

**February 2008 Issue...**

- 1** Tips and Tricks: Unstable Poles?
- 2** PSCAD® Master Library Update!
- 3** Accuracy and Stability Improvements of HVDC Overhead Transmission Lines and Underground Cable Models
- 6** Distribution System Fault Analysis Tool Utilizing Transient Simulation Intelligence
- 12** PSCAD® 2008 Training Sessions

## Tips and Tricks: Unstable Poles?

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**Solving transmission line parameters for use in PSCAD® is a complex task to say the least. In order to achieve full frequency dependence in a time domain simulation, the line or cable must first be solved in the frequency domain.**

Frequency domain calculations are relatively simple, when compared to the difficulty of actually transforming these results into the time domain. The Frequency-Dependent (Phase) model in PSCAD® first calculates the characteristic admittance  $Y_c$  and the propagation function  $H$  at all specified frequencies, and then curve fits the points to derive an approximate equation for each parameter; both of which can be transformed directly to the time domain.

Depending on the complexity of the transmission system (usually underground cables), 'non-physical' results may occur when calculating the propagation function  $H$  in the frequency domain, and these results may require unstable poles to properly curve fit. If we could use unstable poles, there would be no problem; however, unstable poles translate to instability in the time domain, so they must be avoided at all costs. The curve fitting algorithm removes unstable poles by forcing them to their equivalent stable region. Although this avoids instability in the time domain, it introduces error in the fitting results. Normally this error is insignificant, but sometimes it may cause difficulties in arriving at a reasonable result – or success in solving a transmission system for that matter.

The following describes how to detect that unstable poles may be causing a problem, and how to maneuver around the problem once found.

A portion of the log file for an underground cable system is shown below:

<b>Attempt #5</b>		<b>Target Error: 1.5625%</b>
Group #	Relative Fitting Error	Number of Poles
1	1.3245%	3
2	0.5063%	5
3	1.5578%	13
4	0.9987%	5
Maximum Absolute Error:		1.5273%
Maximum Requested:		0.2000%
<b>Attempt #6</b>		<b>Target Error: 0.7812%</b>
Group #	Relative Fitting Error	Number of Poles
1	0.4531%	4
2	0.5063%	5
3	1.4725%	20
4	0.3363%	6
Maximum Absolute Error:		1.0180%
Maximum Requested:		0.2000%

**Figure 1** A portion of the log transmission line file for an underground cable system.

Above you can see attempts to fit the propagation function  $H$  within the specified error. Pay particular attention to the 'Number of Poles' for each delay group. At attempt #5, it is obvious that the number of poles for the 3rd delay group is beginning to shoot away from the rest – quickly reaching the specified pole limit by attempt #6.

From this attempt onwards, the fitting error for the 3rd group does not improve. The PSCAD® Line Constants Program (LCP) however, looks at the overall average error of all groups and continues to iterate, increasing the number of poles used in

the other delay groups until the average error is within the set tolerance. If this is even possible (it is in this case), it means that the error in the other delay groups must be very small indeed to offset the bad fitting in the 3rd group. This inadvertently causes a large residue/pole ratio, which may lead to time-domain instability (occurs in this case).

The reason for the problems in the fitting of the 3rd delay group is that unstable poles are required to fit this group. Due to the fact that unstable poles cannot be used, the LCP converts them to their stable equivalent. Unfortunately, the stable pole equivalents cannot represent the function it is supposed to fit exactly, hence the minimum achievable error of 1.4725%. To correct a problem like this, find the attempt where the above begins to occur.

Write down the fitting error at that attempt and then modify your maximum propagation fitting error in the line model so that the LCP does not iterate past this point. I chose 1.1%, as the error at attempt #6 was 1.0180%. This ensured that the algorithm stopped at attempt #6 in the following solve, a small residue/pole ratio and a reasonable fitting error of 1.018% for the propagation function H.

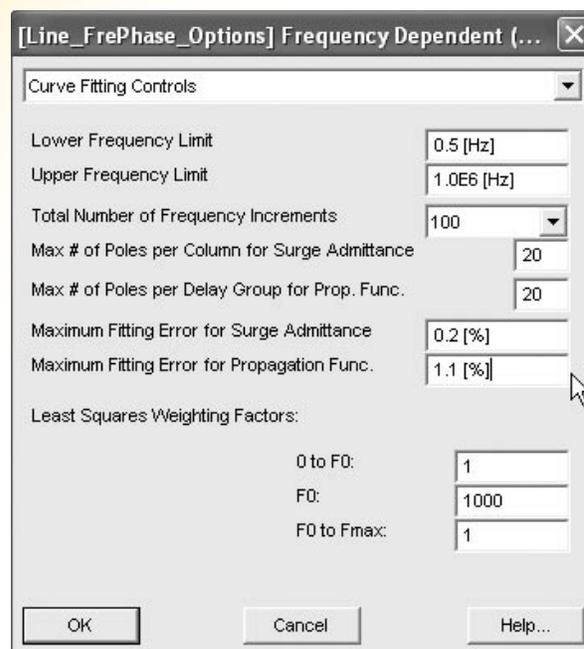


Figure 2 Frequency dependent (phase) model parameter dialog.

