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Power Quality On Electric Ships

John Prousalidis (Greece) & Dharshana Muthumuni (Canada)

Electric power system simulation and analysis software has been used by energy utilities for the analysis of power quality problems for many years. Power quality problems can be simplistically defined as cases where the electric quantities (voltage or current) diverge from the ideal. Power quality issues involve virtually all aspects of the power system operation, from steady state voltage regulation to the control of high frequency transients caused by lightning or system switching operations. Since many power quality problems involve complex interactions between the power system, control systems and industrial equipment, simulation tools can be very helpful toward developing an understanding of the dynamics of power quality problems and then evaluating the effectiveness of various solution alternatives.

The electric power grid of a ship can be regarded as a small scale industrial power system. A ship's electric energy system consists of a generator set and a distribution cabling system serving the loads. In the case of a conventional ship's power system, there are at least two main AC generators driven by diesel engines, gas turbines or the main propulsion engine. Power is supplied to the electric loads consisting of:

- the conventional auxiliary systems similar to an industrial plant (lighting and motors driving rotating machinery)
- the main and auxiliary ship propulsion systems.

Typical ship electrical networks can operate at 50/60 Hz while naval applications often require 400 Hz systems. Increased electric power demands in ships have led to the introduction of medium-voltage (high in ship terms) operating levels of 3.3 and 6 kV.

Recent developments in power semiconductor and power electronics technology and their application in drive and control systems have now enabled the integrated full electric propulsion of ships. The term electric ship now generally refers to a ship with a full electric propulsion system. It is the advent of AC electric propulsion in ships that has introduced a whole new set of power quality complexities on ships.

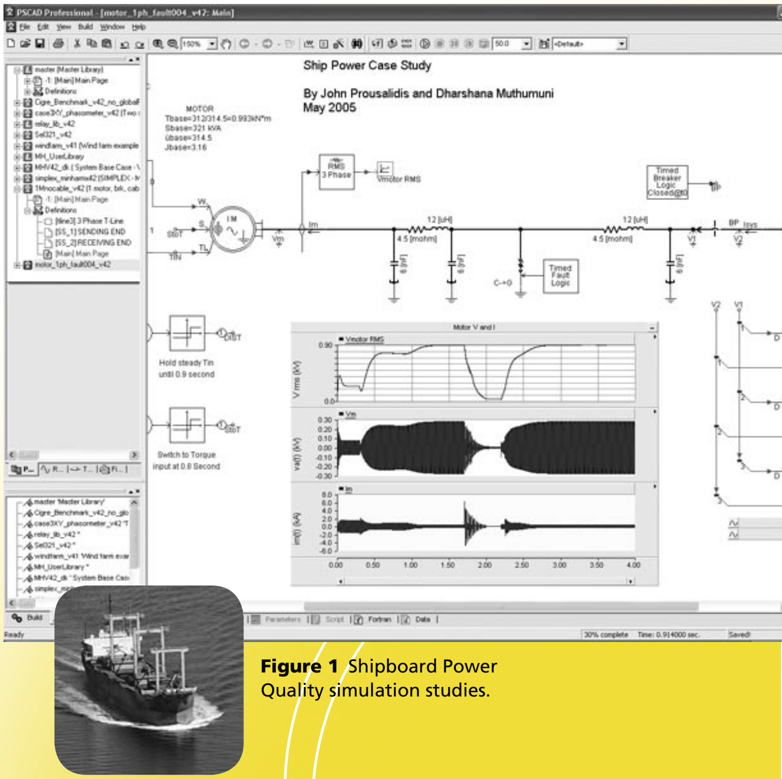


Figure 1 Shipboard Power Quality simulation studies.

With the trend toward electric vehicles and transit systems, simulation programs are no longer just for the use of electrical utilities.

Characteristics of a Ship's Power System

Hybrid Energy System The nature of a ship's electric energy system is highly hybrid comprising of both AC and DC subsystems of various operation voltages and frequencies. This scenario closely resembles the Flexible AC Transmission Systems (FACTS) of energy utility electrical grids (i.e. the recently developed power electronic devices, which can attain optimal exploitation of transmission systems by accurately controlling their real and reactive power flows through them).

