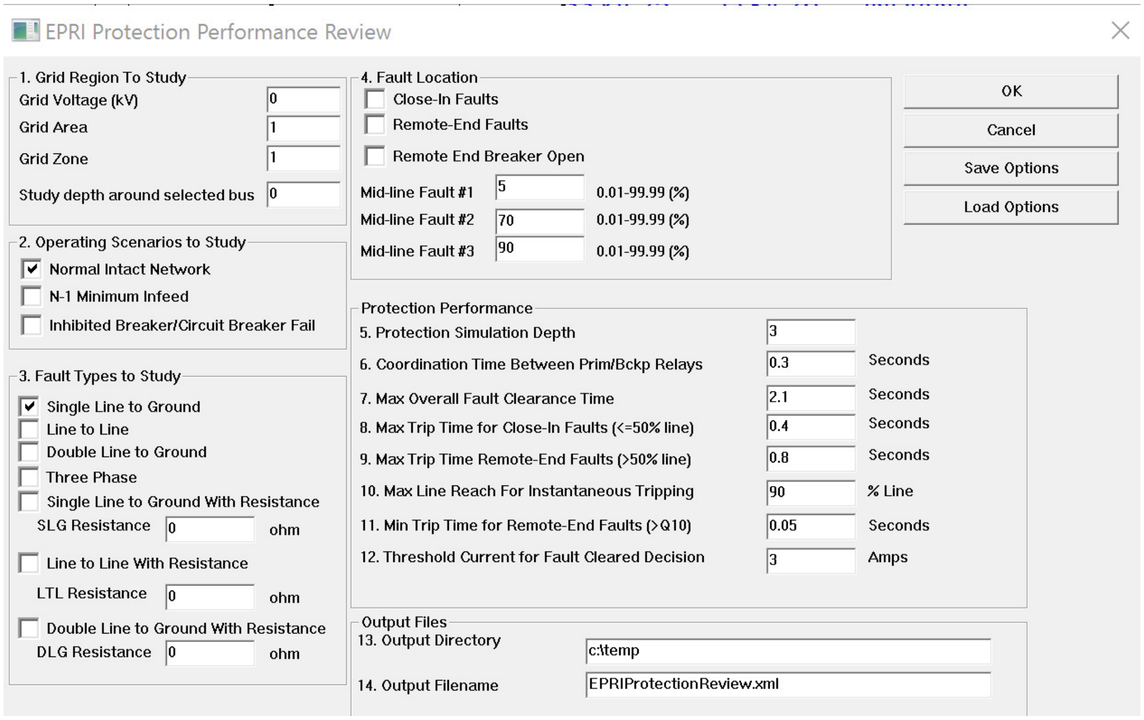

Figure 1 PSET Configuration Options Dialog Box (ASPEN OneLiner Edition)

Various network operating scenarios may be automatically studied including intact network, N-1 (minimum infeed), or Inhibited Breaker/Circuit Breaker fail. For intact network case no grid outages are assumed, whereas for N-1 the line or transformer providing the greatest fault current to the line under analysis is switched out. For inhibited breaker case each circuit breaker at each end of the studied line is in turn blocked from opening in order to evaluate the performance of backup protection on adjacent lines. For the latter two cases the analysis is performed for each remote-end terminal of a line in turn. Thus, for a three terminal line for N-1 case, faults along the line are studied with the largest short circuit current infeed to the first terminal switched out, then the faults are re-applied with the largest infeed to the second terminal switched out, and then the faults re-applied with the largest infeed to the third terminal switched out.

Multiple different fault types are considered (single phase to ground, phase-to-phase, double phase to ground and three-phase faults), with each unbalanced fault type being studied with or without an associated fault resistance. The locations at which the faults are applied along each line are also selected, be that close-in or remote-end faults or at fixed percentage distances along each line. Where specific fault locations as a percentage along each line are studied, the percentage is calculated based on positive sequence reactance. Figure 2 illustrates where the faults would be applied along an example line if fault locations of 5%, 70% and 90% are specified in the configuration options; it can be seen that the distances are taken from each remote-end busbar in turn. For tapped or multi-terminal lines each permutation of station pairs are considered for each fault location. Thus, if a fault location at 5% is specified and the tool encounters a three-terminal line, six distinct faults are simulated - 5% of the distance between

Station A and Station B, 5% of the distance between Station A and Station C, 5% of the distance between Station B and Station A, and so on. The distance is calculated with reference to the cumulative positive sequence reactance between each pair of busbars.

