A Method for Linking Different Modeling Techniques for Accurate and Efficient Simulation

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***Abstract*—This paper presents a new method for accurate linking of diverse simulation techniques. The method employs a Functional Modeling (FM) approach and facilitates linking of different simulation techniques as well as combining separate simulation engines. In addition, the presented method enables system decomposition with freely selected cuts as well as natural and efficient parallel computations. Discussion of advantages and various applications is also included.**

***Index Terms*—Decomposition, digital simulation, functional modeling, numerical methods.**

I. INTRODUCTION

PLANNING, designing and operating of modem power systems call for extensive and detailed simulation. Some operating tasks require even real-time or semi-real-time modeling. As a result, recent developments in digital simulation of power systems need to focus on modeling of large structures using accurate models. For such tightened requirements, a compromise must always be made between key interrelated issues: Size of the simulated system (extent of simulation), detail of modeling (accuracy) and required computational power (cost). Since accuracy is the primary issue resulting from the purpose of analysis and applicability of the results, the extent and cost issues need to be balanced for a given accuracy with the objective to maximize the simulation efficiency. Traditionally, the system equivalencing is used to deal with the problem size while the system decomposition is applied to enlarge available computational resources by using parallel architectures [1]–[3].

The concept of equivalencing relies on representing a portion of the simulated system using a simplified model. Equivalencing techniques usually reduce the size of the represented portion and use ideal voltage sources and/or a simple network. It is common in transient studies, that the equivalenced part is included in the main model and solved by the differential equation oriented simulation engine. Decreased accuracy of modeling is always a price to pay for increased efficiency of simulation.

The concept of decomposition, in turn, gains efficiency by distributing the computational burden between a number of independent processing nodes. Decomposition methods break down a modeled system into a number of subsystems usually cutting across transmission lines [3]. This takes advantage of the natural propagation times of the lines and facilitates parallel processing. This calls for substantial hardware resources to be associated with a given computational node despite system decomposition. This may not be easy to accommodate on a cost effective basis. To solve the problem one needs a decomposition technique capable of breaking down an island, already separated by transmission lines, further into several subsystems.

This paper presents a new approach to balancing the size, accuracy, and computational power. A novel approach is applied to both the way the modeled system is partitioned and the way the created subsystems are represented and solved.

First, the proposed method partitions the system freely, not necessarily by cutting across the transmission lines. This enables one to break down fragments of the system requiring very large computational power into a number of submodels and use parallel architectures to perform the computations. This approach preserves simulation accuracy for large systems but gains efficiency by enabling parallel processing.

Second, the equivalencing method presented in this paper is unique in applying a different type of model to the equivalenced fragment instead of reducing its size. The equivalenced subsystems are simulated using phasor-type models in full (in terms of size). This approach preserves accuracy but gains efficiency by avoiding solving differential equations for the equivalenced parts and enabling much longer time steps when solving the phasor-type models.

Third, the decomposition and equivalencing methods presented in this paper show numerous by-products that enable new applications such as linking separate simulation engines and physical simulators.

This paper is organized as follows. Section II states the decomposition problem, Section III presents the adopted decomposition method, Section IV shows the solution technique for the complete system, while Section V shows how the proposed method enables one to link diverse simulation techniques. A numerical example is presented and discussed in Section VI. Advantages and various additional applications are discussed in Section VII.

II. NEW APPROACH TO DECOMPOSITION

With reference to Fig. 1, this paper offers for consideration three categories of models:

- waveform-type,
- phasor-type,
- algebraic-type.

The accurate frequency dependent model of a transmission line for digital relaying studies is perhaps the best example of how the use of the above models can improve efficiency of

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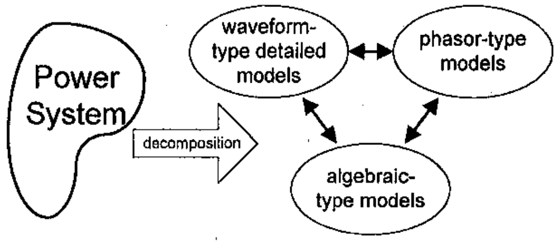

Fig. 1. Proposed decomposition technique.