## PSCAD® Master Library Update!

PSCAD® Technical Support Desk, Manitoba HVDC Research Centre



An update of Master Library for PSCAD® 4.2.1 is now available in the PSCAD® V4 download pages of [www.pscad.com](http://www.pscad.com). The updated Master Library 4.2.1.4 fixes a problem with breaker animated power display when P,Q parameters are something other than numbers represented in default English format. For example INF, NaN, or a localized number where commas are used instead of decimals (i.e. 100,35 for 100.35).

If you have questions regarding this update, please contact the PSCAD® Support Team at [support@pscad.com](mailto:support@pscad.com)

# Accuracy and Stability Improvements of HVDC Overhead Transmission Lines and Underground Cable Models

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**High voltage direct current (HVDC) transmission of power over long distances is seeing increasing application with HVDC lines and cables being installed all over the world.** Simulation models for such systems are required to be accurate over a very wide frequency range from zero Hertz – which is the nominal frequency on the line; to several tens of kilohertz – for thyristor switching and other transients. In general, the frequency domain expressions for the line or cable parameters are complicated. In order to have a time-domain implementation, the line's characteristics (element of admittance or propagation matrix) are first approximated by rational transfer functions and then transients on transmission lines can be investigated with arbitrary (including non-linear) terminations.

PSCAD®/EMTDC™ uses modern phase domain modelling techniques coupled with transfer function estimation using Vector Fitting. This approach has greatly improved the accuracy of time-domain models for transmission lines and cables [2]. However, although these time-domain models simulate the frequency range from a few Hertz to about several kilohertz, it has been difficult to get a good fit in the close neighborhood of 0 Hz (DC), as is important in simulating HVDC systems. The required order of the fitted function rises rapidly as the lower fitting frequency is reduced. As will be described below, we have developed a new solution to this problem which not only corrects for the DC error but also greatly reduces the likelihood of a non-passive and hence potentially unstable formulation. We are in the process of incorporating this algorithm into PSCAD®/EMTDC™.

**Methods for DC Correction** The simplest method for correcting the error at low frequency is by adding a suitable series resistance in each conductor. Although the correction does compensate for the DC response, it can introduce errors at higher frequencies. A more serious problem with this method is that the added resistance can sometimes have a negative value which could, in many instances, result in a non-passive formulation and lead to unstable simulations. Hence, this method is not recommended. Instead, we recommend a new procedure which re-casts the system transfer

function into a different form in which the DC value can be independently selected. Hence, the DC response is always precisely correct. This procedure is now described.

## DC Correction by Functional Form Method

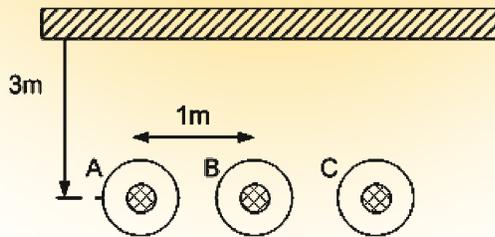
In this method, the functional form of the rational function used to fit the characteristic admittance and (unwound) propagation functions, is modified as shown in Equation 1 [1]. The DC value is factored out as an additive constant ( $d_{dc, theoretical}$ ) which can be directly selected. The resulting characteristic can be fitted with more accuracy without having to substantially increase the number of poles (M). The form of Equation 1 is readily converted to a time-domain model for the cable.

$$f^{mod}(s) = \sum_{m=1}^M \frac{c_m s}{s - a_m} + d_{dc, theoretical}$$

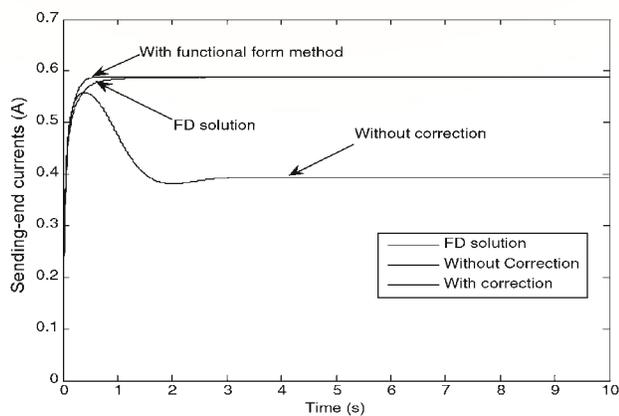
Equation 1

## Numerical Inverse Laplace Transform as a Validation Tool

One of the problems in attempting to validate time-domain models of cables is that it is difficult to have a template for validation. Hence we have implemented a method for obtaining the analytical solution for cables with simple linear terminations. The analytical solution then becomes the template for comparison. This method uses a frequency domain (FD) formulation and obtains the correct solution by numerically inverting the Laplace Transform of the accurate transfer function. As an example, consider the 50 km cable system shown in Figure 1. Phase "A" is energized with 1V step voltage while all other terminations are connected to the ground. Figure 2 shows the corresponding sending-end current waveform of phase "A" for the conventional (without correction) and proposed (with correction) time-domain simulation approaches. The analytical FD solution is also plotted for comparison. The simulation covers a period of 10 s and, in contrast with the uncorrected formulation; the result from the proposed (corrected) method closely conforms to the theoretical response obtained by frequency domain calculations.



