DEVELOPMENT OF A VERSATILE PACKAGE FOR THE DIGITAL SIMULATION OF TRANSIENT IN MTDC SYSTEMS

K.R. Padiyar and J. Senthil
Department of Electrical Engineering
Indian Institute of Science
Bangalore 560 012, India

ABSTRACT

This paper describes the development of a novel Digital Simulation package (DISIPACK) for transient simulation of MTDC systems. The major features of this program are, modularity, fast and efficient simulation of converters, compatibility with EMTP program, user defined controller models and generality in terms of simulation of monopolar/bipolar DC links, two or multi-terminal systems, and back-to-back links. The development of the digital simulation package with component models is described in this paper. The capability of this package is illustrated by simulation of two and three terminal DC systems.

INTRODUCTION

The rapid pace of the applications of modern HVDC transmission systems is in a large measure due to the development of high power thyristor valves and novel control techniques. This has rendered the fast and reliable control of power flow in a DC link, one of the most attractive features of HVDC technology and is of considerable significance in the control of interconnected AC systems. The scope of application of HVDC systems is expanded by the introduction of multi-terminal DC (MTDC) systems.

The economic design and optimal operation of two or multi-terminal DC systems requires detailed study of AC-DC system interactions and the performance evaluation of converter controls under various system conditions. HVDC simulators (physical models) are still widely used for this purpose wherever detailed transient simulation of converters and the controls is a necessity. While they offer several advantages in terms of realistic controller models and fast interactive computations, the cost of these simulators is prohibitive to be used on a large scale.

The digital simulators offer significant cost benefits with the advent of low cost personal work stations. Furthermore, digital models can be accurate and versatile wherever the mathematical models of components are well defined. Several special purpose digital computer programs [1-7] have been developed for specific applications, but the recent trends appear to favour the adoption of EMTP (Electro Magnetic Transients Program) which is used internationally for the transient simulation of AC networks [8,9]. Programs similar to EMTP, but smaller in size and more specialized have also been developed [10].

The major drawbacks of EMTP are (a) large size which makes it inefficient for simulating only DC systems with simplified AC network models, (b) small step sizes which increase computation time and (c) numerical problems that are inherent to the EMTP modelling of network elements. Yet EMTP is undoubtedly well established in the simulation of AC network transients.

This paper describes the development of a novel Digital Simulation package (DISIPACK) for transient simulation of MTDC systems. The main features, the simulation methodology and the component models used in DISIPACK have also been described. The capability of this package is illustrated with the help of two case studies related to a (i) two terminal system and a (ii) three terminal system with parallel connected converters.

FEATURES OF DISIPACK

The main features of DISIPACK are described below.

1. Modularity

For the purpose digital simulation of HVDC systems, the approach employed is to model each component separately and in a modular fashion. The identity of each component in a converter station such as bridge, controller is maintained and modelled individually. These models are interconnected using appropriate interface variables. This enables the simplified representation of AC/DC networks and converters for diagnostic purposes and faster computations when required.

2. Fast and Efficient Simulation of Converters

Converters have a time varying topology, the conduction pattern changing with the turn-on or current cessation in a valve. The simulation is simplified by considering a time varying equivalent circuit of a bridge on the dc side. Elimination of the need to store connection matrices and a fast and efficient way of generating the converter equivalent circuit parameters by identifying patterns makes the simulation fast and efficient.

3. Compatibility with EMTP Program

EMTP has come to be accepted internationally due to the established confidence of multi-user validation. Hence any versatile digital simulation package for converters and DC systems must have the feature of being adaptable for use with EMTP.

DISIPACK has the feature that the AC and DC networks can be simulated using the EMTP.

4. Generality

The program is general and can be used for the simulation of monopolar/bipolar DC links, two or multi-terminal systems and back-to-back links.

5. User Defined Controller Models

The program has the feature that each terminal/pole can have upto two controllers which can be specified by the user, although a default (generic) controller model is provided.

