Detailed Modeling of CIGRÉ HVDC Benchmark System Using PSCAD/EMTDC and PSB/SIMULINK

M. O. Faruque, *Student Member, IEEE*, Yuyan Zhang, and Venkata Dinavahi, *Member, IEEE*

Abstract—This paper focuses on a comparative study of the modeling and simulation of the first CIGRÉ HVDC benchmark system using two simulation tools PSCAD/EMTDC and PSB/SIMULINK; an interface between them (PSCAD-SIMULINK) has also been implemented and used as a simulator. The CIGRÉ HVDC system and its controller has been carefully modeled in all three simulation environments so that the differences are minimal. Comparison of steady-state and transient situations have been carried out, and a high degree of agreement in most of the cases has been observed.

Index Terms—HVDC transmission, modeling, simulation.

I. INTRODUCTION

THE DESIGN, analysis, and operation of complex ac-dc systems require extensive simulation resources that are accurate and reliable. Analog simulators, long used for studying such systems, have reached their physical limits due to the increasing complexity of modern systems. Currently, there are several industrial grade digital time-domain simulation tools available for modeling ac-dc power systems. Among them, some have the added advantages of dealing with power electronics apparatus and controls with more accuracy and efficiency. PSCAD/EMTDC [1] and PSB/SIMULINK [2] are such two simulators that are being increasingly used in the industry as well as in the universities. Both programs allow the user to construct schematic diagram of electrical networks, run the simulation, and produce the results in a user-friendly graphical environment. Furthermore, several real-time digital simulators use models or the graphical front-end that are similar to PSCAD/EMTDC and PSB/SIMULINK.

The objective of this paper is to report a detailed comparison between PSCAD/EMTDC and PSB/SIMULINK for the modeling and simulation of ac-dc power systems. In a digital simulator, the system model and the algorithm used to solve that model directly affect the accuracy and consistency of the simulation results. Therefore, based on the objective of the study, careful attention should be given to the selection of the model, the numerical solver, and the algorithm. A comparative study among simulation tools will help in identifying the pros and cons that the programs inherit. For the last two decades, digital simulators have been widely used for the simulation of HVDC

and its control system. However, to compare the performance of any two simulators, similar circuit topology with control is a prerequisite. To achieve that goal, a benchmark system for HVDC, known as the CIGRÉ Benchmark Model, was proposed in 1985 [3]. It provided a common reference system for HVDC system studies. Later in 1991, a comparison of four digital models has been carried out by the CIGRÉ Working Group [4], [5], and a benchmark system for HVDC control study was also proposed. A detailed comparison between ATP and NETOMAC for the simulation of HVDC system was first reported in [6], where the fundamental differences between the two software and their effects on simulation results have been discussed. The study found a good agreement between the two simulation results. More recently, custom power controllers such as DSTATCOM and DVR have been simulated [7] using PSCAD/EMTDC and SIMULINK to compare their performance. However, for a rigorous comparison between simulation tools and to gain insight into their capabilities and limitations, the modeled system should be able to offer the highest degree of difficulty. The main motivation for using the CIGRÉ Benchmark HVDC System in this paper is that not only is it a widely used test system but also it is complex enough, with deliberate difficulties introduced for a comprehensive performance evaluation of the two simulation tools.

Section II of this paper gives a brief introduction about the two simulation tools highlighting their solution techniques, and Section III introduces the CIGRÉ HVDC benchmark system. Sections IV–VI present the detailed model of HVDC system and its controller in three simulation environments: PSCAD/EMTDC, PSB/SIMULINK, and PSCAD-SIMULINK interface. Results are presented in Section VII, followed by conclusions in Section VIII.

II. PSCAD/EMTDC AND PSB/SIMULINK

PSCAD/EMTDC is a powerful time-domain transient simulator for simulating power systems and its controls. It uses graphical user interface to sketch virtually any electrical equipment and provide a fast and flexible solution. PSCAD/EMTDC represents and solves the differential equations of the entire power system and its control in the time domain (both electromagnetic and electromechanical systems) [8]. It employs the well-known nodal analysis technique together with trapezoidal integration rule with fixed integration time-step. It also uses interpolation technique with instantaneous switching to represent the structural changes of the system [9], [10].

MATLAB/SIMULINK is a high-performance multifunctional software that uses functions for numerical computation,

The authors are with the Electrical and Computer Engineering Department, University of Alberta, Edmonton, AB T6G 2V4, Canada (e-mail: faruque@ece.ualberta.ca; yuyan@ece.ualberta.ca; dinavahi@ece.ualberta.ca).
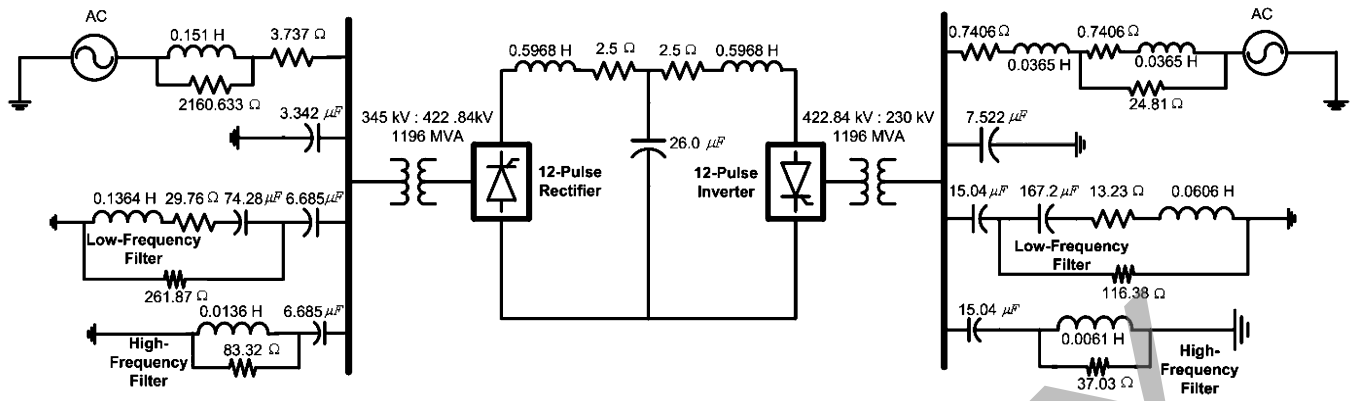
Fig. 1.   Single-line diagram of the CIGRÉ benchmark HVDC system.

system simulation, and application development. Power System Blockset (PSB) is one of its design tools for modeling and simulating electric power systems within the SIMULINK environment [2], [11]. It contains a block library with common components and devices found in electrical power networks that are based on electromagnetic and electromechanical equations. PSB/SIMULINK can be used for modeling and simulation of both power and control systems. PSB solves the system equations through state-variable analysis using either fixed or variable integration time-step. The linear dynamics of the system are expressed through continuous or discrete time-domain state-space equations. It also offers the flexibility of choosing from a variety of integration algorithms.