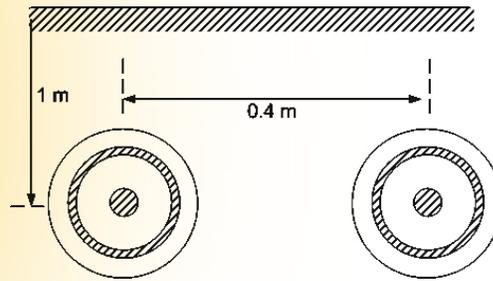
**Figure 1** Simple cable system: three single-core coaxial cables.



**Figure 2** Sending-end current of first conductor with and without functional form.

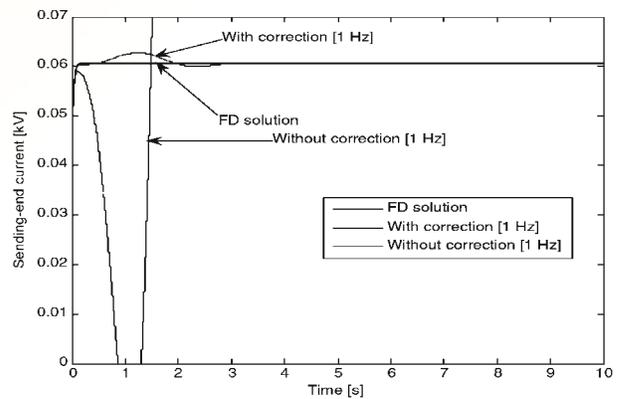
### Improved Passivity with Functional Form Method

One of the difficulties in DC correction is that it is difficult to guarantee that the curve-fitted model is always passive. A non-passive formulation for the transmission line or cable can sometimes lead to an unstable simulation. One important advantage of the functional form method is that it minimizes the likelihood of passivity violations. For example, a short circuit test is carried out for the cable system shown in Figure 3. With the correction method applied, the sending-end current is stable and converges to the correct steady state response as shown in Figure 4, while the original formulation is unstable. The test for passivity is that all eigenvalues of the transfer admittance matrix are positive at all frequencies. The plot of a critical eigenvalue of transfer admittance with and without correction is shown in Figure 5.

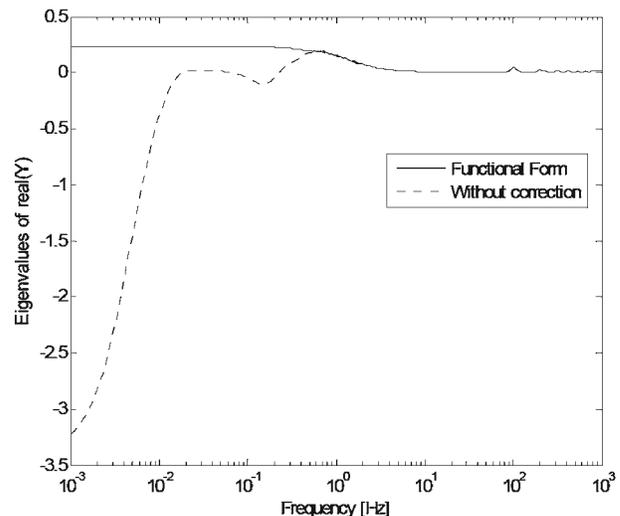


**Figure 3** Cable system: two coaxial cable system.

With the functional form method, the critical eigenvalue curve is positive at all frequencies, while without any modification, the eigenvalue plot becomes negative at very low frequencies, indicating passivity violation.



**Figure 4** Short circuit current at sending-end.



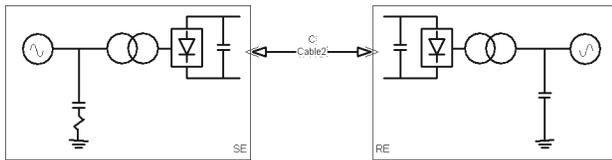
**Figure 5** Critical eigenvalue of transfer admittance with and without functional form method.

### Application Example - Voltage Sourced HVDC with Underground Cables

The voltage sourced converter (VSC) based medium voltage DC transmission system example shown in Figure 6 [3] was modelled to show the applicability of the proposed method

**...the proposed DC correction method yields a model that is applicable over the full frequency range...**

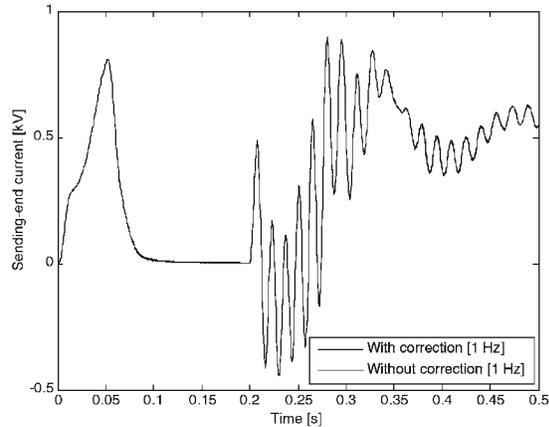
in simulating large systems with non-linearities. The converter consists of six pulse VSC rated at 110 kV, 75 MW transmitting power to the receiving-end through the 100 km underground cable system shown earlier in Figure 3. Here, the proposed functional form method yielded a well-behaved passive formulation for the transmission line. In contrast, the original (uncorrected) approach initially yielded a non-passive formulation and the lower fitting frequency and conductance to ground had to be manually adjusted to render a non-passive formulation which increased the number of poles and hence the complexity of the line-model. Even then, as the results below will show, the uncorrected formulation still resulted in significant low-frequency error.