MODELLING AND SIMULATION OF AC/DC SYSTEMS

General

The AC/DC systems can be divided into three subsystems as shown in Fig. 1. The AC and DC networks can be modelled with lumped or distributed parameters as in EMTP. The effect of the converter terminal (each pole is considered separately) is to introduce three (phase) currents in the AC network, injected at the converter AC bus and the DC current at the converter DC bus. The AC filters, magnetising branch of the converter transformers are inserted as components of AC network. Leakage impedances of the converter transformer and the smoothing reactors are included in the converter model. DC filter is included in the DC network.

The AC and DC networks are modelled using the Dommel's approach [8] where lumped inductances and capacitances are modelled as conductances in parallel with current sources which depend upon past history. The transmission lines can be modelled as lumped or distributed parameter models. The converters are modelled using the graph-theoretic approach [11]. This is discussed next.

Modelling of Converters

The converters in a station consists of one or more series connected 6/12 pulse units made up of graets bridges each fed by converter transformers.

A three-phase bridge converter system is shown in Fig. 2. The bridge converter is supplied through a converter transformer which is represented by a voltage source behind its leakage impedance. The source voltages e_a, e_b, e_c are related to converter bus voltages. The dc current in the bridge is shown as an external current source.

From the graph-theoretic analysis given in [11] it can be shown that the converter current i_d can be determined from the equivalent circuit shown in Fig. 3. Although only a single 12-pulse converter is considered in Fig. 3, extension to multiple units is straightforward. Each bridge is represented by an equivalent circuit consisting of a voltage source in series with a time varying impedance. For a given conduction pattern in a bridge the equivalent circuit is uniquely defined. For e.g., if valves 1,2 and 3 are conducting,

$$e_{eq} = (R_b\, e_a + R_a\, e_b)/(R_a + R_b) - e_c - 2V_D \qquad (1)$$

$$r_{eq} = R_c + R_a R_b/(R_a + R_b) \qquad (2)$$

and

$$l_{eq} = T\, r_{eq} \qquad (3)$$

where V_D is the forward voltage drop across the valve when it is conducting. The current in a valve is assumed to be zero when it is not conducting. The derivation of the equivalent circuit is based on the assumption that $L_a/R_a = L_b/R_b = L_c/R_c = T$. This is a mild restriction and variations in the leakage impedances are permitted.

The expressions for valve currents and voltages are also obtained from graph-theoretic analysis. For the above example when 1, 2 and 3 are conducting

$$pi_3 = -\frac{1}{T}\, i_3 + \frac{R_a}{R_a + R_b}\left(\frac{1}{T} + p\right) i_d + \frac{e_b - e_a}{T(R_a+R_b)} \qquad (4)$$

and $i_1 = i_d - i_3, \quad i_2 = i_d$ (5)

$$V_4 = V_5 = V_6 = -V_d - V_D \qquad (6)$$

where V_d is the dc voltage across the bridge and $p \overset{\Delta}{=} d/dt$

The auxiliary differential eqn. (4) is solved using trapezoidal rule of integration. There will be two auxiliary equations when the number of conducting valves equals four and none when the number of conducting valves in a bridge is two.

The graph-theoretic analysis permits the consideration of all possible modes, both normal and abnormal. There are 39 possible modes corresponding to valve model chosen and when the dc current is considered to be continuous. The simulation of the converters is made efficient by identifying patterns among different modes.

Controller Model

Although the user can model controller to suit his requirements, a default controller model is provided with DISIPACK.

The firing scheme is essentially an equidistant pulse control with pulse frequency control. The control law for a 12-pulse controller is [12]

$$n_i = n_{i-1} + 30^0 + Q \qquad (7)$$

where n_i : present firing instant

n_{i-1} : previous firing instant

Q for a current controller (CC) is

$$Q = K_1(I_d - I_{dref}) + K_2\frac{dI_d}{dt} \qquad (8)$$

and for Extinction angle controller (EAC)

$$Q = K_3 \, (r - r_{ref}) \qquad (9)$$

I_{dref} is the reference value of the direct current I_d, while r_{ref} is the reference value of the extinction angle r. K_1 and K_2 are the CC gains while K_3 is the EAC gain.