III. First CIGRÉ HVDC Benchmark System

The first CIGRÉ HVDC benchmark system shown in Fig. 1 was proposed in [3]. The system is a mono-polar 500-kV, 1000-MW HVDC link with 12-pulse converters on both rectifier and inverter sides, connected to weak ac systems (short circuit ratio of 2.5 at a rated frequency of 50 Hz) that provide a considerable degree of difficulty for dc controls. Damped filters and capacitive reactive compensation are also provided on both sides. The power circuit of the converter consists of the following subcircuits.

A. AC Side

The ac sides of the HVDC system consist of supply network, filters, and transformers on both sides of the converter. The ac supply network is represented by a Thévénin equivalent voltage source with an equivalent source impedance. AC filters are added to absorb the harmonics generated by the converter as well as to supply reactive power to the converter.

B. DC Side

The dc side of the converter consists of smoothing reactors for both rectifier and the inverter side. The dc transmission line is represented by an equivalent T network, which can be tuned to fundamental frequency to provide a difficult resonant condition for the modeled system.

C. Converter

The converter stations are represented by 12-pulse configuration with two six-pulse valves in series. In the actual converter, each valve is constructed with many thyristors in series. Each valve has a (di/dt) limiting inductor, and each thyristor has parallel RC snubbers.

IV. CIGRÉ HVDC System Model in PSCAD

The full three-phase model of the CIGRÉ HVDC benchmark system is available as an *example* file in PSCAD/EMTDC Version 4.0.1. Data for the CIGRÉ HVDC benchmark system [4], [5] is given in Table V.

A. Power Circuit Modeling

1) Converter Model: The converters (rectifier and inverter) are modeled using *six-pulse Graetz bridge* block, which includes an internal Phase Locked Oscillator (PLO), firing and valve blocking controls, and firing angle (α)/extinction angle (γ) measurements. It also includes built-in RC snubber circuits for each thyristor. Thyristor valves are modeled as ideal devices, and therefore, negative turn-off and firing due to large (dv/dt) or (di/dt) are not considered.

2) Converter Transformer Model: Two transformers on the rectifier side are modeled by three-phase two winding transformer, one with grounded Wye–Wye connection and the other with grounded Wye–Delta connection. The model uses saturation characteristic and tap setting arrangement. The inverter side transformers use a similar model.

3) DC Line Model: The dc line is modeled using an equivalent-T network with smoothing reactors inserted on both sides.

4) Supply Voltage Source: The supply voltages on both rectifier and inverter sides have been represented through three-phase ac voltage sources.

5) Filters and Reactive Support: Tuned filters and reactive support are provided at both the rectifier and the inverter ac sides, as shown in Fig. 1.

B. Control System Model

The control model mainly consists of α/γ measurements and generation of firing signals for both the rectifier and inverter. The PLO is used to build the firing signals. The output signal of the PLO is a ramp, synchronized to the phase-A commutating

bus line-to-ground voltage, which is used to generate the firing signal for Valve 1. The ramps for other valves are generated by adding 60° to the Valve 1 ramp. As a result, an equidistant pulse is realized. The actual firing time is calculated by comparing the α order to the value of the ramp and using *interpolation* [10] technique. At the same time, if the valve is pulsed but its voltage is still less than the forward voltage drop, this model has a logic to delay firing until the voltage is exactly equal to the forward voltage drop. The firing pulse is maintained across each valve for 120°.

The α and γ measurement circuits use zero-crossing information from commutating bus voltages and valve switching times and then convert this time difference to an angle (using measured PLO frequency). Firing angle α (in seconds) is the time when valve i turns on minus the zero crossing time for valve i. Extinction angle γ (in seconds) for valve i is the time at which the commutation bus voltage for valve i crosses zero (negative to positive) minus the time valve i turns off. The control schemes for both rectifier and inverter of the CIGRÉ HVDC system are available in the *example* file in PSCAD/EMTDC Version 4.0.1. Following are the controllers used in the control schemes:

- Extinction Angle (γ) Controller;
- dc Current Controller;
- Voltage Dependent Current Limiter (VDCOL).

1) Rectifier Control: The rectifier control system uses Constant Current Control (CCC) technique. The reference for current limit is obtained from the inverter side. This is done to ensure the protection of the converter in situations when inverter side does not have sufficient dc voltage support (due to a fault) or does not have sufficient load requirement (load rejection). The reference current used in rectifier control depends on the dc voltage available at the inverter side. Dc current on the rectifier side is measured using proper transducers and passed through necessary filters before they are compared to produce the error signal. The error signal is then passed through a PI controller, which produces the necessary firing angle order α. The firing circuit uses this information to generate the equidistant pulses for the valves using the technique described earlier.

2) Inverter Control: The Extinction Angle Control or γ control and current control have been implemented on the inverter side. The CCC with Voltage Dependent Current Order Limiter (VDCOL) have been used here through PI controllers. The reference limit for the current control is obtained through a comparison of the external reference (selected by the operator or load requirement) and VDCOL (implemented through lookup table) output. The measured current is then subtracted from the reference limit to produce an error signal that is sent to the PI controller to produce the required angle order. The γ control uses another PI controller to produce gamma angle order for the inverter. The two angle orders are compared, and the minimum of the two is used to calculate the firing instant.

V. CIGRÉ HVDC SYSTEM MODEL IN PSB

The CIGRÉ HVDC system model developed using PSB/SIMULINK Version 6.5 release 13 is shown in Fig. 9. To implement this model, a total of 106 states, 37 inputs, 112 outputs, and 31 switches were used.

A. Power Circuit Modeling

The rectifier and the inverter are 12-pulse converters constructed by two *universal bridge blocks* connected in series. The converter transformers are modeled by one *three-phase two winding transformer* with grounded Wye–Wye connection, the other by *three-phase two winding transformer* with grounded Wye–Delta connection. The converters are interconnected through a T-network.

1) Universal Bridge Block: The universal bridge block implements a universal three-phase power converter that consists of six power switches connected as a bridge. The type of power switch and converter configuration can be selected from the dialog box. Series RC snubber circuits are connected in parallel with each switch device. The vector gating signals are six-pulse trains corresponding to the natural order of commutation. The α and γ measurements are not realized in this model.

2) Three Phase Source: A three-phase ac voltage source in series with a R-L combination is used to model the source, and its parameters are set as in Table V.

3) Converter Transformer Model: The three-phase two winding transformers models have been used where winding connection and winding parameters can be set through mask parameters. The tap position is at a fixed position determined by a multiplication factor applied on the primary nominal voltage of the converter transformers (1.01 on rectifier side; 0.989 on inverter side). The saturation has been simulated. The saturation characteristic has been specified by a series of current/flux pairs (in p.u.) starting with the pair (0,0).

The dc line, ac filters, and reactive support are similar to the ones used in the PSCAD/EMTDC model.

B. Control System Model

The control blocks available in SIMULINK have been used to emulate the control algorithm described in Section IV-B, and enough care has been taken to ensure that exact parameters as in PSCAD/EMTDC simulation are used. Some control parameters required conversion to their proper values due to differences in units. The rectifier side uses current control with a reference obtained from the inverter VDCOL output (implemented through a lookup table), and the inverter control has both current control and γ control operating in parallel, and the lower output of the two is used to generate the firing pulses. Unlike PSCAD/EMTDC, the angle γ is not provided directly from the converter valve data. It needed to be implemented through measurements taken from valve data. The control block diagrams are shown in Fig. 2.

