been tested on a number of 11 kV radial distribution feeders in an Indian distribution system and the results of one such actual feeder have been presented in the paper highlighting the effects of growth factors on the optimal allocation of fixed capacitors. The study shows that the switched capacitors are not economical for on-line application due to its high cost and due to the fact that the feeder capacities released by the capacitors have no practical value as the same cannot be used for monetary gain.

The proposed MLV approach is shown to be more efficient than the DP approach from the point of view of computational requirements and simplicity. The method suggested provides the overall optimal solution taking the growth factors into account. The proposed method is simple, easy to program, efficient and in the authors' opinion is quite promising.

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Digital Simulation of DC Links and AC Machines

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Since more and more transmission planning engineers have access to small, dedicated but powerful computers, electromagnetic transient simulation of power system networks by digital programs is becoming standard practice. Digital high voltage direct current (HVDC) transmission simulation is one area slow in developing, but the time is now right for its more serious consideration.

The Bonneville Power Administration's electromagnetic transients program (BPA's EMTP) is potentially a powerful tool for HVDC simulation. Because the present structure of this program intimidates the average user seeking the flexibility needed for advanced HVDC simulation, a smaller and more specialized program was developed at Manitoba Hydro. Known as MH EMTDC and based on the algorithms described by H. Dommel [1], it provides ease in interfacing user developed fortran models with an electromagnetic transients solution. MH EMTDC has the following features:

1) The main program solves the electromagnetic transients for the network under study and calls two user written subroutines. The first subroutine interfaces the network solution of voltages, currents and branch elements for the user to process and control voltage and current sources and switch branch elements. The second subroutine allows the user to access and process any variable, solved voltage, or current for output and plotting.

2) Disconnected subnetworks described in Ref. [1] are used to minimize matrix size and maximize speed of the solution.

3) Valve group models, synchronous machines with exciters, stabilizers and governors and control circuits are available and can be assembled as subroutines by the user. In Fig. 1, a simple diagram of the subnetworking process for value groups is shown.

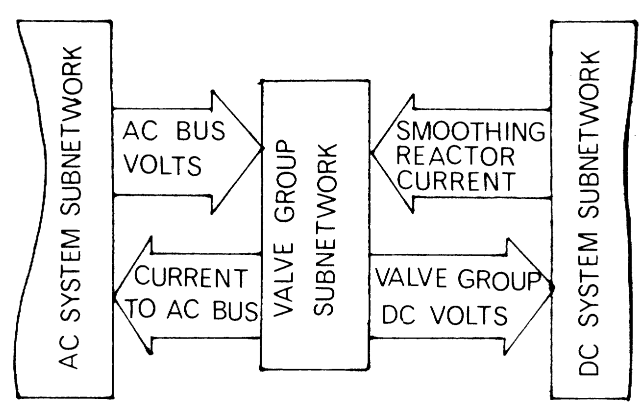

Fig. 1. Disconnected subnetwork representation for valve groups.

A complete ac machine model was developed by the authors from the University of Manitoba for the MH EMTDC. The attractive features of this machine model are the following:

1) It is fairly detailed, with a complete two axis (six coil) representation, with *d* axis saturation included, and with additional modeling for accurate rotor side studies.

2) The solution can use a different timestep and integration procedure from the MH EMTDC program. In this way, it differs from other programs [2], which try to include the machine equations in a submatrix of the main system matrix.

Conclusions

The digital dc simulator with ac machine modeling capability described here is a working computer program being used in system studies. Experience has shown that a good appreciation of HVDC transmission, machines and electromagnetic transients phenomena is needed to utilize the simulator effectively. Until this appreciation is gained, the program is an effective educational tool in modern power system transient operation and analysis.

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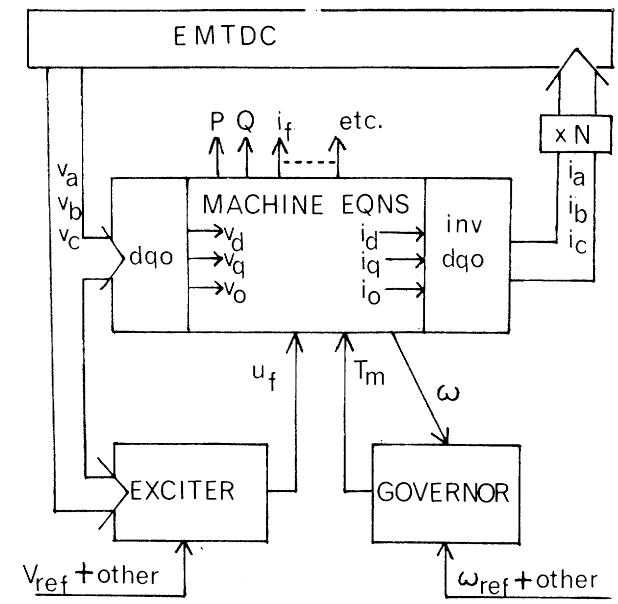

Fig. 2. Modeling scheme for the ac machine.