Large Power System The total power installed per unit volume is large, especially in propulsion applications of an electric ship. For example, the installed power system of a modern container-ship with electric propulsion can be in the range of 80–100 MVA.

Non-Linear Loads with Non-Conventional Behaviour The greatest amount of energy on a ship is used by electric motors (acting either as main propulsion units or as drivers of auxiliary engines). Besides rotating electric motors comprising of dynamic loads, there is a significant amount of non-linear loads with non-conventional behaviour.

Sensitivity to Power Quality & EMI Problems A considerable number of electronic devices installed onboard (automation systems, controllers and navigation systems) are sensitive to power quality and EMI problems provoked in particular by the extensive use of power electronics. Hence, the power quality problems related to harmonic distortion, voltage dips or switching electromagnetic transients are of extreme importance and have to be thoroughly analysed.

According to the all electric ship concept, every major or minor system onboard the ship, propulsion being the predominant one, will eventually be electrified and served by a large scale electric system (of several 10s of MW) with multiple redundancy in components and circuits.

Figure 2 Single-line diagram of study case.

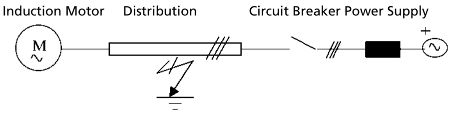
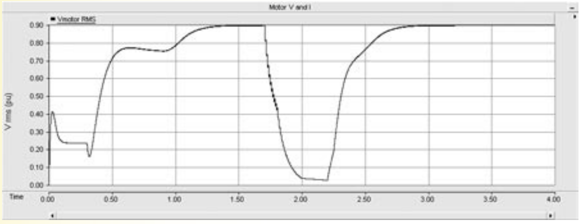


Figure 3 Motor terminal voltage (RMS-value) fluctuation.



Power Quality problems in ship systems can be grouped as follows:

Propulsion Main or auxiliary propulsion motor start-up and steady-state operation in conjunction with their power electronic converters.

Switching Transients Overvoltages and overcurrents due to making or breaking of circuit breakers (i.e. transformer electrification, cable disconnection, fault clearances and load shedding).

Harmonic Distortion Introduced by the use of power electronic devices.

Consequences of Ship Power Quality Problems

- Improper operation of sensitive electronic equipment due to electromagnetic interference,
- Increased reactive losses,
- Increased insulation stresses or even equipment breakdowns,
- Raise of resonance phenomena, and
- Increased electromagnetic signature.

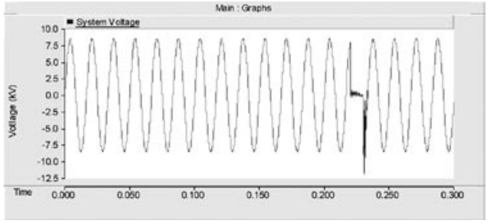
Examples Two examples of power quality problems that can be encountered on a ship system are:

- The clearance of a single-phase shipboard fault occurring nearby an induction motor
- Voltage quality problems caused by pulsed loads.

Single-Phase Shipboard Fault This particular example comes from an actual scenario that took place on a passenger ship with auxiliary electric propulsion (thrusters). Specifically, near the induction motor driving one of the ship's thrusters, a single-phase fault occurred (see Figure 2).

Initially, when the electric motor starts-up, a transient inrush over-current is absorbed by the motor leading to the first voltage sag. When the fault takes place in phase C, at 1.7 seconds, a significant over-current flows in this faulty phase resulting in a very severe voltage dip, especially in this phase of the motor feeding the line. A few ms later (at 1.9 seconds), the corresponding circuit breaker protecting the feeder trips, interrupting the power supply to the motor. This time, the motor suffers from an abrupt voltage zero and starts decelerating rapidly (refer to plots of voltage and

Figure 5 System voltage with sag due to pulse load.



current shown on Figure 1, and Figure 3). At the same time, the circuit breaker contacts are subjected to a transient recovery over-voltage reaching 160% of the nominal value. Then, at 2.2 seconds the circuit breaker re-closes identifying no further faults as the latter fault has already cleared at 2.0 seconds. The motor re-enters a starting-up procedure, absorbing a transient inrush current, which in turn, provokes another minor voltage sag in all three phases. Eventually, the simulated voltage converges to its steady-state value of approximately 220 V (rms value).