VI. PSCAD-SIMULINK INTERFACE

PSCAD Version 4.0.1 has the capability of interfacing with MATLAB/SIMULINK commands and toolboxes through a special interface. MATLAB programs or block-sets that would be interfaced, with PSCAD needing to be designed and saved as a MATLAB program file or as a SIMULINK block file. Then, a user-defined block must be provided in PSCAD, with the necessary inputs and outputs, to interface the MATLAB/SIMULINK file. In this paper, the power circuit of CIGRÉ HVDC system has been modeled in the PSCAD/EMTDC environment while
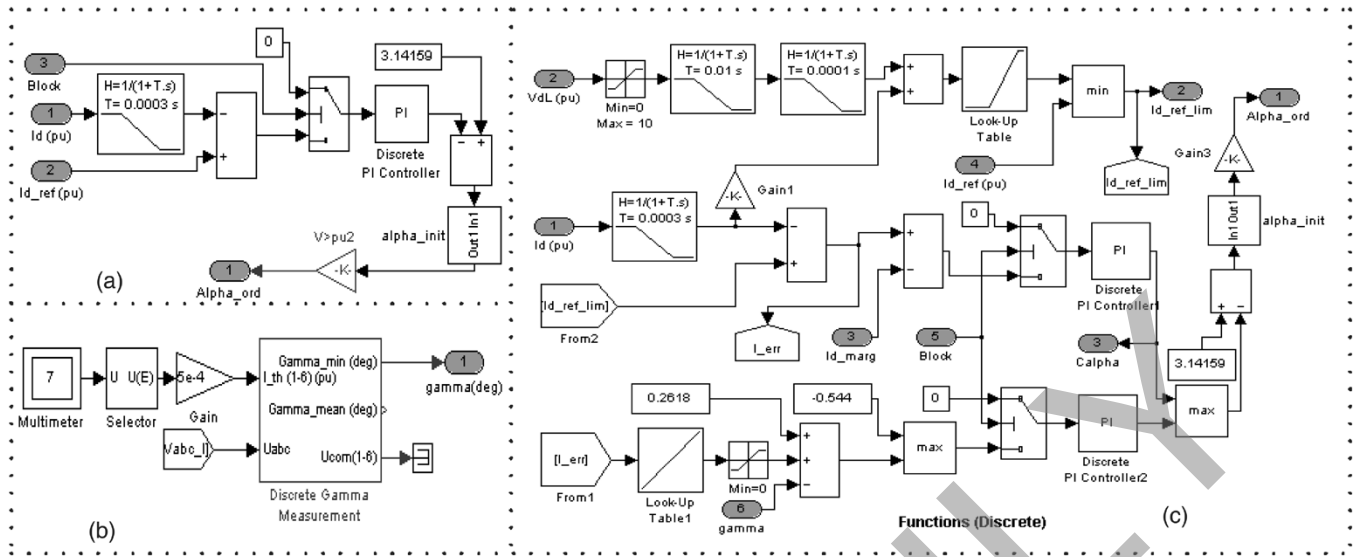
Fig. 2. CIGRÉ HVDC control system in SIMULINK. (a) Rectifier control. (b) Gamma measurement. (c) Inverter control.

the control system has been modeled using block-sets from PSB and the SIMULINK Control Library. An interfacing block has been created in PSCAD/EMTDC that linked the SIMULINK files through FORTRAN scripts defined within the block. A reverse scenario, where the power circuit is modeled in PSB/SIMULINK and the control system is modeled in PSCAD/EMTDC, is also feasible. Fig. 3 shows the block diagram of PSCAD-SIMULINK interface used to simulate CIGRÉ HVDC system. The time step used for the simulation is 50 μs; the two programs exchange information between them continuously at every time step.

VII. SIMULATION RESULTS

With the goal of performing a rigorous comparative study among the simulation tools, the CIGRÉ HVDC system has been simulated in three environments:

1) using PSCAD/EMTDC only;
2) using PSB/SIMULINK only;
3) using the PSCAD-SIMULINK Interface.

Steady-state and transient results (created through various faults) were recorded and then compared. The comparison reveals a high degree of similarity among the results obtained through the three simulation environments with minor discrepancies.

A. Steady State

For steady-state analysis, the system has been simulated for a duration of 2 s in all three simulation environments. There were some initial transients that subsided within about 0.5 s and the system reached steady state.

1) DC Voltages and Currents: Fig. 4 shows the results where the first column is produced by PSCAD/EMTDC, the second from PSB/SIMULINK, and the third by the PSCAD-SIMULINK interface. Row-wise, the first row shows the rectifier dc voltage produced by the three simulation tools; the second and fourth row are the magnified view of dc voltages on both the rectifier and inverter side; the third and fifth row
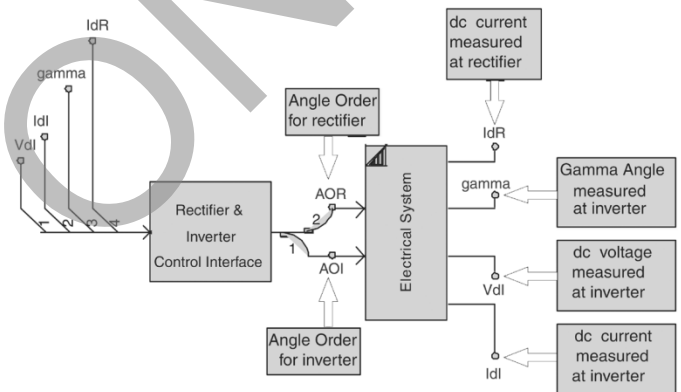

Fig. 3. PSCAD-SIMULINK interface.

show the harmonic spectrum. The following observations can be made from Fig. 4.

- For both inverter and rectifier, the dc voltages show small oscillations around the reference value (1 p.u); however, they are almost identical, except for minor differences at start-up. During initialization, PSCAD/EMTDC and PSCAD-SIMULINK interface do not show any negative dc voltage, whereas PSB/SIMULINK shows a negative transient (-0.3 p.u). However, all three simulation tools have produced identical waveforms in terms of phase and magnitude in steady state, and there is hardly any discrepancy among them. The zoomed view of their steady-state waveforms reflects that fact.

- The mean of output dc voltage produced by PSCAD/EMTDC and PSCAD-SIMULINK interface falls short of reference outputs by (1–2)% (0.99 p.u. for PSCAD/EMTDC and 0.98 p.u. for PSCAD-SIMULINK interface), whereas it is 1.0 p.u. for PSB/SIMULINK.

