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Current and voltage dependent sources modelling in MATE–multi-area Thévenin equivalent concept☆

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ABSTRACT

The objective of this paper is to provide a clear derivation of the Multi-Area Thévenin Equivalent Concept (MATE) including current- and voltage-dependent sources. The links concept in MATE is advantageous in representing branches connecting subsystems. MATE deviates from Diakoptics and from the Modified Nodal Analysis (MNA) methods in the way it is solved, by manipulating the submatrices in a form that preserves the individuality of the internal subsystems while solving their interdependences at the level of Thévenin Equivalents. The generalization presented in this paper expands the link branch equations to dependent, coupled, linear or nonlinear relations, thus resulting in unsymmetrical matrices. Its significance occurs when complex control systems and power system equations are simultaneously solved in an Electromagnetic Transients Program (EMTP). In this case, exact results can be achieved with less computational effort for power system dynamics studies. A test case with simulation results illustrates the main modelling concepts.

1. Introduction

The solution of large complex systems has been investigated by many researchers resulting in different techniques. For example, Diakoptics (from the greek “dia” for “very” and “kopto” for “tearing”) was introduced in the 1950’s [1] and further explored in Happ [2]. Direct solutions of sparse network equations by optimally ordered triangular factorization was proposed in 1967 [3]. Modified Nodal Analysis (MNA) was presented in 1975 [4]. The Waveform Relaxation method for time domain analysis of large scale integrated circuits has been reported in the 1980’s [5–7]. For historical reasons, sparsity techniques [3] became widely used for the simulation of large power systems. The main computational advantage of the “Multi-Area Thévenin Equivalents” (MATE) algorithm [8] used in this paper over sparsity techniques is realized when the algorithm is implemented with parallel computers or multiple CPU’s, which did not become widely available until recent times. Because of its solution time advantages, MATE has also been used in real-time power systems dynamics simulations [9,10]. When compared with other subsystem decoupling solutions (e.g. [5–7], MATE is not an iterative solution but a two-stage simultaneous solution and, therefore, the solution is exact.

This paper presents an extension of the MATE algorithm [8,11–14] to incorporate dependent sources, controllers, and other asymmetrical branches for simulations with the electromagnetic transients program (EMTP) [15,16].

Beyond EMTP solutions, MATE has also been used in parallel computation of large power system networks [13,14]. As discussed in Tomim [13], the MATE algorithm yields a theoretical speedup limit of p/2, where p is the number of subsystems and corresponding CPU processors. In Tomim et al. [14] MATE was applied to solving in parallel power systems of about 2,000 and 15,000 buses. The results showed that the attained speedup closely followed the theoretical maximum. In Tomim et al. [14] a test case from the Western Electricity Coordinating Council (WECC) system was simulated as part of a transient stability study. The size of the system was of approximately 15,000 buses. The solution using sparsity on a single CPU and MATE using multiple CPUs (using sparsity in the individual subsystems) were compared. The obtained speed ups were again very close to the theoretical

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optimum. With MATE, it is also possible to apply latency techniques for EMTP solutions [17,18]. The advantages of multirate simulations with simultaneous-solution using direct integration methods in a partitioned network environment are discussed in Moreira et al. [19].

In this paper, MATE is extended to incorporate dependent branches and control blocks in a simultaneous solution, without using the delay blocks in closing the loops of other approaches. We first review the mathematical derivation of the MATE method [8] and then we incorporate current and voltage-dependent sources [20–21]. Finally, control blocks, can be realized using the implemented dependent sources [21].

The MATE algorithm generalization presented in this paper expands the link branch equations to include dependent, coupled, linear or non-linear relations, thus resulting in unsymmetrical matrices. A test case with simulation results from Armstrong [11] illustrates the main modelling concepts, especially with regards to the simultaneous solution of complex control systems and the power system equations. Simultaneous solution of the control system equations and the power network equations [11,20–23] are particularly relevant in the development of distributed control strategies in the emerging smart grid real-time supervisory control applications.

2. Mathematical conceptual derivation of the MATE concept

The Multi-Area Thévenin Equivalent (MATE) concept provides a means for partitioning large systems of equations into subsystems connected through links. The subsystems are solved independently (even with different solution techniques and with parallel processing) and the overall solution is integrated at the level of the links. In the Multilevel MATE algorithm each subsystem becomes the basis for another level of MATE partitioning, thus allowing further parallelization of the solution [11,12].

2.1. General formulation of MATE

Consider initially, for didactic reasons, any power system composed of only two subsystems, A and B, and any set of dependent, independent, coupled, uncoupled, linear or nonlinear branch relations among them, as illustrated in Fig. 1. These branch relations can be any impedances, switches, dependent sources, or nonlinear elements connecting the two subsystems. One can solve the full matrix directly, however, those links between the two subsystems, A and B, can be used for tearing purposes with MATE's two-step exact solution technique.