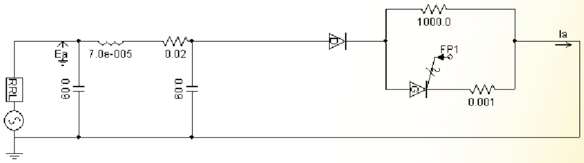
Pulsed Loads A second example of a ship power quality issue that can be studied with PSCAD™ relates to the voltage quality problems caused by pulsed loads.

Pulsed loads have been introduced in modern shipboard energy systems via the installation of weaponry or navigation systems. This pulse energy demand has to be provided by the ship energy sources, while not impacting the operation of the rest of the system. One example of a pulsed-load on shipboard is the rail-gun weapon system in naval ships. Also, the radar power demands on shipboard can be regarded as pulsed-like peaks occurring on a periodic time basis.

The pulsed load behaviour can be modelled in PSCAD™ via the parallel combination of two resistive elements. The first resistance, R_M, being always on-line is of fairly large value, whereas the second branch comprises of an extremely small valued resistance, Rp, where the current flows only when a power electronic switch is triggered.

As the current flowing in the actual pulsed load device is only positive, the corresponding model is complemented by a rectifier diode placed in series to the parallel combination of branches. The complete circuit set-up of the study case considered is depicted in Figure 4. Thus, the pulse load is supplied with energy via a distribution feeder.

Figure 4 System with pulsed load modelled in PSCAD.™



The pulsed load waveform is approximated by a circuit model synthesized in PSCAD™ via conventional components. The simulated voltage across the load terminals is subjected to significant sag (see Figure 5), due to the voltage drop on the source and cable impedances. It is noticed that the cable stray capacitance, which is of relatively high value compared with the overhead lines or distribution cables used in continental grids, tends to ameliorate the phenomenon. More specifically, they offer an amount of reactive power acting as voltage stabilizers.

During the current pulse, the terminals at the generator busbars are subjected to significant sag if not voltage zero, which consequently can cause other problems to the rest of the loads connected. For instance, the motors would experience an abrupt deceleration due to this sag and would restart again resembling the short-circuit cases. A solution to this problem would be the installation of an auxiliary power source (e.g. capacitor bank, or batteries in conjunction with an inverter) injecting temporarily the amount of excess energy demanded by the pulsed load. It is also worth noting that in this case, after the end of the pulse, a transient over-voltage is developed mainly due to the interaction between distribution cable inductance and capacitance.

The two case study examples are just a sample of the power quality issues that can be encountered on a modern ship. The simulation of power quality phenomena occurring in ship electric power systems and propulsion systems helps us to better understand and mitigate the issues. Phenomena occurring in both AC and DC ship subsystems including voltage sags, transient inrush over-currents and transient over-voltage spikes, are successfully simulated in PSCAD,™ analysed and discussed, while the effect of certain critical parameters are investigated.

PSCAD™/EMTDC A Simulation Tool For Ship Electric Power Quality Studies, J. Prousalidis, I.K Hatzilau, Cdr S. Perros, School of Naval Architecture and Marine Engineering, National Technical University of Athens, Greece and Hellenic Naval Academy, Greece, International Naval Engineering Conference, Amsterdam, March 2004 The full paper appears on the PSCAD™ Forum in the section, *Paper Trail, www.pscad.com.*

Fault Analysis of an AC Electric Railway System

Hanmin Lee, KwangHae Oh, Gilsoo Jang and Sae-hyuk Kwon (Korea)

The Korean Railroad Research Institute (KRRI) in cooperation with the Department of Electrical Engineering at Korea University has modelled their AC electric railway system in PSCAD™. KRRI is presently introducing a next generation high speed electric train and using PSCAD™ to model both the electrical components of the train and the electric railway system.

When designing and planning an AC electric railway system, it is important to carry out a careful study of potential fault occurrences. Thus, it is important to accurately model the AC electric railway system and to conduct simulated fault studies.