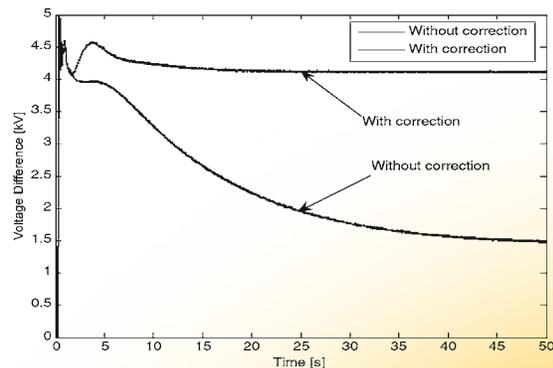
**Figure 6** VSC Transmission System

Figure 7 compares the DC line current through the underground cable with and without correction between 0 to 0.5 seconds indicating that the functional form method does not alter the high frequency response of the original curve fitted model. Figure 8 shows the voltage difference between the two ends of the cable system for a much longer duration (50 s). With the functional form method, the steady-state voltage drop and the DC current observed are 4.1 kV and 0.495 kA respectively. This is in exact agreement with the theoretical DC resistance of 8.3 Ω (note: 4.1 kV/0.494 kA = 8.3 Ω).

Without any correction, the voltage difference is 1.45 kV for the line current of 0.52 kA, which implies an incorrect DC resistance of 2.84 Ω. The above simulations demonstrate that the proposed DC correction method yields a model that is applicable over the full frequency range of interest and is thus useful for studying the steady-state and low frequency dynamics as well as the high frequency transient and harmonic behaviour of the DC link.



**Figure 7** DC line current of the converter.



**Figure 8** Voltage difference between the converter and inverter.

**References**

- [1] Atef Morched, Bjorn Gustavsen, Manoocher Tartibi, "A Universal Model for Accurate Calculation of Electromagnetic Transients on Overhead Lines and Underground cables", *IEEE Transactions on Power Delivery*, Vol 14, No 3, July 1999.
- [2] Bjorn Gustavsen, Adam Semlyen, "Rational Approximation of Frequency Domain Responses by Vector Fitting", *IEEE Transactions on Power Delivery*, Vol 14, No 3, July 1999.
- [3] PSCAD®/EMTDC™ Library example, "VSC TRANSMISSION WITH AC TRANSMISSION CHARACTERISTICS".

# Distribution System Fault Analysis Tool Utilizing Transient Simulation Intelligence

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**Several electric utilities in USA have emphasized that having the capabilities of automatically detecting any type of faults as well as anticipating the type and location of momentary and permanent (more than 5 minutes) faults in distribution power systems are crucial to their planning and operational activities.** Quickly and accurately detecting temporary and high impedance faults/failures including voltage dips/sags, distortions, will help utilities increase the reliability of their distribution systems at a lower cost. Under a Department of Energy program *Concurrent Technologies Corporation (CTC)* has recently developed a fault-locator software named "Distribution Systems Fault Locator" or DSFL capable of predicting the location of permanent faults in distribution power systems [1]. This comprehensive fault location software minimizes the errors between measured and expected parameters. Current and voltage values as well as the number of customer calls and their distance to the fault location are used. It uses a combined heuristic/genetic algorithm approach where the following 5 rules are satisfied [1-2]:

1. Comparison of predicted and recorded fault currents
2. Recloser status
3. Recloser voltage and current RMS values
4. Customer call information
5. Time synchronized phase angles and waveforms

The DSFL software was integrated with Distribution Engineering Workstation (DEW) [3] and Advanced Energy Management Power Flow Analysis System Technology (AEMPFAS™) [4]. A dynamic link library (dll) version of the DSFL was also developed for easy integration with other software tools including CYMDIST software [5]. DSFL software is a very promising operational, decision-support tool that can be used to predict the most likely fault locations in power systems. The fault locator was validated with faulted circuit data from DTE. The number of possible fault locations was narrowed down significantly by the fault locator software and the recorded fault locations were captured in all predictions. This article describes the AFAS software that is currently being developed under the DoE, CGM program. It involves utilizing the transients information simulated using PSCAD® simulator to advance the accuracy in predicting fault locations.