CASE STUDIES

The capability of DISIPACK has been illustrated by examples of two and three-terminal DC system simulation, the system configuration of which are shown in Figs. 4 and 5 respectively. The system parameters have been adapted from [13]. AC system parameters have however been suitably modified to suit the required AC system representation.

The transient cases which have been simulated are:

I) 12 cycle, 100% single-phase (R-phase) voltage dip of the infinite bus voltage at the inverter for 2-terminal system.

II) 12 cycle, 25%, 3-phase voltage dip at the infinite bus voltage at inverter 2 for the 3-terminal system.

RESULTS AND DISCUSSIONS

The results of the transient simulation are shown in Figs. 6 to 11 for the 2-terminal system while Figs. 12 to 21 are for the 3-terminal system. The values of the gain K_1 of CC and gain K_3 of EAC have an effect on the overall transient response of the system. The values chosen for the 2-terminal transient study are 15 deg./kA and 0.9 deg./deg. for both rectifier as well as inverter. For the 3-terminal system, the inverter 1 is under CC and inverter 2 under EAC. The controller gains chosen are (a) for rectifier, K_1 = 33 deg./kA, (b) for inverter 1, K_1 = 36 deg./kA, K_3 = 0.5 deg./deg. and (c) for inverter 2, K_1 = 42 deg./kA and K_3 = 0.5 deg./deg.

For the disturbance considered, it is found that the value of gain K_1 at inverter 2 is critical although it is on voltage control. For a lower value of K_1 = 33 deg/kA the terminal current and voltage for the inverter 2 are shown in Figs. 20 and 21 respectively. In obtaining these figures, rectifier and inverter 2 were also considered to be connected to infinite buses.

In both cases considered, the system recovers within 5 cycles after the fault is cleared. The voltage dependent current order limiter has not been considered and the controller gains are not optimal.

CONCLUSIONS

A novel Digital Simulation package (DISIPACK) for the transient simulation of MTDC systems is presented. The major features of this package are modularity, fast and efficient simulation of the converters, generality, user defined controller models and compatibility with EMTP. These features make the package versatile enough to study not only a specific system but also to gain valuable understanding of the effect of various modelling assumptions in analysing transients. Thus the package can also serve as a tool for research and training in addition to transient simulation of converters for system studies.

ACKNOWLEDGEMENT

The financial assistance provided by the Department of Electronics, Government of India, under the National HVDC R and D Programme is gratefully acknowledged.

APPENDIX

System Data

I) 2-Terminal System

a) DC Line Parameters

Resistance (Ω/mile) = 0.0062
Inductance (mH/mile) = 0.70789
Capacitance(μF/mile) = 0.04183
Length of line (miles) = 489

b) Converter Transformer Parameters

	Rectifier	Inverter
Leakage Inductance (mH)	15.72	15.72
Winding Resistance (Ω)	0.025	0.025
Nominal Voltage Ratio	345 kV/206.2 kV	500 kV/202.4kV

c) AC/DC Operating Conditions

	Rectifier	Inverter
DC link current	1.6 kA	1.6 kA
DC terminal voltage	510 kV	505.15kV
Firing angle	15°	157.3°
Extinction angle	17°	17°
Open circuit DC voltage	268.68kV	268.85kV
RMS voltage of converter Bus	204.81kV	290.42kV
Short-circuit ratio	2.21	6.03
AC system impedance angle	80°	80°

II) 3-Terminal System

a) DC Line Parameters

The resistance, inductance and capacitance values are same as for the 2-terminal system. The line lengths are as follows:

Rectifier to inverter 1 = 289 miles
Inverter 1 to Inverter 2 = 200 miles

b) Converter Transformer Parameters

Converter transformer parameters are same as for the 2-terminal system.

c) AC/DC Operating Conditions

	Rectifier	Inverter 1	Inverter 2
DC link current	1.6kA	0.798kA	0.802kA
DC terminal voltage	503.86kV	500.98kV	500kV
Firing angle	15°	157.3°	157.3°
Extinction angle	17°	17°	17°
Open circuit DC voltage	265.5kV	266.66kV	266.16kV
RMS voltage of converter bus	208.41kV	288.67kV	269.46kV
Short-circuit ratio	2.21	-	6.03
AC system impedance angle	80°	-	80°

AC system of inverter 1 is represented by a voltage source with zero internal impedance.