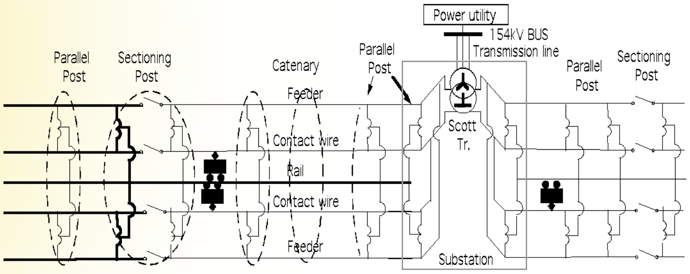
The electric railway system is composed of individual subsystems, such as the power supply network, the auto-transformer, the catenary system and other subsystems.

In order to verify the validity of the model, studies for the fault current are carried out. Hand calculations are compared with PSCAD™ simulation results to obtain an acceptable accuracy for a complete integrated model of all the constituent subsystems.

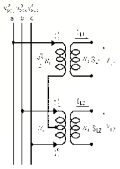
The AC Electric Railway System The Korean AC electric railway system is based on single phase power at 27.5 kV/55 kV. The system is connected to a three-phase power system to be supplied with a large single-phase load. AC feeding circuits supply vehicles with the power by 3–2 phase Scott transformers through the feeder, the contact wire and the rail. Auto transformers are installed at intervals of about every 10 kilometres with circuit breakers which connect adjacent up and down tracks at parallel post (PP). Substations (SS) are located about every 50 kilometres and there is a sectioning post (SP) midway between two substations. The SP has circuit breakers, which enable one feeding circuit to electrically separate from the other. They may be closed in the event that an adjacent substation is out of service.

In order to achieve an overall model to provide reliable results for the system shown in Figure 1, particular attention must be given to the modelling of each subsystem. Figure 5 shows an integrated model of each subsystem as designed using PSCAD™.

Figure 1 An AC electric railway system.



The Power Supply The electric power utility supplies 154 kV to the AC electric railway system through the transmission line. The Scott transformer in the substation is stepped down from 154 kV(N_1) to 55 kV(N_2). Two pairs of single-phase power is obtained from a Scott connecting transformer. The turn ratios of T-phase and M-phase are $\sqrt{3}/2N_1 : N_2$ and $N_1 : N_2$ respectively. The connection diagram of windings in the Scott transformer appears in Figure 2.



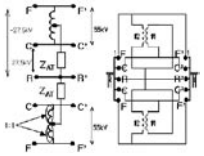


Figure 2 Scott transformer. **Figure 3** Auto-transformer.

The Auto-Transformer The auto-transformer is connected between the catenary and an adjacent feeder with the rails connected to the centre point on the winding. The AC electric railway system supplies 55 kV between the contact wire and the feeder with auto-transformer of ratio l:l (feeder-rail:rail-contact wire) to obtain 27.5 kV. The auto-transformer of the AC electric railway system steps down the high voltage from 55 kV to 27.5 kV

Auto-transformers are installed about every 10 kilometres along the railroad. The equivalent circuit of the auto-transformer is shown in Figure 3.

The Catenary System Overhead catenary systems of the electric railway have several conductors with a complex geometry. This system could consist of contact wires (4,6), messenger wires (3,5), feeders (1,2), rails (7, 8, 9, 10), and protection wires (11, 12) (Figure 4). Droppers every few metres connect two conductors, such as the contact wire and messenger wire.

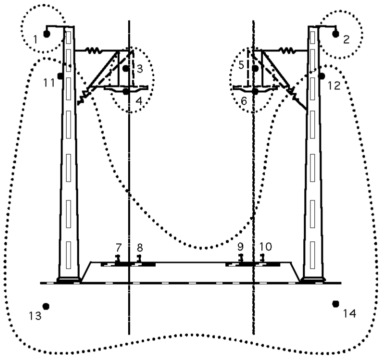


Figure 4 Configuration of the contact lines.