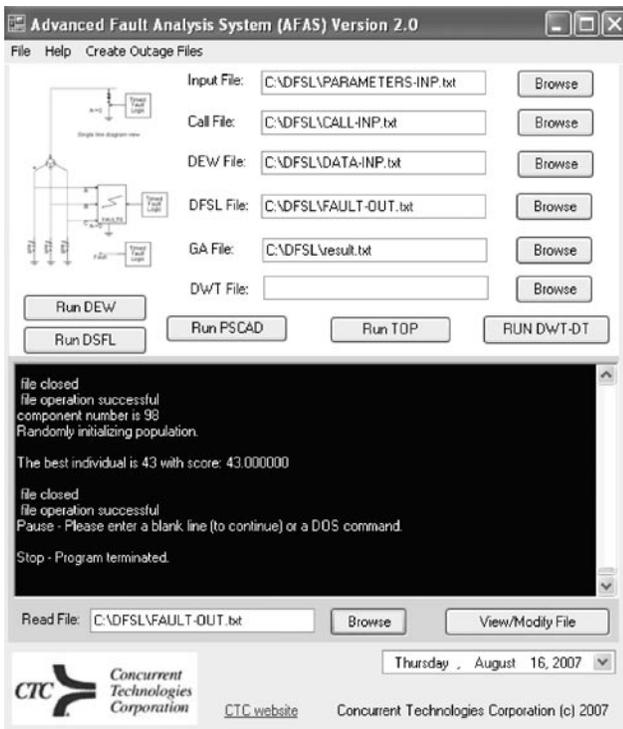
**Methodology Description** Power system analysis tools PSCAD®, DEW, CYMDIST, AEMPFAS™ and DSFL are integrated under the AFAS platform. After thorough validation of the PSCAD® models for the distribution systems, a wide range of transient simulations were performed to develop a comprehensive library of fault signatures to be used for advanced fault/failures location and diagnosis of momentary and permanent faults using AFAS. Both the RMS and time-waveforms of voltage and currents are used. The available faulted circuit data (from Detroit Edison [DTE] and American Electric Power) for momentary and permanent faults were used to validate the results in the signature library, as well as to investigate and develop a methodology to create the signatures based on the simulation data available from PSCAD® studies. Lastly, modelling and analysis studies using the developed computational modelling platform (e.g. AFAS) were performed to demonstrate predictive capabilities of AFAS. AFAS interface and the PSCAD® custom simulation set up are presented below [6-7].

**AFAS GUI Development** The AFAS GUI screen design Version 2.0 is shown in Figure 1. Some of the features of the AFAS GUI include:

- (i) Logon form
- (ii) Input form to enter simulation parameters
- (iii) Communication between GUI and console application
- (iv) Ability to view the output data file
- (v) Launch other software modules such as PSCAD®
- (vi) The GUI allows the user to view and save/modify the Outage Call and PQ monitoring data files specific to an outage event.

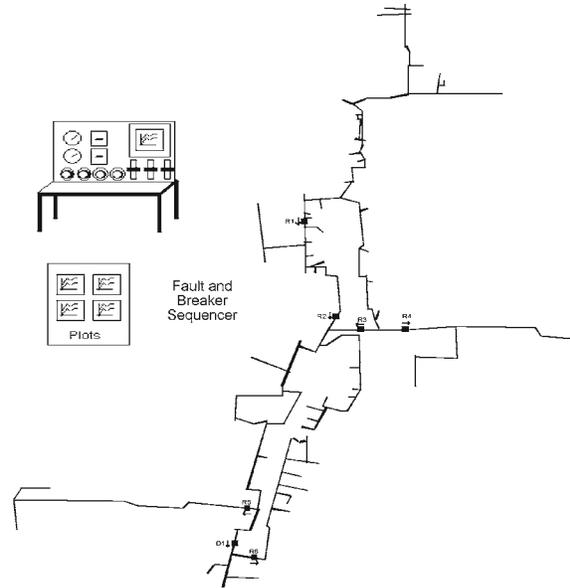
**PSCAD® Case Development** A PSCAD® model of the DTE-Orion distribution network was developed based on the circuit available in the DEW software. The DEW Orion model consists of more than one thousand elements. However, it was not necessary to model all the elements in PSCAD® for transient simulation purposes. Components such as station poles and fuses are ignored. The substation bus is modelled as a voltage source behind an equivalent impedance. Transformers are modelled with their leakage reactances. Saturation has been disabled; however,

an option is available to enable it with default parameters. Feeders are modelled with equivalent RL branches between load buses or couple PI section models. Loads are modelled as constant impedance or constant PQ loads. Both three phase and single phase circuits can be modelled.



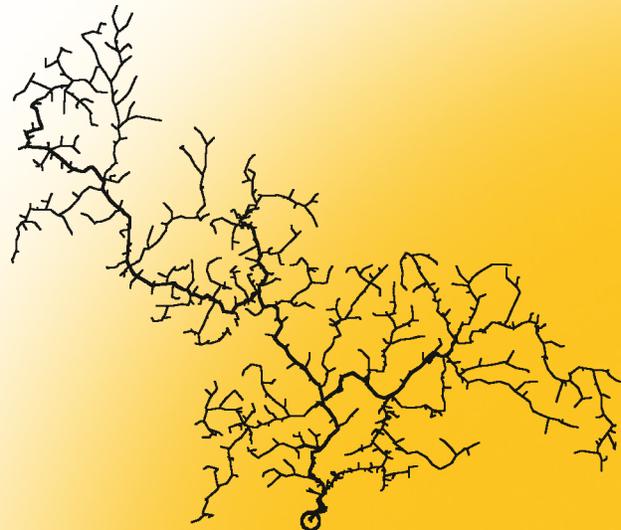
**Figure 1** AFAS GUI screen design version 2.0.

The PSCAD® case system was developed during proof of concept phase by manually examining each and every component in the DEW and CYMDIST graphical interface. Figure 2 shows a case developed manually. Two filter programs (DEW\_PSCAD & CymDist\_PSCAD) have now been developed to automate the conversion process. Figure 3 shows the AEP's Clendenin feeder in PSCAD® generated using CymDist\_PSCAD filter. Three phase circuit is shown with black sections and single phase circuits are represented in red, green and blue sections. Further details such as shunt loads, capacitors, etc. are visible by zooming inside the hierarchical block.