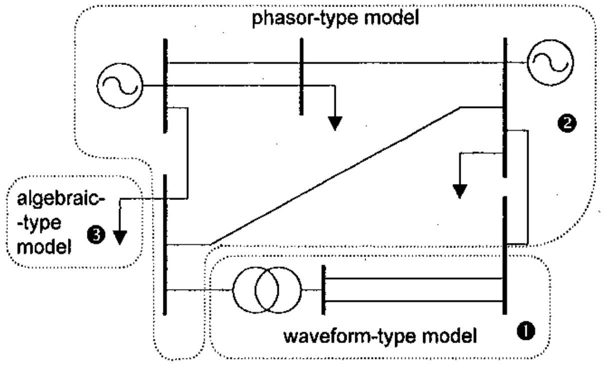

Fig. 2. Illustration of the new decomposition method.

the simulation without a decrease in accuracy (see Fig. 2). The detailed mathematical description of a fragment important for a given study, shown in Fig. 2 as ① is based on differential equations for the instantaneous values of involved quantities. To be solved, this segment calls for the differential equation type solver.

The rest of the network, shown as ② is not equivalenced in terms of its size, but modeled by a phasor-type program. Either steady-state, such as Short-Circuit Program (SCP), or transient, such as Transient Stability Program (TSP), simulation engines may be used. Using standard (SCP or TSP) or customized phasor-type routines enables one to take advantage of the vital features of such programs. This includes the widely accepted models (a simplified synchronous machine with auxiliaries and controls, for example) or the system control strategies (frequency control, for example).

The third category of models, shown as ③in Fig. 2, includes power system components functionally described by algebraic equations without any reference to the physical nature of those elements. The commonly accepted frequency-dependent load model is perhaps the best example.

Advantages of the above decomposition method are the following:

- higher simulation accuracy for the equivalenced portion of the system compared to the model comprising of ideal voltage sources behind RL branches,
- lower computational burden compared to modeling of the entire system without any equivalencing,
- ability to access signals in the equivalenced parts,
- opportunity to include high-level explicit description of loads and other components,
- opportunity to use the tools and models inherent in SCP or TSP, such as transient representation of machines, simplified representation of protective relays, representation of power system stabilizers (PSS's) and other controllers.

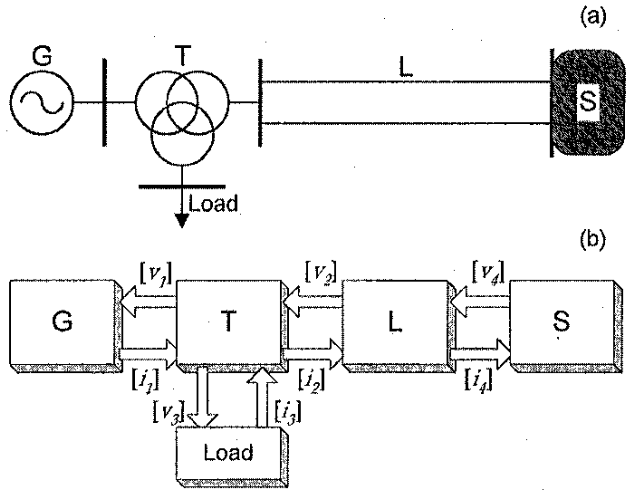

Fig. 3. (a) A sample power system and (b) its decomposition.

The next sections show how to practically accomplish the outlined simulation technique.

III. DECOMPOSITION METHOD

The decomposition method used in this paper is based on the functional modeling (FM) approach [4], [5]. The FM technique decomposes the simulated system between a number of subsystems using their functions as the basis. This means that each physical element of a power system (or a group of elements) is substituted by its own model (subsystem). Each subsystem is an input–output representation of an associated element. Fig. 3 depicts an example of (a) a sample power system and (b) its decomposition.

Once the cuts are selected, the decision must be made as to which boundary signals to assign as inputs for a given block [4]. The two fundamental constraints are:

- signals between two interconnected elements must match, i.e. inputs of one subsystem are outputs from the connected subsystem [Fig. 3(b)].
- mathematically, the solution of a given subsystem with a selected set of inputs must exist (for example, for a transmission line as a subsystem, one cannot select currents at both ends to be inputs and the voltages at both ends to be outputs).