1 Kwanghae Oh, Hanmin Lee, Sanghoon Chang, *Harmonic Analysis Model Based on 8-Port Representation for Korean High Speed Railway, WCRR*, 2001
2 Hanmin Lee, Kwanghae Oh, Cnangmu Lee, Sanghoon Chang, Gilsoo Jang, Saehyuk Kwon, *A Reduced Equivalent 5 Conductors Modelling of the Catenary System, Trans. KIEE, Vol.52A. No.12,* DEC, pp684–690, 2003
3 Sanghoon Chang, Kwanghae Oh, Junghoon Kim, *Analysis of Voltage Unbalance in the Electric Railway Depot Using Two-port Network Model*, International Conference on Electrical Engineering, pp852–858, 2001
4 Korea Railroad Research Institute, *Urban Transit Standardization Research*, 2002
5 Hanmin Lee, Kwanghae Oh, Gilsoo Jang and Saehyuk Kwon, *Fault Analysis of AC Electric Railway System Model by PSCAD™/EMTDC, Trans, KIEE,* Vol.52A, *No.9*,SEP,2003

The full text of this paper can be found on the PSCAD Forum, *Paper Trail*, *www.pscad.com*

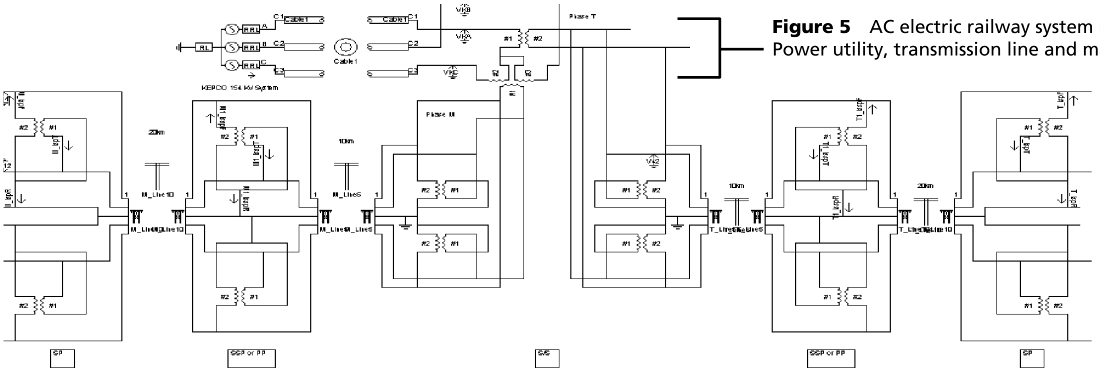
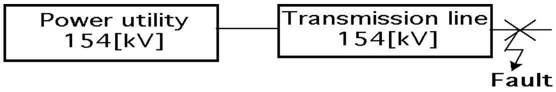


Figure 5 AC electric railway system model using PSCAD™/EMTDC. Power utility, transmission line and main transformer (left).

Faults Studies In order to verify the PSCAD™ system model, a number of fault studies (single phase to ground, three phase to ground, etc.) were conducted and the simulation results were compared to the theoretical calculations.

154 (kV) single phase-to-ground fault



An example of the theoretical calculations conducted for each fault type is:

Zero-Sequence Impedance Z_0	R^0	X^0	
Power Utility 154 [kV]	0.5810	4.5694	SERIES
Transmission Line 154 [kV]	0.4410	0.4743	
Total	1.0220	5.0437	

Positive-Sequence Impedance Z_1	R^1	X^1	
Power Utility 154 [kV]	0.2075	3.2510	SERIES
Transmission Line 154 [kV]	0.3651	0.5620	
Total	0.5726	3.8130	

Negative-Sequence Impedance Z_2	R^2	X^2	
Power Utility 154 [kV]	0.2075	3.2510	SERIES
Transmission Line 154 [kV]	0.3651	0.5620	
Total	0.5726	3.8130	

$$Z_0 = 1.0220 + j5.0437[\Omega]$$
$$Z_1 = 0.5726 + j3.8130[\Omega]$$
$$Z_2 = 0.5726 + j3.8130[\Omega]$$
$$Z_0 + Z_1 + Z_2 = 2.1672 + j12.6697[\Omega]$$
$$Z_{SF} = \sqrt{2.1672^2 + 12.6697^2} = 13.1143[\Omega]$$

Fault Current 154[kV] Three phase-to-ground fault

$$Ig = \frac{3E}{Z_0 + Z_1 + Z_2} = \frac{3}{12.855} \times \frac{154{,}000}{\sqrt{3}} = 20.749[kA]$$

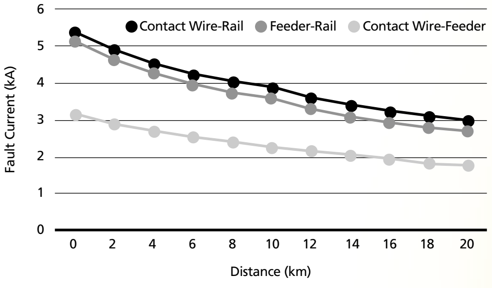


Figure 6 Fault current simulated by PSCAD™ for various scenarios.