- The Fourier spectrum of the corresponding waveforms have very few differences. The dc component is close to 1.0 for all environments, but in the plot, it is not shown in full magnitude, for the sake of highlighting the harmonics
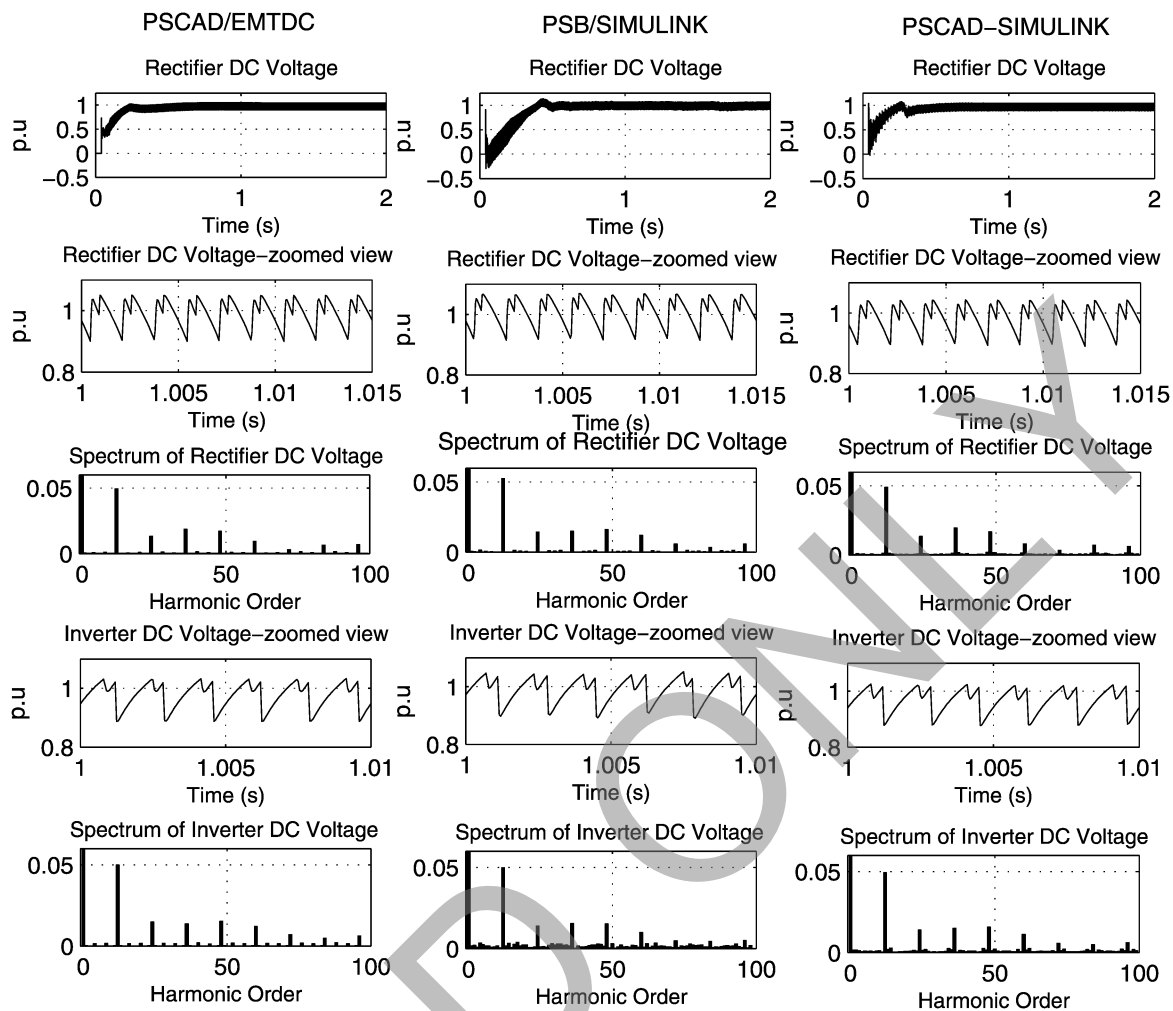
Fig. 4.   Steady-state results for dc voltage.

TABLE I
COMPARISON OF THD (%), MEAN, AND MAD FOR DC VOLTAGES AND CURRENTS PRODUCED BY DIFFERENT SIMULATION TOOLS

Parameter	PSCAD/EMTDC			PSB/SIMULINK			PSCAD-SIMULINK		
	THD	Mean	MAD	THD	Mean	MAD	THD	Mean	MAD
Rectifier DC Voltage	5.96	0.99	0.035	6.10	1.00	0.037	6.03	0.98	0.035
Rectifier DC Current	0.579	1.000	0.003	0.6162	1.000	0.005	0.674	1.000	0.004
Inverter DC Voltage	6.15	0.972	0.036	6.21	0.983	0.037	6.19	0.965	0.035
Inverter DC Current	0.598	0.999	0.003	0.676	0.999	0.006	0.653	0.999	0.004

present in the signal. The THDs found in the three cases for different waveforms are also very close.

- Table I shows further information about the fine differences in terms of mean value, THD, and Mean Absolute Deviation (MAD). Close results have also been observed for dc currents on both the rectifier and inverter sides.

2) AC Voltages and Currents: All ac side waveforms on both the rectifier and inverter sides have also been compared. The results were found to be similar, and only the ac current waveforms and their harmonic spectrum are shown in Fig. 5. Both rectifier and inverter ac currents are similar in terms of phase angle and their magnitude; their spectrum is identical, which reaffirms the accuracy of all three simulation techniques. The 11th and 13th harmonics are the dominant harmonics

on both rectifier and inverter sides; their THDs have been found to be close for all simulation environments. Table II compares other control outputs (γ, inverter α, and rectifier α). PSCAD-SIMULINK shows the maximum rectifier α (17.28°), while PSB/SIMULINK shows the minimum (14.44°). This result agrees with the mean value of the dc voltage produced on the rectifier side by the three simulation environments. Similarly, for γ, PSCAD-SIMULINK shows the highest (15.72°), and PSB/SIMULINK shows the lowest (14.95°). However, these differences are small, and the produced results are consistent.