**Figure 2** Top level PSCAD® view of manually assembled Orion case.

The PSCAD® circuit coordinates use the GIS coordinates of the circuit and hence the automated circuit layout looks identical to that of the DEW or CYMDIST layout. Special PSCAD® component library has been created to achieve this special layout capability. The circuit is arranged in hierarchical blocks for ease of navigation. The pictures of the hierarchical blocs also show the graphics of what is inside the page. All the components in PSCAD® have labels corresponding to their serial number or IDs which helps to search the components easily.



**Figure 3** Clendenin Circuit in PSCAD® (Filtered from CymDist Case).

There are about 130 fault locations in the Orion circuit which have been identified as critical by DTE and CTC. The model has been set up such that any one of the faults can be selected at a time during a transient simulation. The case automation is discussed in the subsequent section on transient simulation setup.

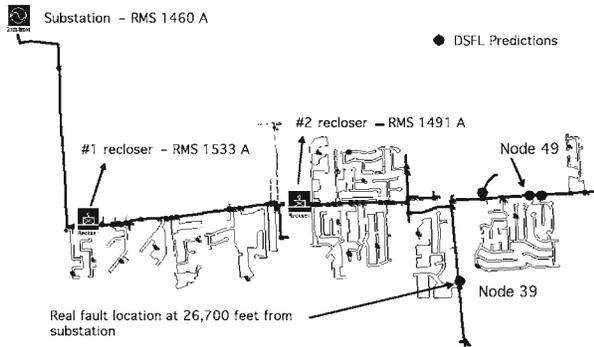
**PSCAD® Case Validation** The Orion model was validated against the DEW solution by comparing the steady state power-flow solution and short circuit solution. These quantities are tabulated for side-by-side comparison. The results show a reasonable match within expected tolerance. Transient performance was validated by comparing fault waveform against DEW short circuit current as well as against field data for known faults. The substation relay measurement for a single-phase A-G fault current was 2291 A (fault occurred at recloser 1 in Figure 3). The fault current prediction was 2405 A, which is within 5% of the measurement. The fault resistance was assumed to be equal to 1.0 ohm. In addition, several validations using DEW and field recordings were performed.

**PSCAD® Custom Transient Simulation Setup** The case is automated to perform various fault types at a given location. The fault duration can be varied. For each fault, voltage and current waveforms and RMS values are recorded at the fault location, substation as well as at all circuit re-closers. The record length consists of pre-fault duration, fault duration and post-fault duration, all of which can be varied using sliders in the case control module or in a multiple run process. There are 7 fault types, 4 fault incidence angles, three fault resistance classes (0-1, 5-15, 50-100 ohms). The following seven fault types are simulated for each fault location: A-G, B-G, C-G, AB, BC, CA, and ABC. The case is automated such that it loops through multiple simulation runs, varying one parameter during each run till all combinations are run. The recorder data is stored in a customizable directory structure for easy identification of fault data for analysis.

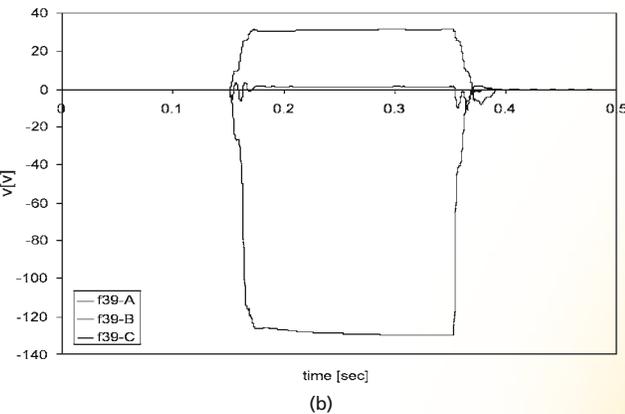
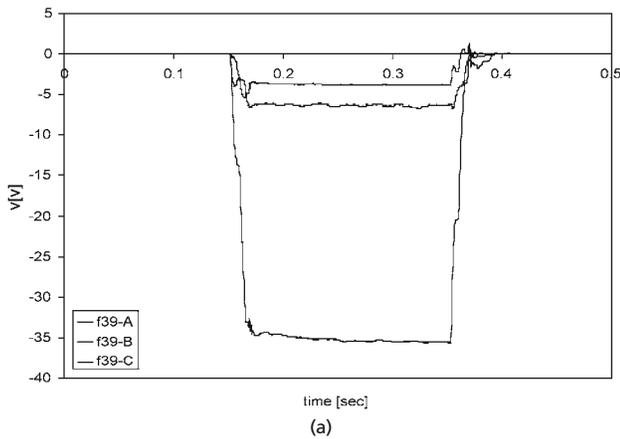
**Signature Library** A methodology was developed to generate a signature database using the PSCAD® simulation records. The DTE Orion circuit is used next to describe a typical circuit library of fault signatures. The Orion circuit has 1078 components, 125 probable fault locations, 8 recorders for each simulation run (1 substation, 6 reclosers, 1 fault location), 56 runs for each location, and 7000 runs for all circuit fault locations. The time step is 50 microseconds and the plot step is 250 microseconds. The total CPU time to make the 7000 runs is less than 24 hours in a standard PC computer and the memory size to store the results in zipped Comtrade format is about 1.5 GB. The search scheme is developed based on the V&I indices, which will be discussed later in this paper. Thus, for the Orion circuit, a library of 7000 signature V&I indices can be used to compare with the measured indices and detect/locate the fault in real time. Several digital libraries of V&I fault signatures are under development for several DTE and AEP circuits. The effect of the fault inception angle on the instantaneous peak fault current, RMS peak fault current, and average RMS fault current was studied in detail in [4]. It was determined that the difference between the maximum and minimum average RMS fault current is about 3%. Accordingly, the effect of the fault angle on the current indices is negligible. Also, the effect of the fault angle on the fault current will decrease with the fault resistance (Table 1), becoming negligible for a high impedance fault.