PSCAD™ Version 4 Simulation In order to verify the AC electric railway system made by PSCAD,™ a number of simulations were carried out. Without showing the mathematical formulae and the details of the theoretical calculations, the PSCAD™ simulation results, as compared to theory, are shown in Table 1:

Table 1 Comparing Fault Current (kA)

	PSCAD™ Result	Calculation
154 (kV) SLG	22.00	20.33
154 (kV) 3 Phase	23.56	23.04
55 (kV) LL	3.12	2.60
27.5 (kV) SLG	5.36	4.79

The results of the calculations and the PSCAD™ simulation results compare very closely. There is some difference in the results because the catenary system, PP and SP behind the substation have been made by a continuous parallel connection in PSCAD.™

Also, the impedances of systems simulated by PSCAD™ are a little bit lower than those in hand calculations. Therefore, the fault currents in the simulation are somewhat higher than those in hand calculations. However, the errors are small and the simulation results are well in accordance with theory.

The AC electric railway system, as designed using PSCAD™ provides a means for efficient and accurate modelling of all components, and proves to be very useful for fault study analysis. We can easily simulate realistic fault scenarios using PSCAD,™ such as: contact wire-to-rail, feeder-to-rail and contact wire-to-feeder.

The results for the fault current measured at the fault location are shown in Figure 6.

In conclusion, we find that the fault current rises at the point of the auto-transformer. When we look at the original system at the substation: the impedance gets higher at the mid point of two auto-transformers (PP-PP or PP-SP), in the case of short circuit, and lower near the auto-transformer. Thus, the fault current rises at the point of the auto-transformers (PP and SP) which are located at intervals of 10 kilometres and 20 kilometres.

Because the voltage level of the contact wire-to-feeder is higher than that of the contact wire-to-rail, the fault current on the contact wire-to-feeder is lower respectively.

Get Ready for PSCAD™ V4.2!

PSCAD™ users will have lots to smile about upon the release of PSCAD™ Version 4.2. The Centre is in the final Beta and acceptance testing stages. PSCAD™ V4.2 sees the addition of new functions, enhanced stability and accuracy with the introduction of new models, and furthers the ease-of-use and ease-of-navigation already associated with the PSCAD™ Version 4 platform. PSCAD™ users can look forward to these features in PSCAD™ V4.2 in addition to a number of other fixes and enhancements.

Automatic Units Conversion PSCAD™ now includes a unit conversion utility built into the data manipulation code of PSCAD™ components. This conversion tool is designed to handle three basic actions:

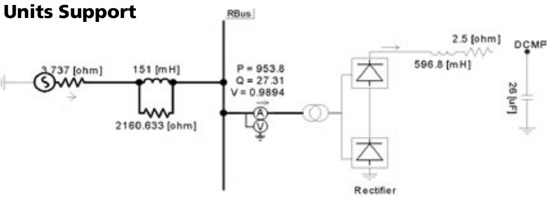
1. Domain to domain base conversion (metres to feet)
2. Scaling factors (2 km to 2000 m)
3. Domain inverse relationship (sec to Hz)

The Units Conversion utility makes PSCAD™ easier to apply to lower voltage and current applications in fractional motors and power electronic systems.

Drag & Drop Extensions To speed up the creation and movement of curves on the design canvas, the capabilities have been extended to allow the user to drag curves from one graph to another or around the same graph to sort the order. In addition, copies of the curve can be created by holding down the <ctrl> key and dragging a new curve from the existing one. This makes the manipulation of graphs very efficient.