Step size = 0.6°, ntime = 36000 x time in seconds

REFERENCES

1. N.G. Hingorani, R.H. Kitchen, J.L. Hay, 'Dynamic Simulation of HVDC Power Transmission Systems on Digital Computer', IEEE Trans. Vol. PAS-87. No. 4, pp. 989-996, April 1968.
2. J. Reeve and S.C. Kapoor, 'Dynamic fault analysis of HVDC systems with AC representation', IEEE Trans., Vol. PAS-91, No. 2, pp. 688-696, March/April 1972.
3. J. Reeve and T.S. Rao, 'Dynamic analysis of harmonic interaction between AC and DC power systems', IEEE Trans., Vol. PAS-93, pp. 640-646, March/April 1974.
4. M.D. Heffernan, K.S. Turner, J. Arrillaga and C.P. Arnold, 'Computation of AC-DC System disturbances, parts I, II and III, IEEE Trans., Vol. PAS-100, No. 11, pp 4341-4363, Nov. 1981.
5. J. Milias-Argitis and G. Galanos, 'Dynamic simulation of HVDC transmission systems', IEEE Trans., Vol. PAS-97, pp 587-593, March/April 1978.
6. K.R. Padiyar and Sachchidanand, 'Digital simulation of multi-terminal HVDC system using a novel converter model', IEEE Trans., Vol. PAS-102, No. 6, pp 1624-32, June 1983.
7. K.R. Padiyar, Sachchidanand, A.G. Kothari, S. Bhattacharya and A. Srivastava, 'Study of HVDC controls through efficient dynamic digital simulation of converters', Paper 89, WM 113-2 PWRD, Presented at 1989 IEEE/PES Winter Meeting, New York, Jan. 29-Feb. 3, 1989.
8. H.W. Dommel, W.S. Meyer, 'Computation of electromagnetic transients', Proc. IEEE, Vol. 62, pp 983-993, July 1974.
9. J. Reeve and S.P. Chen, 'Versatile interactive digital simulator based on EMTP for AC/DC power transient studies', IEEE Trans., Vol. PAS-103, No. 12, pp 3625-3632, Dec. 1984.
10. D.A. Woodford, A.M. Gole, R.W. Menzies, 'Digital simulation of DC links and A.C. Machines', IEEE Trans., Vol. PAS-102, No. 6, pp 1616-1623, June 1983.
11. K.R. Padiyar and A.G. Kothari, 'Modelling and simulation of HVDC bridge converters', Electric Machines and Power Systems, Vol. 13, pp 285-298, 1987.
12. C.M. Alegria, et al, 'Microcomputer control of power converters', IEEE Trans., PAS, Vol. PAS-103, pp 2011-2017, Aug. 1984.
13. S. Bhattacharya, 'Simulation of transient phenomena in high voltage direct-current converter systems', Ph.D. Thesis, The Univ. of British Columbia, Canada, March 1987.