B. Transients

Dc and ac faults have been simulated in the three simulation environments. The instant and duration of faults have been
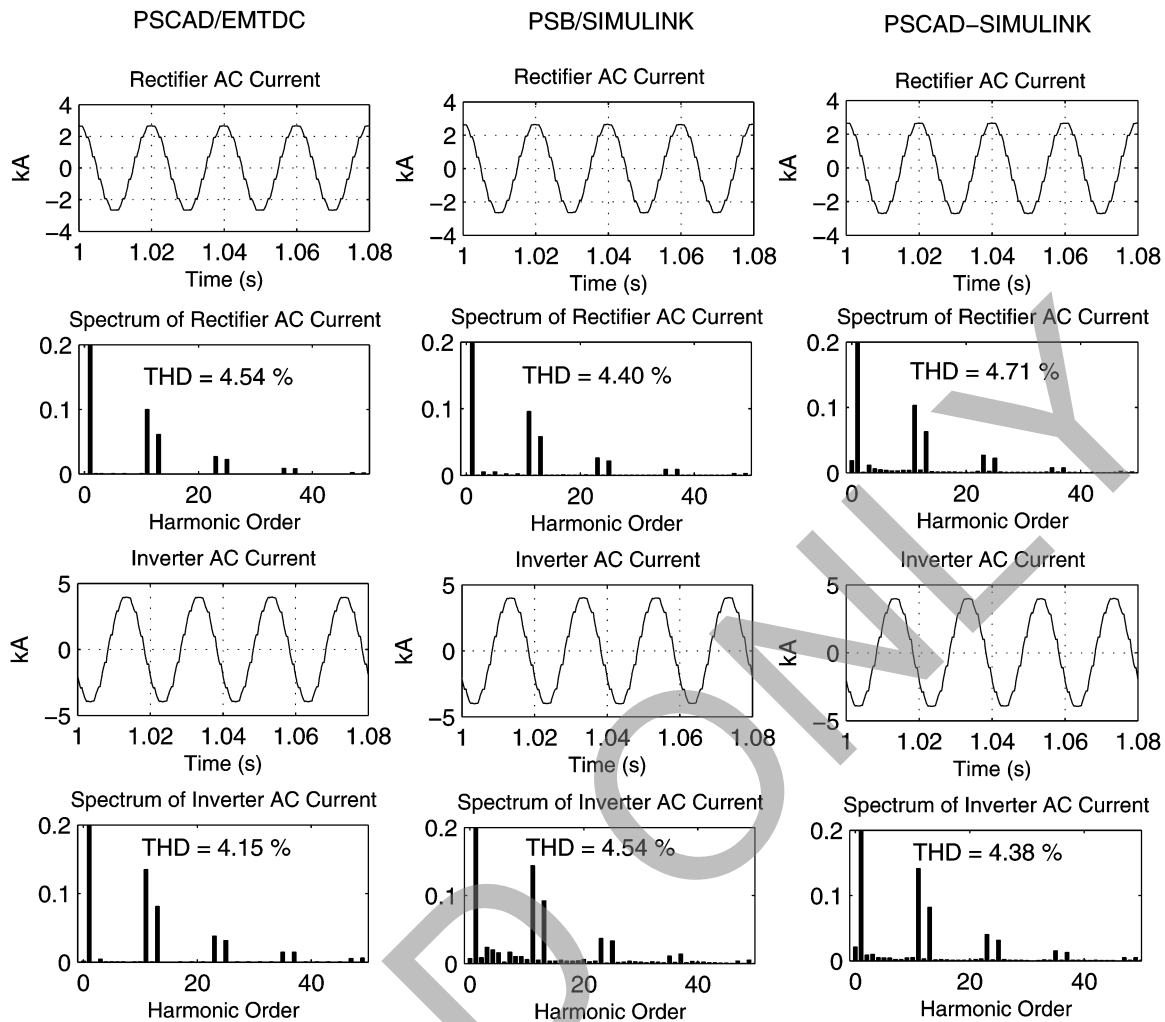
Fig. 5.   Steady-state results for ac currents on the rectifier and inverter side.

TABLE II
COMPARISON OF OUTPUTS PRODUCED BY CONTROL SYSTEMS

Parameter	PSCAD	PSB	PSCAD-SIMULINK
Rectifier α	16.92^o	14.44^o	17.28^o
Inverter α	141.89^o	141.97^o	141.86^o
Inverter γ	15.10^o	14.95^o	15.72^o

maintained the same for all types of faults, i.e., the fault is applied at 1.0 s and cleared after 0.15 s. The fault resistance has been chosen as 0.1 Ω and 1 MΩ for fault-on and fault-off situations, respectively. Clearing of the fault has been allowed, even when there is a fault current flowing.

1) Dc Fault: This fault has been located at the midpoint of the dc line. Fig. 6 illustrates different output parameters of the system. The transient response in all three simulation environments has been found almost similar. During the fault, the dc voltage has gone down to zero (the small oscillation is due to the energy stored in the capacitor), and a momentary transient dc current has been observed. However, control response forces rectifier α and inverter γ to reach maximum and inverter α to reach minimum, thereby reducing the current flow. VDCOL forces the current to stay minimum until the dc voltage situation is improved. Once the fault is cleared, the dc voltage is recov-

ered, and the control system brings the system back to normal operation. The transient response for all three simulation environments has been compared in terms of Rise Time (RT), Settling Time (ST), and Overshoot (OS) in Table III.

2) AC Faults: Two cases of ac faults have been simulated: One is a single line-to-ground fault (see Fig. 7), and the other is a three-phase to ground fault (see Fig. 8). Both are applied on the inverter side of the system. During fault, the dc voltage has gone down to zero (neglecting oscillation due to capacitor energy storage), the dc current faces a momentary overshoot, and then goes to minimum limit with some oscillation present (due to the oscillation of dc voltage). Rectifier α, inverter α, and inverter γ reach to maximum value, thereby blocking the system for the fault duration. Once the fault is cleared, the system comes back to its normal operation. During an ac fault, commutation failures happen, resulting in a momentary drop-down of dc voltage. This causes the VDCOL to limit the dc current to a minimum, and ac voltages also get disturbed (not shown in the figure). The voltage and current waveforms for the three environments are similar; however, the following minor discrepancies were observed.

• In all three cases, the rise-time for inverter dc voltage for ac faults is shorter than that for the dc fault. Even though PSCAD/EMTDC and PSCAD-SIMULINK show
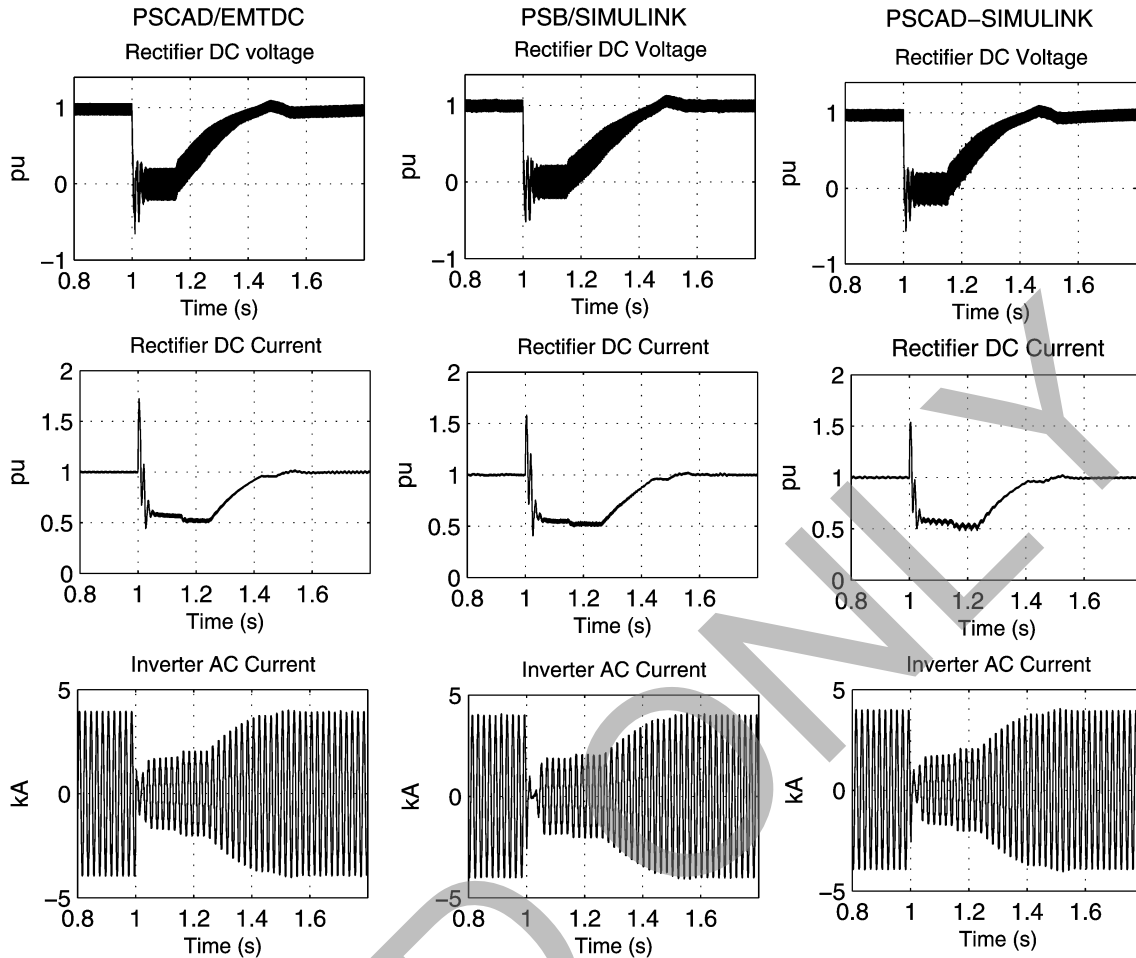
Fig. 6. Voltages and currents under a short duration dc fault.