If the branch equations are nonlinear, a fixed point or Newton-Raphson type iteration algorithm can be used for the solution of the branches to any desired accuracy, as illustrated in Fig. 2. This iteration constitutes a local loop at the level of these nonlinear branches. Once the branches are solved, the branch currents are injected into the subsystems and the overall system of systems solution remains simultaneous (the only deviation from an "exact" solution is the convergence of the nonlinear branches solution, which as indicated can be achieved to any desired accuracy). The system of Fig. 1, with the "assumed conventions for voltage polarities and current directions", can be represented by the matrix Eqs. in (1) [8]:

$$\begin{bmatrix} [G_A] & [0] & [p] \\ [0] & [G_B] & [q] \\ [m] & [n] & -[z] \end{bmatrix} \cdot \begin{bmatrix} [v_A] \\ [v_B] \\ [i_\alpha] \end{bmatrix} = \begin{bmatrix} [h_A] \\ [h_B] \\ [V_s] \end{bmatrix} \tag{1}$$

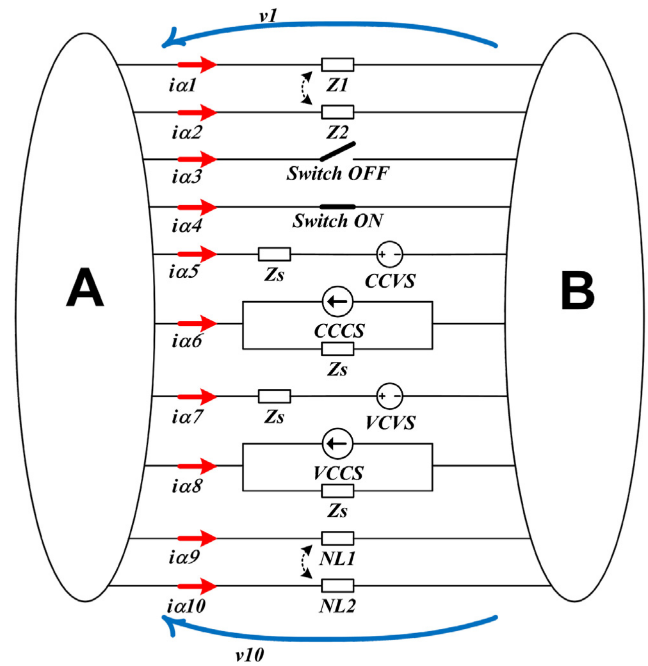

Fig. 1. MATE concept expansion considering link branch equations for dependent, coupled, linear or nonlinear relations.

where:

$[G_A]$ is the EMTP conductance matrix of subsystem A;

$[v_A]$ is the vector of nodal voltages of subsystem A;

$[h_A]$ is the vector of current sources of subsystem A;

$[p]$, $[q]$, $[m]$, $[n]$ are "connectivity" submatrices needed to express the branch relations between the subsystems A and B;

$[z]$ is the submatrix of impedance relations of the branches connecting subsystems A and B;

$[V_s]$ is the vector of equivalent voltage sources in each branch connecting subsystems A and B. In the particular case of a single connecting branch, V_s can be an ungrounded independent voltage source in series with an impedance.

The same description applies to subsystems B, C, D, etc.

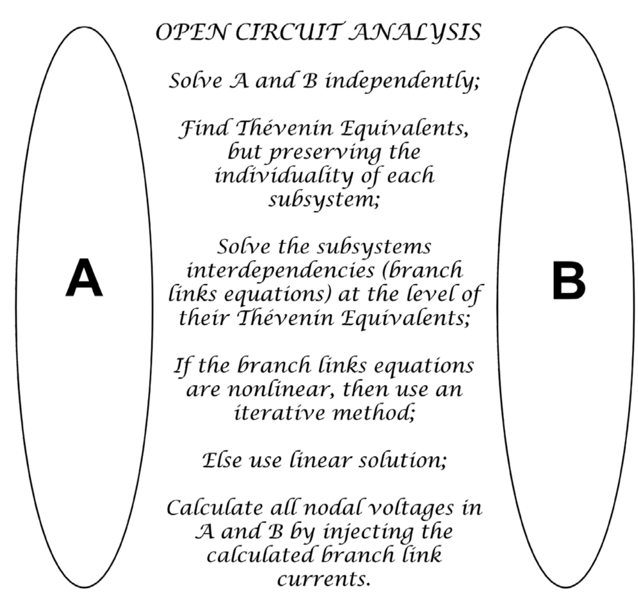

Fig. 2. MATE concept solution in partitioned subsystems with dependent, coupled, linear or nonlinear branch relations.