Fault Resistance (ohms)	RMS Fault Peak Current (A)	
	Fault Angle (degrees)	Fault Angle (degrees)
	0	90
0	1589.7	1400.2
1	1461.0	1350.3
5	1117.4	1117.1
25	712.9	712.8
100	551.0	551.1

**Table 1** The effect of fault inception angle and fault resistance on the RMS fault peak current (recorded at substation, DTE's Jewel circuit).

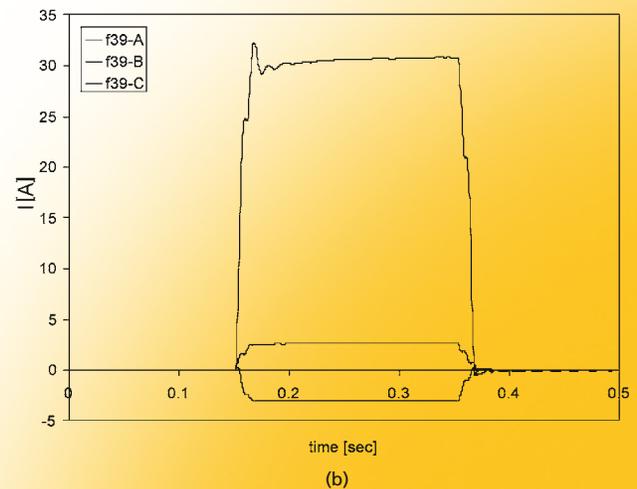
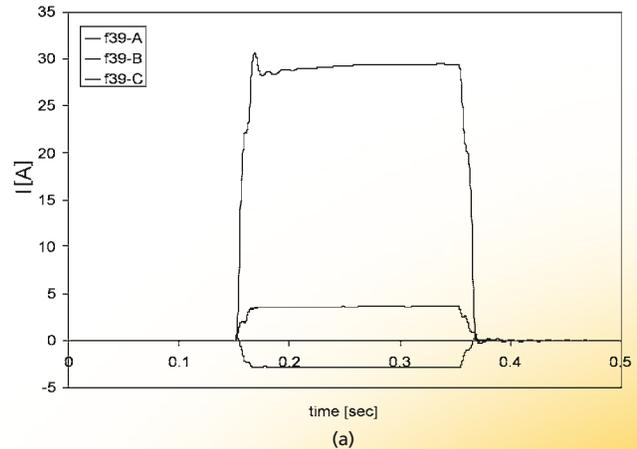


**Figure 4** DTE's Jewel circuit topology and fault data.



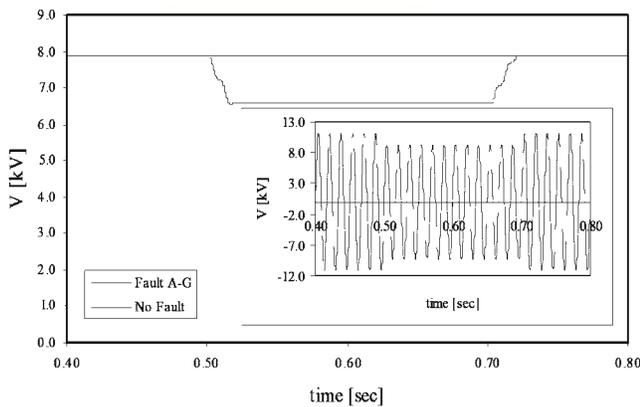
**Figure 5** PSCAD® predictions for DTE's Jewel circuit: RMS voltage differences at substation (a) and recloser #2 (b) for nodes 39 and 49 shown in Figure 4.

**Fault Location Prediction** DTE's Jewel (Figure 4) was selected to perform several simulation studies because: (i) an A-G type fault occurred on July 17, 2006 on a circuit branch at node 39 in Figure 4 and the specific customer call data were unavailable; both reclosers were triggered by the same outage event; thus, it is difficult to predict accurately the fault location with the current steady-state capabilities; (ii) fault RMS current data were recorded at reclosers and substation; and (ii) had a waveform current recording at the substation level that can be an additional piece of information in the current AFAS capability.



**Figure 6** PSCAD® predictions for DTE's Jewel circuit: RMS current differences at substation (a) and recloser #2 (b) for nodes 39 and 49.