a faster rise than PSB/SIMULINK case, PSB/SIMULINK reaches steady state before the other two cases.

- The highest transient values of inverter dc currents during the phase-to-ground fault are 2.58 p.u. for PSCAD/EMTDC, 2.4 p.u. for PSB/SIMULINK, and 2.39 p.u. for PSCAD-SIMULINK.
- The peak value of inverter ac current for the single phase-to-ground fault is 13.2 kA for PSCAD/EMTDC, 14 kA for PSB/SIMULINK, and 13 kA for PSCAD-SIMULINK.
- In case of the three-phase to ground fault, when the fault is cleared at $t = 1.15$ s, in all the three environments, the system is brought back to normal operation within 0.05 s; however, PSCAD/EMTDC and PSCAD-SIMULINK could not stabilize the system, i.e., after a small over-shoot, the system collapses again, though it regains the control very fast, and the system stability is restored. PSB/SIMULINK, however, does not show this behavior.

C. Execution Time and Memory

All three environments were run on a Pentium IV 1.5–GHz processor running Windows 2000 operating system. The execution time was recorded from the *Time Summary* shown on the output window in PSCAD/EMTDC and by using the *cputime* function at the start and end of the simulation in PSB/SIMULINK. Information on memory usage was collected from the *System Performance Monitor* on Windows 2000. Although resource requirements for both programs may not be the same, attempts have been made to allow no other programs except the system files to run while the simulations were performed. Table IV shows the execution time and memory usage for the three environments. PSCAD/EMTDC was found to be the fastest environment, while PSCAD-SIMULINK Interface was the slowest. For a simulation duration of 2 s, PSCAD/EMTDC took 30.5 s with a memory usage of 42 MB, whereas PSB/SIMULINK took 72.2 s with a memory usage of 107 MB. In comparison to these two environments, PSCAD-SIMULINK took a much longer execution time; using a 50 μs sampling period in both PSCAD and SIMULINK environments, the execution time was found to be 12 503.58 s with a memory usage of 63 MB (24 MB for PSCAD and 39 MB for SIMULINK). The reason for such a long simulation time is the necessity of data exchange between the two programs at every 50 μs; the memory usage for the interface was less than the other two environments due to the task partition (electrical system in PSCAD and control system in SIMULINK). A higher control sampling period reduced the execution time by a very small margin (2.5% for 100 μs); however, it also reduced the accuracy of the simulation.

TABLE III
COMPARISON OF RISE TIME (RT) (S), SETTLING TIME (ST) (S), AND OVERSHOOT (OS) (P.U.) DURING RECOVERY FROM A DC FAULT

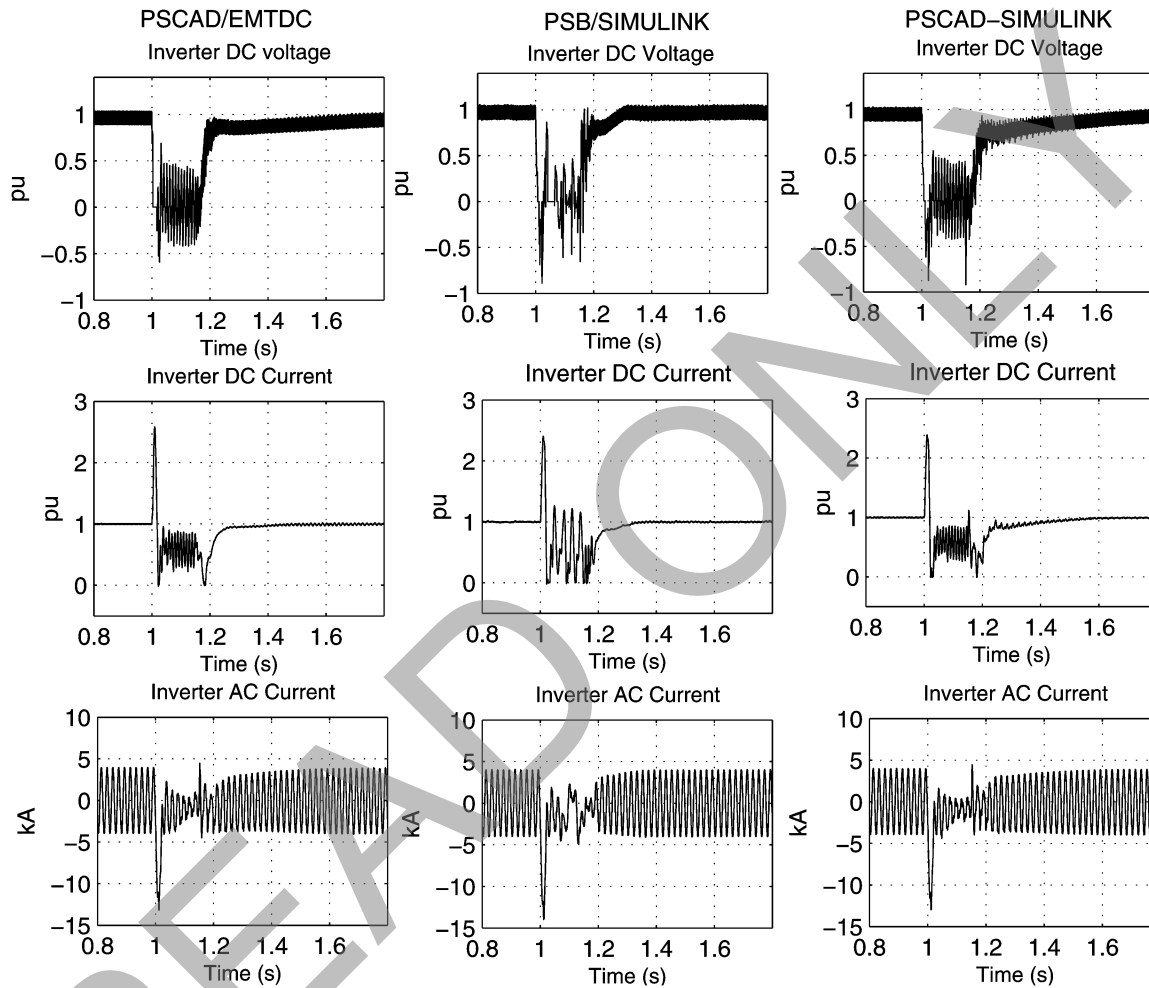| Parameter	PSCAD/EMTDC			PSB/SIMULINK			PSCAD-SIMULINK		
	RT	ST	OS	RT	ST	OS	RT	ST	OS
Rectifier DC Voltage	0.31	0.4	0.08	0.32	0.412	0.13	0.30	0.39	0.10
Rectifier DC Current	0.36	0.44	0.36	0.37	0.45	0.28	0.36	0.45	0.27
Inverter DC Voltage	0.47	0.61	0.07	0.48	0.57	0.09	0.46	0.72	0.07
Inverter DC Current	0.50	0.71	0.01	0.51	0.62	0.012	0.49	0.70	0.015

Fig. 7.   Voltages and currents under a short duration ac fault (phase-A to ground) on the inverter side.