Fig.1 - Interconnection of Various Subsystems

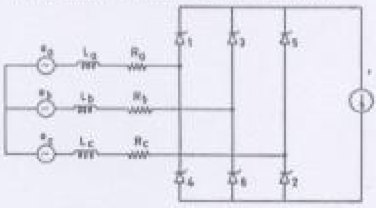

Fig.2 - Three Phase Bridge Converter

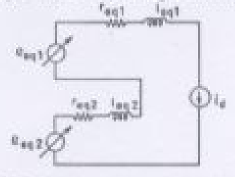

Fig.3 - Equivalent Circuit of a 12-pulse Converter

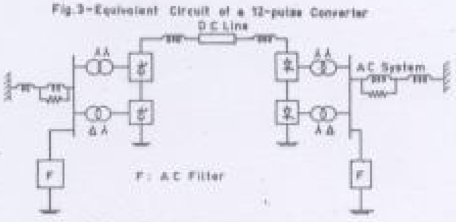

Fig.4 - Two Terminal H V D C System

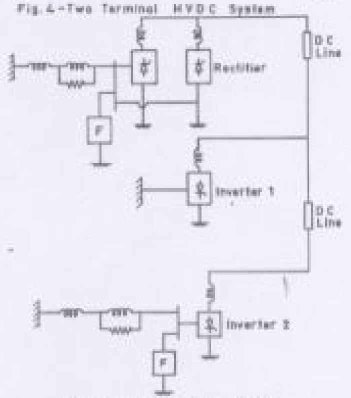

Fig.5 - Three Terminal System

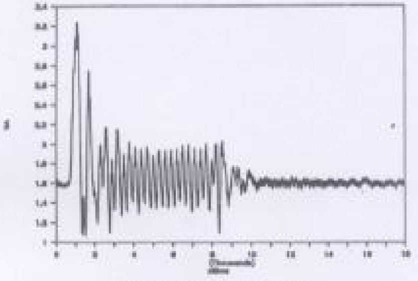
Fig. 6- Rectifier DC Current

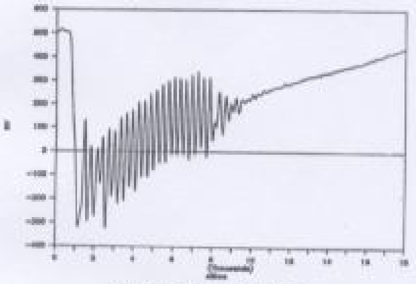
Fig. 7 - Rectifier DC Voltage

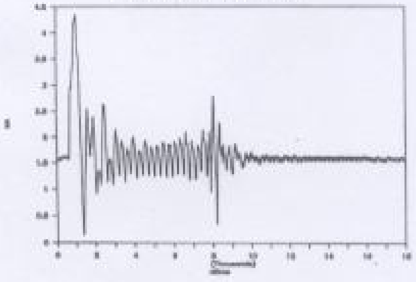
Fig. 8- Inverter DC Current

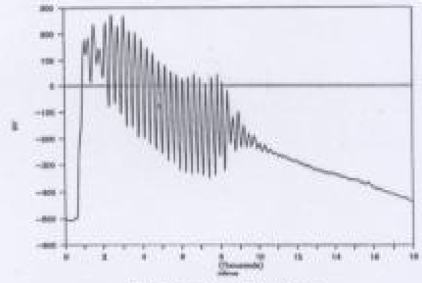
Fig. 9- Inverter DC Voltage

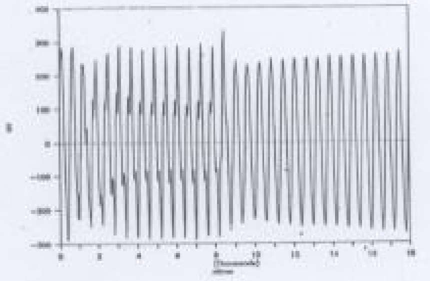
Fig. 10- Rectifier Bus Voltage (R-phase)

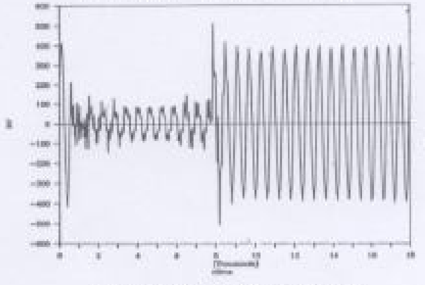
Fig. 11- Inverter Bus Voltage (R-phase)