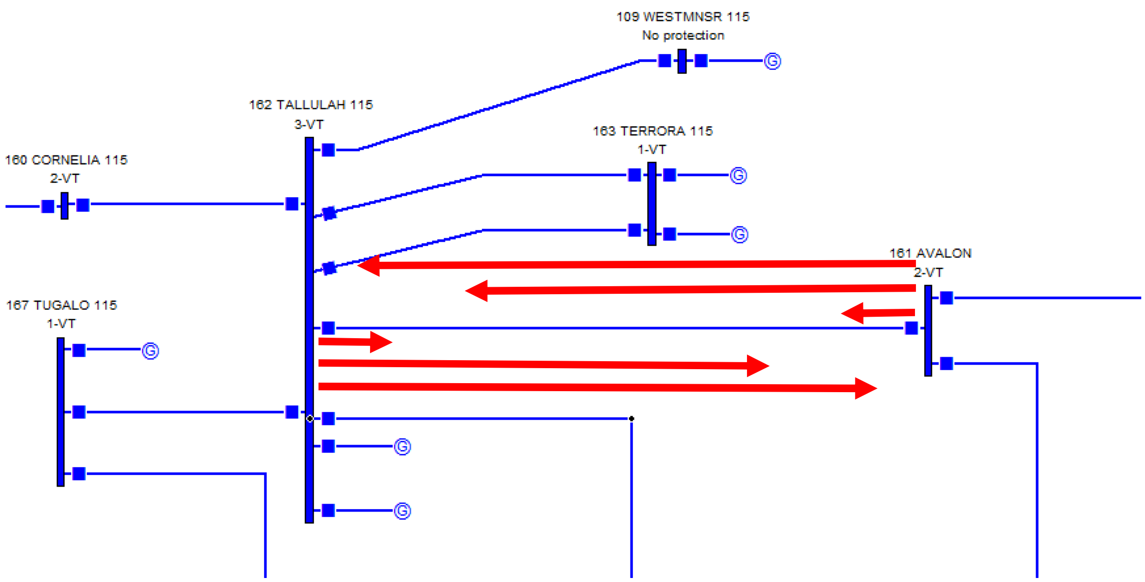

Figure 2 Example definition of fault location (red arrows) when configured to study 5%, 70% and 90% on the line between 162 Tallulah and 161 Avalon 115 kV stations.

Multi-section and multi-terminal lines are automatically considered. The tool distinguishes between real and fictional busbars using the following criteria: a) if a busbar has two lines connected to it and no other equipment such as transformers, capacitors, or generators then it is deemed to be a fictional busbar which is part of a multi-section line, b) if a busbar has three lines connected to it and no other equipment, then it is deemed to be part of a multi-terminal or multi-tapped line. With these decision criteria the tool traverses from the starting bus to all of the remote-end terminals both for simple two-ended lines up to complex circuits with many tapped points, sections, or remote-end terminals.

Faults are studied as stepped-events. This means the fault is simulated and the first relay to trip is identified. The associated circuit breaker(s) are opened then the fault is re-simulated to identify the second relay to trip. This process is repeated until the fault is isolated or no more protection relays are primed to operate.

Once the user has selected the area of the grid to study and the fault types and locations to consider, the tool populates a list of lines and calculates the overall number of fault simulations which will need to be executed. Where multiple fault types, fault locations and grid scenarios are studied the number of permutations quickly grows. For instance, to study single phase to ground and three-phase faults at 5%, 70%, and 90% along each line under normal (intact) network, N-1, and inhibited breaker conditions results in 36 fault studies for every two-terminal line in the study area or 108 fault studies for every three-terminal line. Considering that each fault study may require multiple short circuit simulations as part of the stepped-event analysis the total number of fault simulations for each line will be much greater. For a typical grid where the number of lines can reach many thousands the consequence is a very large set of faults to both simulate and analyze. As such, the time taken for the tool to study a grid area can range from minutes to days depending on the configuration options selected.