D. General Remarks

Both PSCAD/EMTDC and PSB/SIMULINK provides user-friendly graphics for modeling power and control systems through simple functional blocks. However, the following minor differences particular to this case study, are worth mentioning.

- PSCAD/EMTDC is a specialized software designed mainly for the analysis of ac/dc systems. Therefore, it has added advantages such as built-in PLO-based firing control and the measurement of α/γ angles embedded inside the *six-pulse Garetz bridge*. On the other hand, PSB/SIMULINK requires these blocks and the measurement system to be developed by the user.
- PSB/SIMULINK offers more flexibility in terms of choice of the solution techniques: fixed or variable time-step-

based solutions. However, for this study, a fixed step-size trapezoidal rule has been used to be consistent with PSCAD/EMTDC.
- The error debugging system in PSCAD/EMTDC is quite complex. In some cases, instead of locating the exact source of error, it returned general error messages.

VIII. CONCLUSIONS

A detailed comparison of the performance of three simulation environments (PSCAD/EMTDC, PSB/SIMULINK, and PSCAD-SIMULINK Interface) has been demonstrated by modeling the CIGRÉ HVDC Benchmark System. All three environments produced almost identical and consistent results during steady-state and transients situations, validating the accuracy of the modeling and solution algorithms. In terms of computational
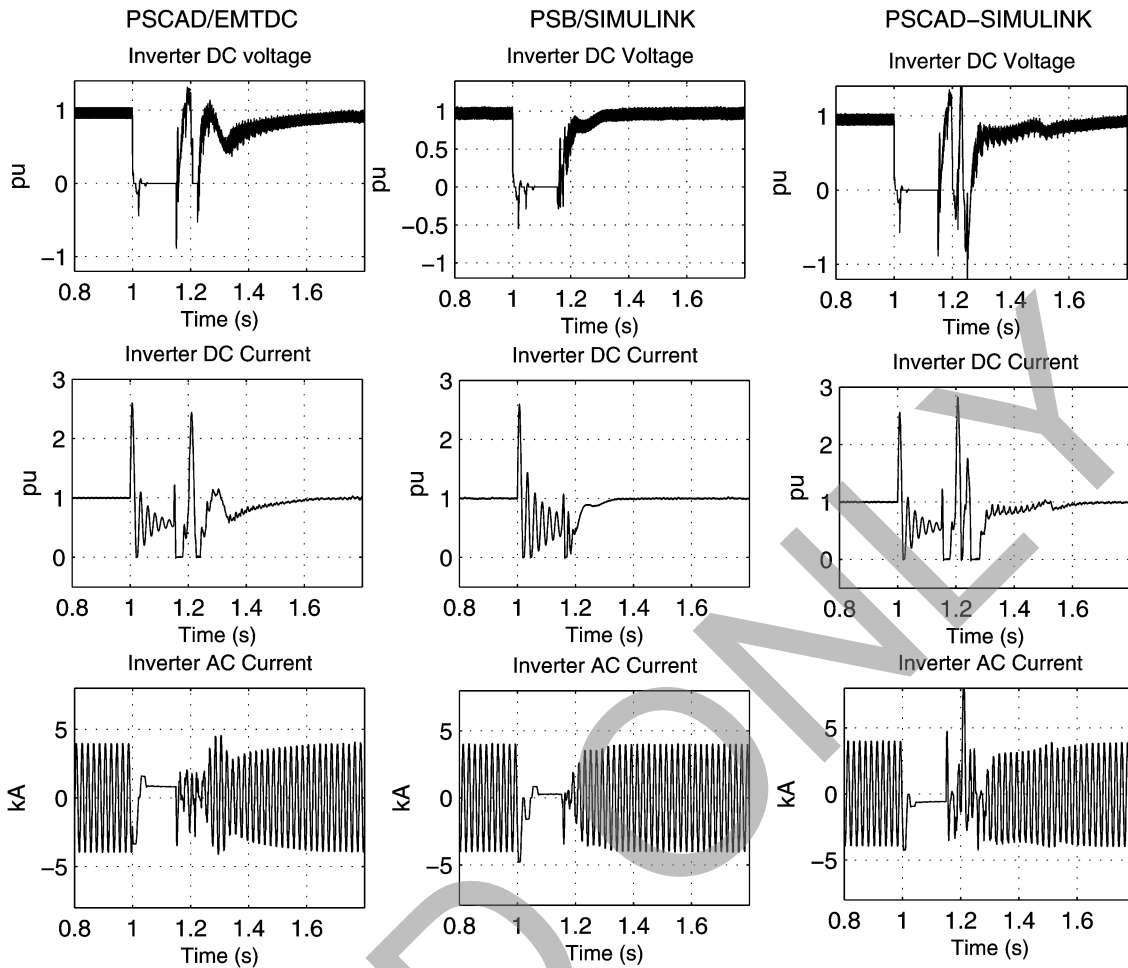
Fig. 8.   Voltages and currents under a short duration ac fault (three-phase to ground) on the inverter side.
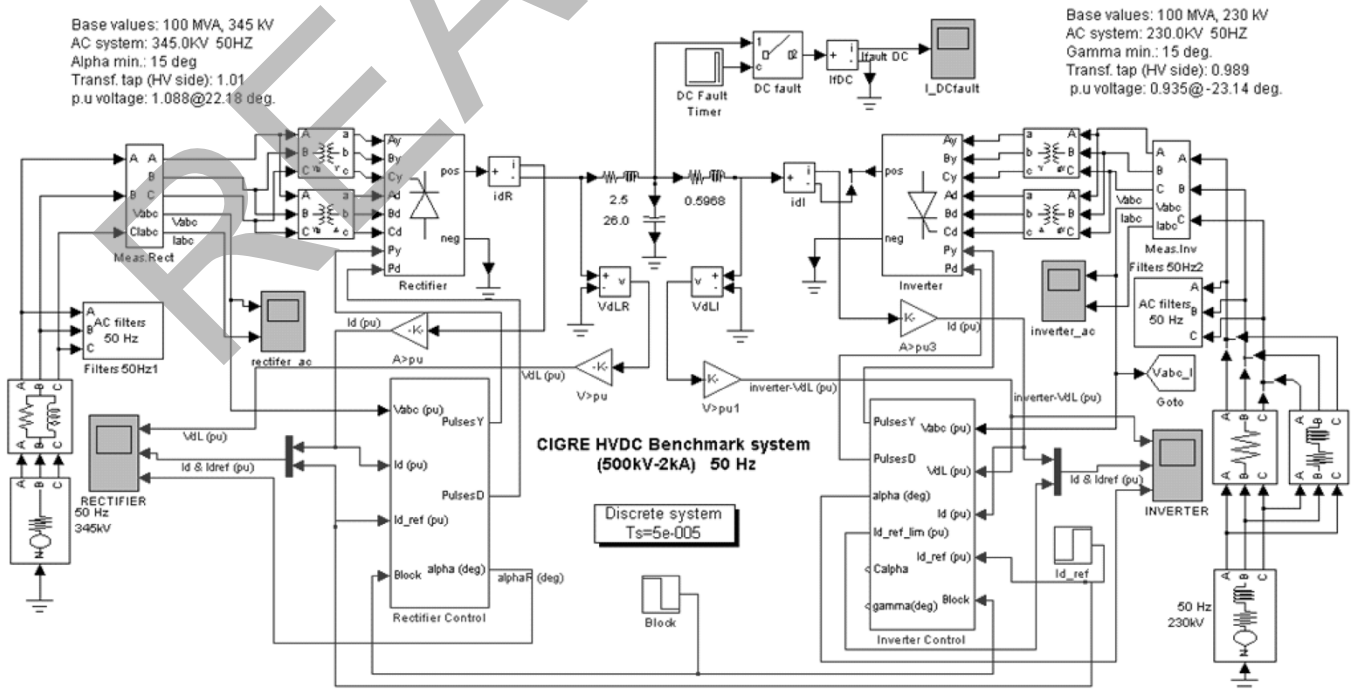