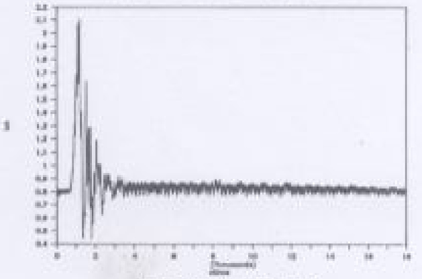
Fig. 12- Rectifier DC Current

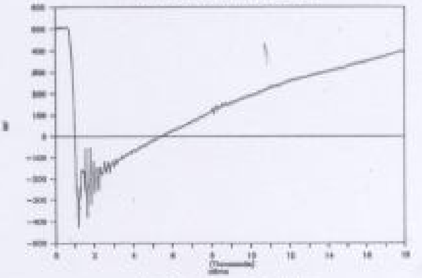
Fig. 13- Rectifier DC Voltage

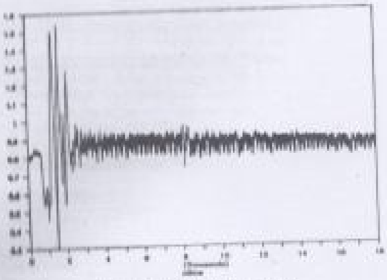

Fig. 14- Inverter 1 D C Current

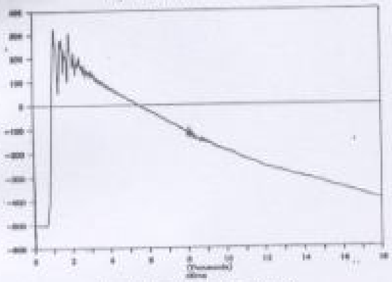

Fig. 15- Inverter 1 D C Voltage

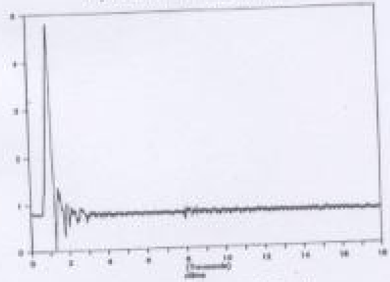

Fig. 16- Inverter 2 D C Current

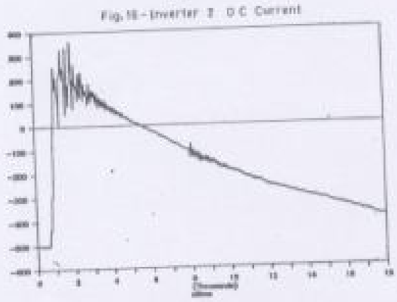

Fig. 17- Inverter 2 D C Voltage

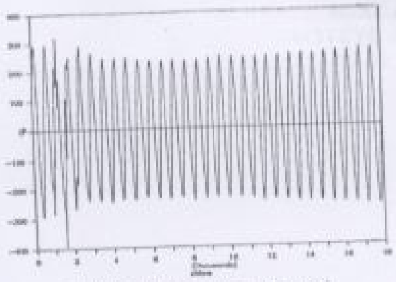

Fig. 18- Rectifier Bus Voltage (R-phase)

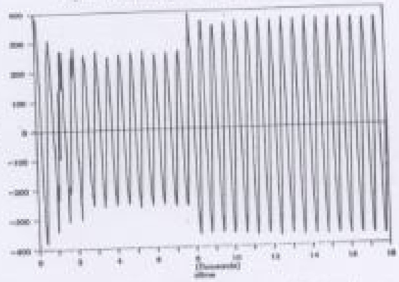

Fig. 19- Inverter 2 Bus Voltage (R-phase)

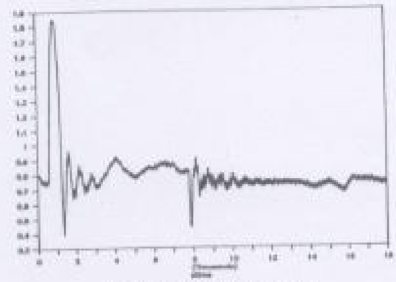

Fig. 20- Inverter 2 D C Current

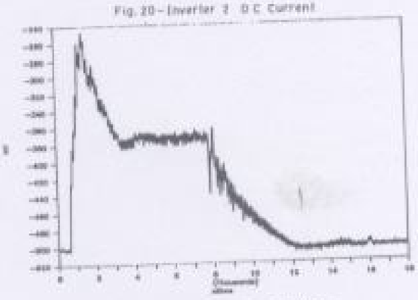

Fig. 21- Inverter 2 D C Voltage