Protection Performance Assessment

When performing each fault simulation, every relay trip decision is assessed against set performance criteria. This is used to identify miscoordinations, misoperations, over-reaching, and slow or uncleared faults.

When a fault occurs the primary protection should operate quickly to isolate the faulted plant. Only if the primary protection fails to isolate the faulted plant should the backup protection operate. It is important that the primary and backup protection are coordinated to ensure that the backup protection does not operate too quickly resulting in the unnecessary tripping of healthy plant and the associated loss of load and reduction in system integrity. Thus, the tool supports the configuration of a Coordination Time which is be considered to be the smallest acceptable time difference between the slowest primary protection relay tripping and the fastest backup protection relay prepared to trip. The tools operates with the assumption that the protection at each end of the faulted line are primary protection, whereas protection on nearby lines, transformers, and other plant are designated as backup protection. This removes the need for the manual configuration of relay coordination pairs.

The maximum permissible protection tripping time for close-in faults (0% to 50% along the faulted line) and remote-end faults (50% to 100% along the faulted line) are configured to ensure primary protection is found to be tripping fast and in-line with expectations. Thus, if protection is found to be too slow in operating for the given fault it is flagged in the results file as a slow fault clearance. Conversely, a minimum permissible trip time can be configured for remote-end faults in order to identify primary protection which trips too quickly for remote-end faults. This protection may be at risk of over-reaching and tripping for remote busbar faults or faults on adjacent equipment and will be labelled as such in the results file. For this test function the definition of remote-end is configurable so, for example a value of 90% may be selected in which case undelayed tripping for faults beyond 90% of the line are considered over-reaches and the relay is deemed to have misoperated.

Near-misses are also identified as part of the performance assessment. The simulations discussed above are deterministic and assume that the simulation is perfectly accurate, there is no error in current or voltage measurement, and the relay behaves exactly in accordance with its configuration. In practice, there will be some difference between simulations and actual short circuit events and the instrument transformers are not perfectly accurate. For this reason protection relay settings are normally developed with an error margin. When simulating faults the tool may optionally compare short circuit current against overcurrent pickup settings. If the fault current is within a user-configured margin of the protection setting it is labelled as a near-miss. For example, if a relay is configured to trip instantaneously with a settings of 1000 A, but the simulated fault current is 999 A or 1001 A the simulation and protection system inaccuracies cannot give certainty that the relay will trip or not trip for that fault. As such, it is considered a near-miss and is flagged for further investigation. The acceptable margin is configured by the user and the value is entered in terms of a percentage of the relay setting.

Visualization and Review of Results

Even in the case of small grids this analysis can result in large output datasets due to this large number of permutations of different fault simulations. To simplify the visualization and interpretation of the results the output file produced by PSET can be opened directly in a web browser, a spreadsheet, or loaded into a database for further analysis. These results analysis interfaces provide the capability to significantly simplify the process of identifying the most critical vulnerabilities with a grid in order to prioritize mitigation of protection issues. While the results files can be opened in any spreadsheet tool, a bespoke MS Excel spreadsheet has been developed to provide additional advanced visualization and analysis features. They have also been designed to support long-term trending of results; such that if the tool is run regularly it can be used to quickly identify new protection issues that did not exist in earlier grid studies.

The script creates three output files – an XML file, an XSD file and a XSL file.

- The XML file contains all of the output data
- The XSD file describes the structure of the XML file
- The XSL file describes how the XML file should be displayed.

While it may be cumbersome to have to store the information across three files the benefits are that the data may be directly opened in web browsers, Microsoft Excel, Microsoft Access and many other programs without translation. Figure 3 shows an example of a results file viewed in a web browser. At the top of the page high level information is shown about which part of the grid was studied. If the user hovers their mouse over this part of the page an information box will appear giving greater detail about all of the configuration options which were selected for that study. Below this, the results of each fault simulation are shown in tabular format with one row per fault. In each row the fault location is given, followed by the fault type, any contingencies which were applied, the fault clearance time and the overall assessment of protection performance in response to that fault. If the mouse is hovered over a row an information box will appear listing all relays which tripped in response to that fault, the relay element which initiated the trip, the trip time, the assessment of that relay's performance, and if a near-miss was detected the overcurrent pickup setting and fault currents at the time of the near-miss are shown. As such, the web browser interface can be used to quickly review the results, can be accessed without the need for special tools, and can be easily shared via email or network shared drives.