Fig. 9.   CIGRÉ HVDC benchmark system model in PSB/SIMULINK.

TABLE IV
EXECUTION TIME (ET) (S) AND MEMORY USAGE (MU) (MB) FOR A
SIMULATION DURATION OF 2 S WITH A TIME STEP OF 50 μs

Parameters	PSCAD	PSB	PSCAD-SIMULINK
ET	30.5	72.2	12503.58
MU	42	107	63

TABLE V
CIGRÉ HVDC BENCHMARK SYSTEM DATA

Parameters	Rectifier	Inverter
AC Voltage Base	345 kV	230 kV
Base MVA	100 MVA	100 MVA
Transf. tap (HV side)	1.01 pu	0.989 pu
Voltage Xource	$1.088\angle 22.18^o$	$0.935\angle -23.14^o$
Nominal DC Voltage	500 kV	500 kV
Nominal DC Iurrent	2 kA	2 kA
Transf. X_l	0.18 pu	0.18 pu
Source Impedance	R=3.737 Ω,	R=0.7406 Ω
	L= 0 H	L= 0.0365 H
System Frequency	50 Hz	50 Hz
Minimum Angle	$\alpha = 15^o$	$\gamma = 15^o$

speed and memory usage, PSCAD/EMTDC was found to be the most efficient environment.

APPENDIX

Table V shows the CIGRÉ HVDC benchmark system data.

REFERENCES

[1] D. A. Woodford, A. M. Gole, and R. W. Menzies, "Digital simulation of DC links and AC machines," *IEEE Trans. Power App. Syst.*, vol. 102, no. 6, pp. 1616–1623, Jun. 1983.

[2] L.-A. Dessaint, H. Le-Huy, G. Sybille, and P. Brunelle, "A power system simulation tool based on SIMULINK," *IEEE Trans. Ind. Electron.*, vol. 46, no. 6, pp. 1252–1254, Dec. 1999.

[3] J. D. Ainsworth, "Proposed benchmark model for study of HVDC controls by simulator or digital computer," in *Proc. CIGRE SC-14 Colloq. HVDC With Weak AC Systems*, Maidstone, U.K., Sep. 1985.

[4] M. Szechtman, T. Wess, and C. V. Thio, "First benchmark model for HVDC control studies," *Electra*, no. 135, pp. 54–67, Apr. 1991.

[5] ——, "A benchmark model for HVDC system studies," in *Proc. Int. Conf. AC/DC Power Transmission*, Sep. 17–20, 1991, pp. 374–378.

[6] P. Lehn, J. Rittiger, and B. Kulicke, "Comparison of the ATP version of the EMTP and the NETOMAC program for simulation of HVDC systems," *IEEE Trans. Power Del.*, vol. 10, no. 4, pp. 2048–2053, Oct. 1995.

[7] W. Freitas and A. Morelato, "Comparative study between power system blockset and PSCAD/EMTDC for transient analysis of custom power devices based on voltage source converter," in *Proc. Int. Conf. Power Systems Transients*, New Orleans, LA, 2003, pp. 91–96.

[8] F. Jurado, N. Acero, J. Carpio, and M. Castro, "Using various computer tools in electrical transient studies," in *Proc. Int. Conf. 30th ASEE/IEEE Frontiers in Education*, Kansas City, MO, Oct. 18–21, 2000, pp. F4E17–F4E22.

[9] *PSCAD/EMTDC User's Manual*, Manitoba HVDC Research Centre, 2001.

[10] G. D. Irwin, D. A. Woodford, and A. Gole, "Precision simulation of PWM controller," in *Proc. Int. Conf. Power System Transients*, Rio de Janeiro, Brazil, 2001, pp. 301–306.

[11] *Power System Blockset User's Guide*, TEQSIM International, Inc., 2001.

M. O. Faruque (S'03) received the B.Sc.Engg degree in 1992 from Chittagong University of Engineering and Technology (CUET), Chittagong, Bangladesh, and M.Eng.Sc. degree in 1999 from the University of Malaya, Kuala Lumpur, Malaysia, in the area of power engineering. He is working toward the Ph.D. degree from the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada.

For the last ten years, he has been working in both academia and industry, and his research interests include FACTS, HVDC, and real-time digital simulation of power electronics and power systems.

Yuyan Zhang received the Bachelor's degree in electrical engineering from South-East University, Nanjing, China, in 1990 and the M.E. degree from the University of Alberta, Edmonton, AB, Canada in 2003.

Since then, she has worked as an Electrical Engineer for a variety of industries, including the Beijing Chemical Plant, Hongkong Wellfine Ltd., Motorola China Ltd., and Siemens Ltd., China, in the power generation group. Her research interests are in the area of power distribution systems, HVDC, and digital simulation.

Venkata Dinavahi (M'00) received the B.Eng. degree in electrical engineering from Nagpur University, Nagpur, India, in 1993, the M.Tech. degree from the Indian Institute of Technology, Kanpur, India, in 1996, and the Ph.D. degree in electrical and computer engineering from the University of Toronto, Toronto, ON, Canada, in 2000.

Presently, he is an Assistant Professor at the University of Alberta, Edmonton, AB, Canada. His research interests include electromagnetic transient analysis, power electronics, and real-time simulation and control.

Dr. Dinavah is a member of CIGRÉ and a Professional Engineer in the Province of Alberta, Canada.