The predicted RMS voltage and current differences between nodes 39 and 49 at substation and recloser #2 are presented in Figures 5 and 6, respectively. Note that, while the current differences between nodes are in general very small at both recloser #2 and substation, the voltage differences are much larger at the recloser #2 (about 130 V) as compared with the substation (about 35 V). The highest voltage drops will occur near the fault location; thus, the voltage differences can be used in determining the fault location. A voltage sag/dip prediction for a bolted fault on a distribution system is shown in Figure 7.



**Figure 7** Voltage sags/dips prediction for an A-G fault on DTE's Orion circuit.

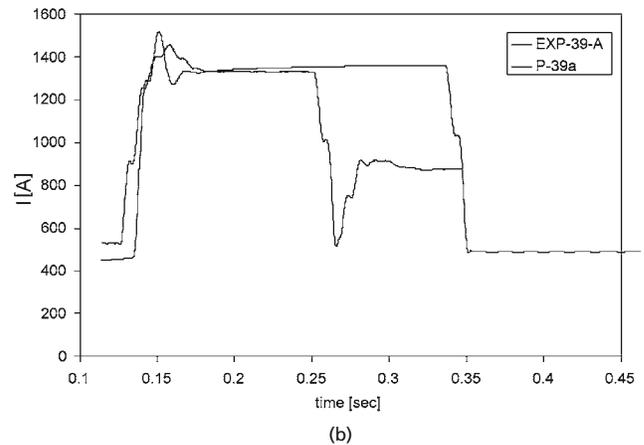
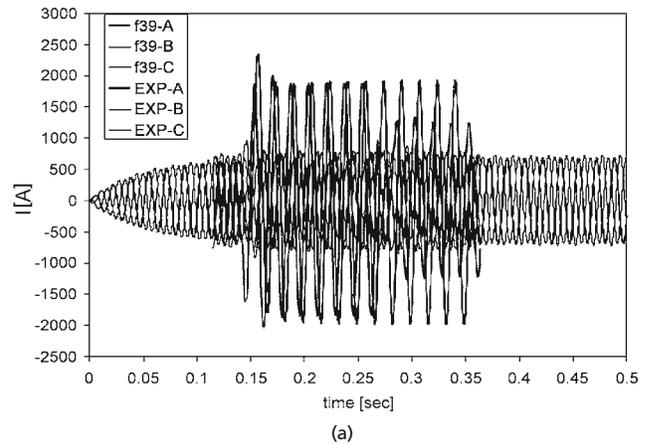
A voltage-dip energy index ( $E_{dip}$ ) can be used to characterize a specific fault. It can be calculated as:

$$E_{dip} = \int_0^T \left[ 1 - \left( \frac{V(t)}{V_{nom}} \right)^2 \right] dt$$

Where  $V(t)$  is the RMS voltage versus time and  $V_{nom}$  is the rated voltage. For the example in Figure 6,  $E_{dip} = 0.00523$  s. Figure 8 shows a comparison between predictions and experimental measurements for the waveform and RMS current recorded at the substation. The resolution of the experimental and PSCAD® waveform recorders were 1440 Hz and 4000 Hz,

respectively. The fault current data comparison for the initial transient and the steady-state regimes of the fault is reasonable, once again validating the correct implementation of the Jewel circuit into PSCAD®. Note that the second experimental fault (starting around 0.27 s in Figure 8) was not simulated in PSCAD®. The RMS current data in Figure 8b were obtained using the following equation:

$$I_{eff} = I_{rms} = \sqrt{\frac{1}{T} \int_0^T |i(t)|^2 dt}$$



**Figure 8** PSCAD® predictions and experimental measurements recorded at substation for DTE's Jewel circuit: (a) waveform currents (b) RMS currents.

The following methodology was developed to determine the exact location of the fault:

(i) Determine the average of RMS currents ( $I_{rms}$ ) during the fault duration (including at least the initial transient period and a portion of the steady-state period) as follows:

$$\bar{I}_{rms} = \frac{1}{t_f} \int_0^t I_{rms} dt$$

(ii) Determine the current index as follows [7]:

$$I_{index} = \sqrt{\frac{1}{2} \sum_k \left[ 1 - \left( \frac{\bar{I}_{rms}^p}{\bar{I}_{rms}^{exp}} \right)^2 \right]}$$

where the subscripts  $p$  and  $exp$  denote predicted and experimental values.

(iii) Compare the measurement and predictions at several nodes that were previously determined by DSFL software. For the Jewel circuit case, a comparison was made between the measurement and predictions at nodes 39, 43, 49, 51 (these locations were predicted by DSFL). Table 2 shows the current index comparison for nodes 39, 43, 49, and 51.

(iv) Minimum current index  $I_{index}$  will show the exact fault location. In this case, the minimum  $I_{index}$  is at node 39, which is also the real fault location (Table 2).

Node Number	$I_{index}$
39	0.071
43	0.188
49	0.159
51	0.146

**Table 2** The predicted current indices based on PSCAD® custom simulation for DTE's Jewel circuit.

**Conclusions and Future Work** AFAS is a powerful transient software tool that can be used for both planning and operational needs to study, detect and locate faults/failures in distribution power systems. An important feature of AFAS is its ability to use only the recording at the substation and, where available, recloser recordings. This eliminates the need for additional sensors to detect faults. Future activities include adding online capabilities by linking it to the substation and recloser fault recorders to automatically locate the faults upon its occurrence.

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