EPRI Protection Assessment Results	
Results Created:	Jun 22 2017 13:16:40
Database:	c:\cape14\dat\cape.gdb
Network Study Date:	06-22-2017
Simulation Voltage:	230
Simulation Area:	0
Simulation Zone:	0
Simulation Zone:	

Fault Number	From Station	To Station	Voltage (kV)	Circuit ID	Distance To Fault	Fault Type	Contingency	Outage(s)	Fault Clearance Time (SECONDS)	Test Result
1	175 BIO 230	176 HARTWELL DAM	230	1	0.05000	SINGLE_LINE_GROUND	Normal Intact Network Case		99999	FAULT NOT CLEARED
2	175 BIO 230	176 HARTWELL DAM	230	1	0.05000	THREE_PHASE	Normal Intact Network Case		99999	FAULT NOT CLEARED
3	175 BI									T CLEARED
4	175 BI									T CLEARED
5	175 BI									T CLEARED
6	175 BI									T CLEARED
7	175 BI									PPING FOR END FAULT
8	175 BIO 230	177 CENTER 230	230	1	0.05000	THREE_PHASE	Normal Intact Network Case		0.467	SLOW TRIPPING FOR REMOTE-END FAULT
9	175 BIO 230	177 CENTER 230	230	1	0.70000	SINGLE_LINE_GROUND	Normal Intact Network Case		0.465	SLOW TRIPPING FOR REMOTE-END FAULT
10	175 BIO 230	177 CENTER 230	230	1	0.70000	THREE_PHASE	Normal Intact Network Case		0.050	SLOW TRIPPING FOR NEAR-END FAULT
11	175 BIO 230	177 CENTER 230	230	1	0.90000	SINGLE_LINE_GROUND	Normal Intact Network Case		0.495	SLOW TRIPPING FOR REMOTE-END FAULT

Station	Circuit Breaker	Voltage (kV)	Ckt ID	Tripping Relay	Tripping Element	Trip time (SECONDS)	Test Result	IA (pu)	IB (pu)	IC (pu)	IN (pu)	Relay Setting (pu)
161 AVALON	174 BIO 115	115	1	AVALON:Bio 115 Line	PH_IOC	0.212	MISCOORDINATION	0.0	0.0	0.0	0.0	0.0
177 CENTER 230	175 BIO 230	230	1	CENTER:Bio 230 Line	ZDT2	0.512	MISCOORDINATION	0.0	0.0	0.0	0.0	0.0
223 ELBERTON 115	174 BIO 115	115	1	ELBERTON:Bio 115 Line	ZD_FD,ZDT3	0.533	MISCOORDINATION	0.0	0.0	0.0	0.0	0.0
174 BIO 115	161 AVALON	115	1	BIO:Avalon 115 Line	PH_IOC	0.542	MISCOORDINATION	0.0	0.0	0.0	0.0	0.0

Figure 3 Example Results File Opened using a Web Browser

While the results can be opened directly in any spreadsheet program with a layout much like that of the web browser page shown above, a custom MS Excel spreadsheet and a custom MS Access database have also been developed for further analysis of the results. Either tool may be used depending on user preference. These interfaces enable protection performance to be tracked and trended over time and, in particular, to support the comparison of sets of results. Figure 4 and Figure 5 illustrate the title page and main analysis page of the Excel spreadsheet, while Figure 6, and Figure 7 focus on particular details of the analysis page. With this Excel spreadsheet advanced, dynamic filtering methods are offered including the ability to quickly display the differences between two or more sets of results, display only faults resulting in particular misoperations, or only display results from particular substations. When any of the filtering options are selected the report quickly and automatically updates to show the associated simulations results.

The automated comparison of historical sets of results may be beneficial. In this case the user need not examine all fault study results every time the tool is executed, which can easily reach the order of tens of thousands for a typical grid, but instead can view only those faults where protection performance has deteriorated since the last time the tool was run are shown. This enables protection engineers to quickly identify where grid changes such as the addition of new transmission lines or transformers, commissioning or de-commissioning of generators and so on cause an existing relay configuration to gain risk of misoperations. This renders the tool less resource intensive to run on a regular basis as it can just be set to run overnight or over a weekend and only (typically few) changes if any will be flagged at the end.