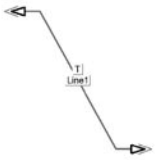
Enhanced Message Balloon Currently the errors and warning messages are displayed in a balloon component on the circuit canvas. Refinements to the balloon have extended to display not just the current message but rather all messages pertaining to the component in question. Multiple messages are handled using small label components in a scrolling list. This way, the user does not have to click on each message in the output window to see all the diagnostic information.

Units Support



New Wires

New Tri-Segmented Transmission Lines



A New Wire Class A handy new wire class has been created to support advanced movement and manipulation. The new wires provide fundamental support for single and multi segmented wire types, buses and new tri-segmented types used to support transmission lines. This new wire type provides new drawing constructs that allow for multi-rectangle (region) based components. The region concept extends the capabilities of many PSCAD™ components, not just those based on the new wire class.

Tri-Segmented Wire Type A new tri-segmented wire type has been developed to specifically handle situations where a pure orthogonal wire is not sufficient. The tree segments are composed of two orthogonal elements, each end and a single diagonal element in the middle. Stretching and resizing these allow for a large number of potential shapes and combinations as in the interconnection between two orthogonal elements and especially for interconnecting buses.

New Line Constants Program The development team has added the ability to increase the number of frequency solution steps between the specified start and end frequencies (frequency dependent [phase] model only). This feature has been found to improve curve fitting results in highly non-linear line segments. The respective calculated and curve fitted output files for surge impedance, attenuation constant and current transform quantities, are now merged. Eigenvalues and eigenvectors are now output to detailed output files. Testing has shown a dramatic increase in solution speed in highly complex line segments (such as complex, multi-layer cables).

Line Constants Output Data Viewer A new Line Constants Output Data Viewer is now available in V4.2. LCP detailed output files are composed of a variety of detailed data, which is written to column formatted, ASCII text files. As the detailed LCP output data are distributed with 14 text files, it also depends on whether the user has selected the FD (Phase) or the FD (Mode) model. LCP data viewer is a dialogue with a data listing area and a residential tool bar. There is also a drop list selection which provides the switching between the various output data files.

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PSCAD™ V4.2 was first demonstrated by the PSCAD™ Development Team at the International Power Systems Transients Conference (IPST 2005) in Montréal, Monday evening, June 20th at the Hilton Montréal Bonaventure Hotel.
A nice overview of PSCAD™ 4.2 can be found on the PSCAD™ Forum at *www.pscad.com*

Phasor Meter Devices A new device has been added to PSCAD™ to support complex pairs of Magnitude and Phase Angle created by the FFT component and other components. The display device will show either a single phasor or up to six phasors in an adjustable gauge display.

New Components!

Permanent Magnet Machine Permanent magnet synchronous machines have been popular in electric drive systems and some new wind turbines. The new PSCAD™ model replaces the field winding of the traditional synchronous machine with permanent magnets. PSCAD™ users have used the existing synchronous machine model with modified data for the field circuit to represent the permanent magnet in the dc field. The new model will allow the user to represent the machine more accurately and conveniently. The model is based on the well known d-q-0 domain equations with a constant flux linkage to represent the magnets.

Multi-Meter Component New multi-meter component that integrates many functions that took several blocks in the past to accomplish. With a single simple component, you can now measure voltage, current, active/reactive powers and the phase angle of a single or three phase node.

Extensions to CSMF Control Components
Several CSMF components in the PSCAD™ Master Library have been modified to fully support the interpolation engine. The components will now accept and process the PSCAD™ interpolation signal two-element array standard, where:
Signal = (Magnitude, Interpolated Time tag).

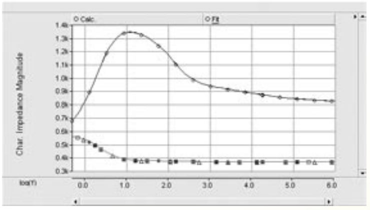
These components may be used as elemental building blocks to construct customized, fully interpolated controls systems. The interpolated time tag is propagated through the controller and manipulated by individual blocks until it reaches the final output. This is especially powerful when time delays are not divisible by time step, or the time step itself is irrational. Interpolation compatibility also decreases the result dependence on time step size.

Several CSMF components can now accept array inputs. There is no need to break the array into elements to do simple CSMF functions on all the elements of the array.