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Digital Simulation of Multiterminal HVDC Systems Using a Novel Converter Model

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The major problem associated with the digital simulation of HVDC system is representation of time varying topology of the converter due to commencement and cessation of valve conduction. This has been considered using two methods. In the first method a set of equations, for all possible configurations of conducting valves, are formulated so that a particular set of equation is chosen at any given time. In the second method, the state equations corresponding to converter conduction state are generated using a transformation matrix.

This paper introduces a novel converter representation based on graph theoretic analysis. The approach is conceptually simpler and leads to efficient formulation of the converter equations corresponding to all possible modes of 2, 3 and 4 valve conduction.

A three-phase bridge converter system is shown in Fig. 1. The effect of the ac system and dc network is represented by the source voltages (e_1, e_2, e_3) and V_c respectively. Fig. 2 shows the graph of the converter system. The tree includes the elements 7, 8, 9 and one of the conducting valves (element S, where S can be valve 1 to 6). The equations for the elements 7, 8 and 9 are

$$\underline{v}_{B1} = Z\underline{i}_{B1} + \underline{e} \tag{1}$$

where $Z = R + \omega Lp$

$$R = \begin{bmatrix} 2R_c & O & R_c \\ O & R_d & O \\ R_c & O & 2R_c \end{bmatrix}; \quad L = \begin{bmatrix} 2L_c & O & L_c \\ O & L_d & O \\ L_c & O & 2L_c \end{bmatrix}$$

$\underline{e} = [(e_3 - e_2) V_c (e_1 - e_2)]^T$,

$\underline{v}_{B1} = [v_7 v_8 v_9]^T$, $\underline{i}_{B1} = [i_7 i_8 i_9]^T$.

v and i are element voltage and current respectively.

For any network, branch and link variables are related as

$$\underline{i}_B = -B_L i_L \tag{2}$$

and

$$\underline{v}_L = B_L{}^T \underline{v}_B \tag{3}$$

where subscripts B and L refer to branches and links respectively. Matrix B_L is the component of fundamental cutset matrix. The tree branches are partitioned into two sets, one set B_1 (consisting of elements 7, 8 and 9) and other B_2 (consisting of valve S). Similarly, the links can be partitioned into two sets, L_1 (corresponding to conducting valves) and L_2 (corresponding to nonconducting valves). Assuming the valves to be ideal switches:

$$\underline{v}_{L1} = O,\ v_{B2} = O,\ \underline{i}_{L2} = O$$

Substituting this in (1)–(3), the dynamics of the converter is described as

$$\frac{d}{d\omega t}\underline{i}_{L1} = -\omega L_1{}^{-1} R_1 \underline{i}_{L1} + \omega L_1{}^{-1} B_{L11}{}^T \underline{e} \tag{4}$$

where $L_1 = B_{L11}{}^T L B_{L11}$ and $R_1 = B_{L11}{}^T R B_{L11}$

$\bar{B}_{L11}$ is the submatrix of $[B_L]$ corresponding to sets B_1 and L_1. The matrix B_L needs to be modified for any change in converter conduction state. To represent 39 modes of converter operation with continuous dc current, it is adequate to use only three such matrices corresponding to a valve group (1, 3, 5 or 2, 4, 6).

The instant of firing of each valve is determined from the controller which utilizes the firing control scheme based on individual phase control or equidistant pulse control. The dc current, obtained as a function of state variables, is injected into the dc network to represent the effect of converter. Transmission lines are represented by a π equivalent.

Based on the procedures outlined above, a computer program has been developed to simulate a controlled multiterminal HVDC system. The program, modular in structure, describes each system component in an individual subroutine. Test simulations on a 2-terminal and a 3-terminal dc systems are presented not only to illustrate the program capability, but also to demonstrate the system response both in steady state and transient conditions following a disturbance in current reference setting or ac system voltage.

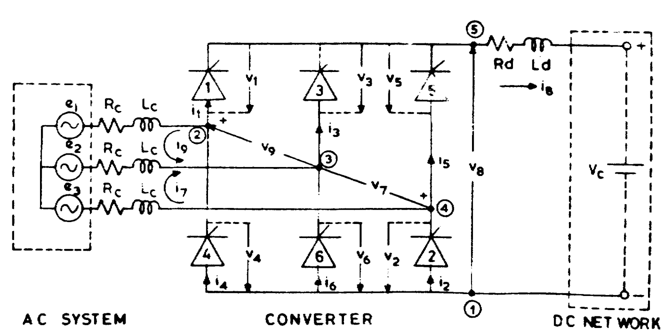

Fig. 1. Converter System.

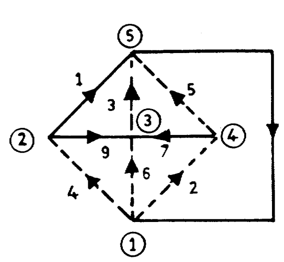

Fig. 2. Tree and Cotree for s = 1.