The ability to track and trend changes in protection performance over time is also beneficial in that the user need not have all their relays modelled in order to derive value from the tool. If only ten relays are modelled on a large system, the first time the tool is executed it will flag many uncleared faults on those lines where no relays are modelled. However, for subsequent times when the tool is executed it will be able to flag if the performance of any of those ten relays changes while hiding the many thousands of uncleared faults on lines without protection models.

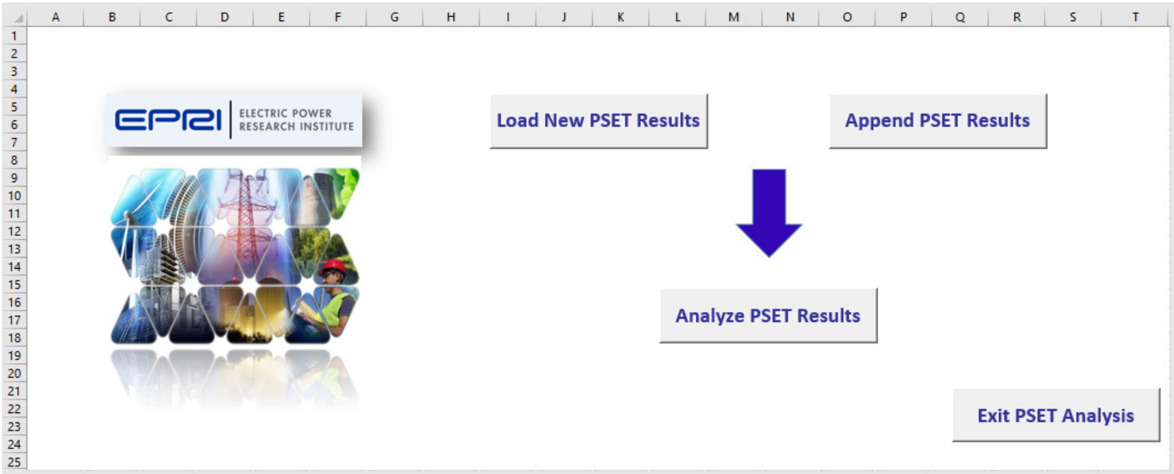

Figure 4 Title page of the bespoke Excel Spreadsheet for Analyzing PSET results files.

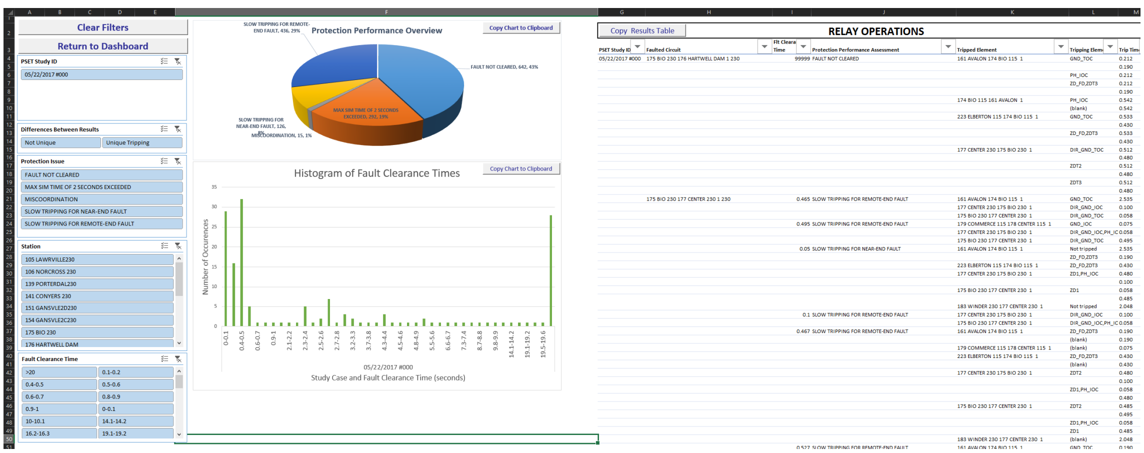

Figure 5 Overview of the Visualization page of the bespoke Excel Spreadsheet for Analyzing PSET results