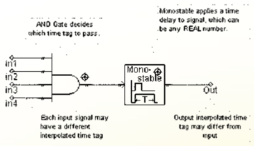
Terminal Condition Data Entry Capability in Source Models. If you have solved power flow data for source terminals, user can now enter terminal conditions into the source models. The source components are now designed to evaluate all the internal parameters based on the terminal conditions.

Potential Transformer Model In addition to existing CVT, CT models, users now have access to a PT model.

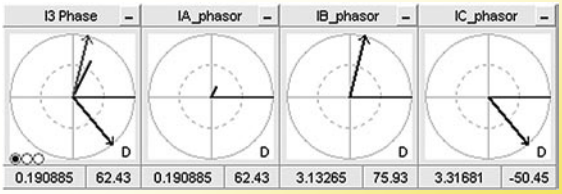
Line Constants Output Viewer



Interpolation Support in Controls

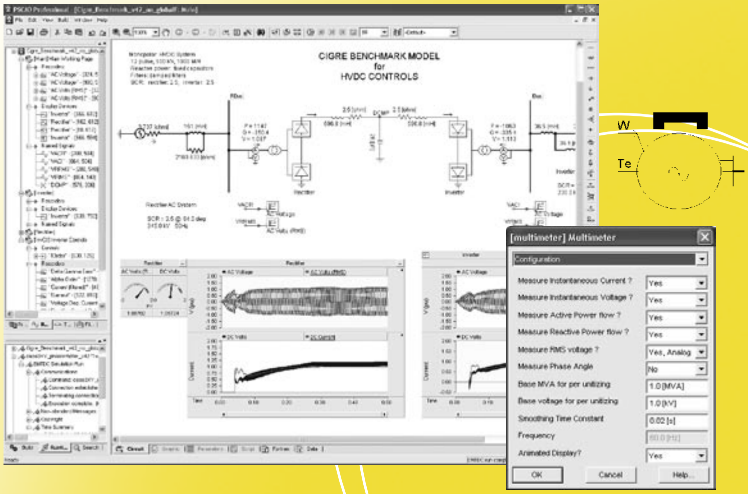


Phasor Meter Devices



I3 Phase: 0.190885 62.43
IA_phasor: 0.190885 62.43
IB_phasor: 3.13265 75.93
IC_phasor: 3.31681 -50.45

PSCAD™ Graphical User Interface & New Permanent Magnet Motor



Measure Instantaneous Current ? Yes
Measure Instantaneous Voltage ? Yes
Measure Active Power flow ? Yes
Measure Reactive Power flow ? Yes
Measure RMS voltage ? Yes, Analog
Measure Phase Angle No
Base MVA for per unitizing 1.0 [MVA]
Base voltage for per unitizing 1.0 [kV]
Smoothing Time Constant 0.02 [s]
Frequency 60.0 [Hz]
Animated Display? Yes

Expanding Knowledge

Introduction to PSCAD™ Version 4
Covers all the basics of using PSCAD™ and how to create power system simulation projects on a variety of topics. *Duration: 2½ to 3 days*

Advanced Topics in PSCAD™ Simulation Training
Includes custom component design and assists users with the analysis of specific simulation models. Topics include HVDC/FACTS, Distributed Generation, Machines, Power Quality and others. *Duration: 3–4 days*

HVDC Theory & Controls
Covers the fundamentals of HVDC Technology and its application. Topics covered include HVDC fundamentals, controls and advanced topics. *Duration: 4 to 5 days*

HVAC Switching Study Applications in PSCAD™
Duration: 2 Days

Lightning Coordination & Fast Front Studies
Duration: 2 days

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Duration: 2 days

Distributed Generation & Power Quality
Includes wind energy system modelling, integration to the grid and power quality issues. *Duration: 3 Days.*

Wind Park Modelling
Wind models, aero-dynamic models, machines and doubly fed connections. *Duration: 2 days*

Modelling of FACTS Devices
The fundamentals of solid-state FACTS systems. System modelling, control system modelling and converter modelling. *Duration: 2 days*

Industrial Systems Simulation & Modelling
Motor starting, power quality, capacitor bank switching, harmonic profile *Duration: 1 Day*

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