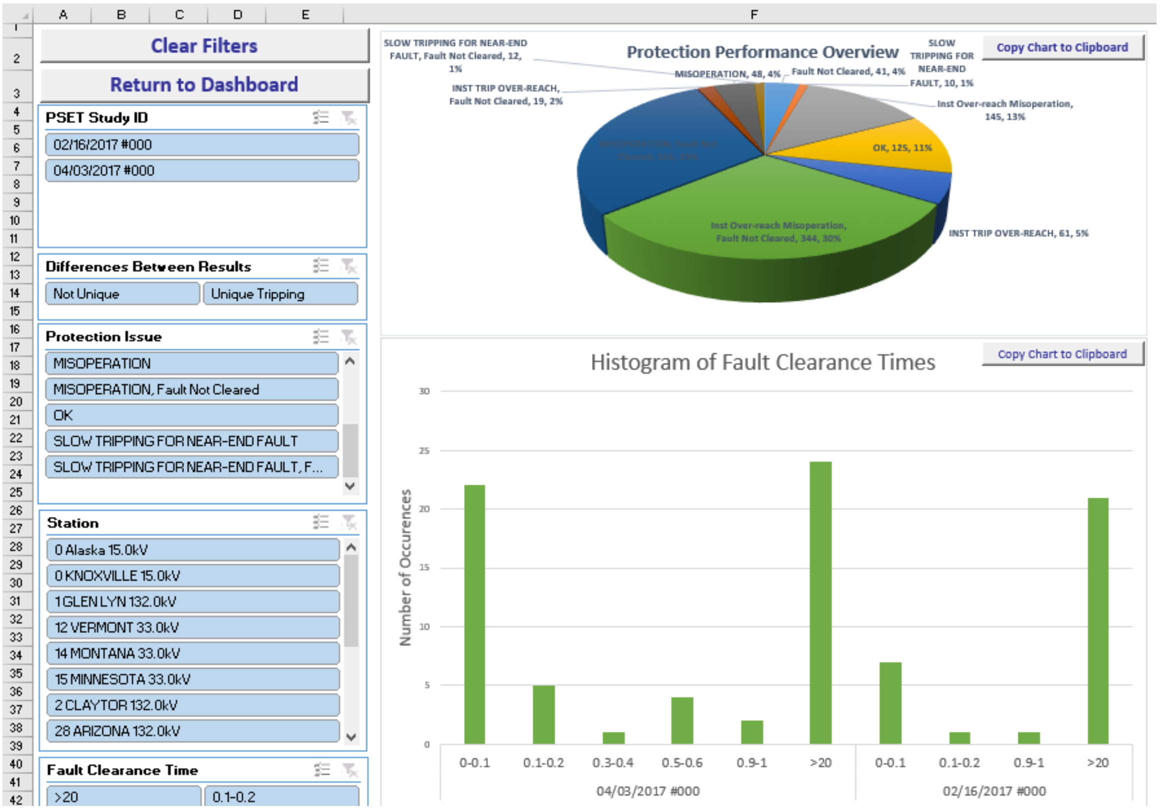

Figure 6 Filtering and Graphical Visualization Capabilities of Excel Results Analysis File

Copy Results Table

RELAY OPERATIONS

PSET Study ID	Faulted Circuit	Flt Clearance Time	Protection Performance Assessment	Tripped Element	Tripping Elemer	Trip Time
11/03/2016 #001	265 AIRLINE 115 174 BIO 115 1 115	0.067	SLOW TRIPPING FOR NEAR-END FAULT	174 BIO 115 265 AIRLINE 115 1	DIR_GND_IOC	0.067
	217 ATHENS 115 178 CENTER 115 1 115	0.142	SLOW TRIPPING FOR REMOTE-END FAULT	178 CENTER 115 217 ATHENS 115 1	DIR_GND_IOC	0.142
				217 ATHENS 115 178 CENTER 115 1	DIR_GND_IOC	0.092
				217 ATHENS 115 178 CENTER 115 2	DIR_GND_TOC	0.438
	217 ATHENS 115 178 CENTER 115 2 115	0.378	SLOW TRIPPING FOR REMOTE-END FAULT	178 CENTER 115 217 ATHENS 115 1	GND_TOC	0.142
				178 CENTER 115 217 ATHENS 115 2	DIR_GND_TOC	0.378
				217 ATHENS 115 178 CENTER 115 1	DIR_GND_TOC	0.092
				217 ATHENS 115 178 CENTER 115 2	DIR_GND_IOC	0.438
	217 ATHENS 115 182 WINDER 115 2 1 115	0.125	SLOW TRIPPING FOR REMOTE-END FAULT	182 WINDER 115 2 217 ATHENS 115 1	DIR_GND_IOC	0.125
				217 ATHENS 115 182 WINDER 115 2 1	ZD_FD,ZD1,DIR_GNE	0.075
	217 ATHENS 115 213 UNION POINT 1 115	99999	FAULT NOT CLEARED	178 CENTER 115 217 ATHENS 115 1	DIR_GND_TOC	0.575
				178 CENTER 115 217 ATHENS 115 2	DIR_GND_TOC	0.510
				182 WINDER 115 2 217 ATHENS 115 1	DIR_GND_TOC	0.567
				217 ATHENS 115 182 WINDER 115 2 1	GND_TOC	0.578
	217 ATHENS 115 451 E.WATKVLE115 1 115	99999	FAULT NOT CLEARED	178 CENTER 115 217 ATHENS 115 1	DIR_GND_TOC	0.575
				178 CENTER 115 217 ATHENS 115 2	DIR_GND_TOC	0.510
				182 WINDER 115 2 217 ATHENS 115 1	DIR_GND_TOC	0.567
				217 ATHENS 115 182 WINDER 115 2 1	GND_TOC	0.578
	217 ATHENS 115 451 E.WATKVLE115 2 115	99999	FAULT NOT CLEARED	178 CENTER 115 217 ATHENS 115 1	DIR_GND_TOC	0.575
				178 CENTER 115 217 ATHENS 115 2	DIR_GND_TOC	0.510
				182 WINDER 115 2 217 ATHENS 115 1	DIR_GND_TOC	0.567
				217 ATHENS 115 182 WINDER 115 2 1	GND_TOC	0.578
	161 AVALON 162 TALLULAH 115 1 115	0.538	SLOW TRIPPING FOR REMOTE-END FAULT	161 AVALON 162 TALLULAH 115 1		
				161 AVALON 174 BIO 115 1	PH_IOC,GND_IOC,GI	0.075
				162 TALLULAH 115 161 AVALON 1	DIR_GND_TOC	0.538
				174 BIO 115 161 AVALON 1	PH_IOC	0.075

Figure 7 Dynamic Reporting Capability of the Excel Results Analysis File

Application

The tool is currently being used or trialed by a number of transmission grid operating companies, where it is used for monitoring protection performance, identification of potential protection misoperations, identifying relay modelling errors, and tracking protection performance over time. The tool is being actively developed and enhanced based on field experiences.

Conclusions and Next Steps

This paper has presented a Protection Settings Evaluation Tool (PSET) which has been developed for two popular protection simulation software platforms. The tools enables the automated simulation and assessment of protection performance under many different fault types under different grid conditions. The tool can be used to track and trend the expected protection performance across large grid areas both for high-level reporting and detailed analysis. The tool will operate regardless of whether only a few relays are modelled or all relays are modelled. As such, for companies who are in the process of building up their relay model databases the tool can be used to immediately begin monitoring the simulated performance of existing relay models, while also tracking the improvement in system protection performance as additional relay models are added to the network model.

Tool development continues and has a roadmap to provide a single platform from which more wide-ranging analysis features including automatic assessment of the impact of grid outages, grounding one circuit of mutually-coupled lines during maintenance, and detailed analysis of individual relays performance when settings are being calculated or revised. It is also planned that the tool act to provide a simple method for visualizing other types of protection analysis.

The tool is being used by a number of companies in order to assess the performance of protection systems, improve relay models, and identify potential relay misoperations with the overall aim of improving protection security and performance over time.

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