It is worth noticing that the FM method is an extension of the decomposition performed uniquely across transmission lines. If a subsystem is an island detached by transmission lines, it may still be included in the FM model.

Generally, connections between the subsystems are more complicated than in the example of Fig. 3 and may involve nodes and loops. Therefore, the practical FM model consists of individual subsystems and linear equations describing the connection topology (Fig. 4).

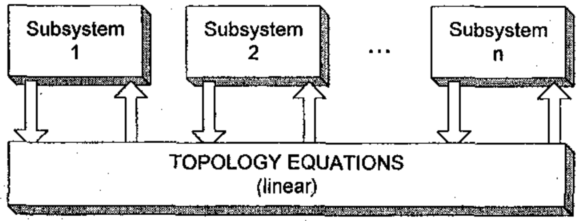

Fig. 4. General FM approach. The subsystems are connected through the topology equations.

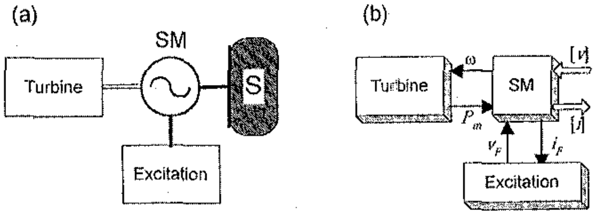

Fig. 5. (a) The subsystem G from Fig. 3 modeled as a set of its own subsystems, and (b) the boundary signals.

The FM model may involve more than one hierarchical level. This means that the blocks in Fig. 4 may internally contain their own submodels. Fig.5 illustrates this by showing the model of a synchronous generator, G (from Fig. 3), as a structure of three subsystems: A turbine, a synchronous machine, and an excitation system.

The FM approach is valid for different types of studies. For steady-state calculations, the boundary signals are the voltage and current phasors or active and reactive powers. In transient simulations, the boundary signals are simply the instantaneous values for a given time step.

The accurate solution for the complete system requires both the equations of all the subsystems as well as the topology (balance) equations to be solved. The latter is achieved in the iterative way.

The simplest linking method executes (calls) first all the submodels and collects their responses. With reference to the example of Fig. 3 this stage may be written as:

$$G\colon ([v_1])_{old} \rightarrow ([i_1])_{new} \tag{1a}$$

$$T\colon ([i_1], [i_3], [v_2])_{old} \rightarrow ([v_1], [v_3], [i_2])_{new} \tag{1b}$$

$$L\colon ([i_2], [v_4])_{old} \rightarrow ([v_2], [i_4])_{new} \tag{1c}$$

$$S\colon ([i_4])_{old} \rightarrow ([v_4])_{new} \tag{1d}$$

$$\text{Load: } ([v_3])_{old} \rightarrow ([i_3])_{new}. \tag{1e}$$

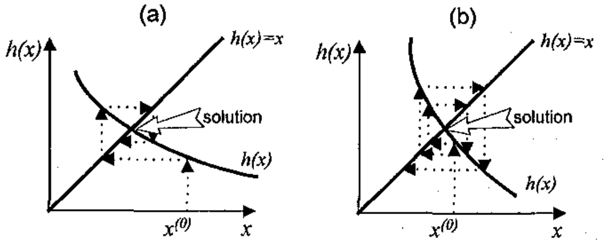

Fig. 6. (a) Illustration of stable and (b) unstable simulation using the iteration mode (4).

Note, that all the boundary signals are inputs and outputs at the same time. Denoting:

$$x^k = ([v_1], [v_2], [v_3], [v_4], [i_1], [i_2], [i_3], [i_4])_{old} \tag{2}$$

where k is an iteration step, and

$$h(x^k) = ([v_1], [v_2], [v_3], [v_4], [i_1], [i_2], [i_3], [i_4])_{new} \tag{3}$$

one may close the iteration loop as follows:

$$x^{k+1} = h(x^k). \tag{4}$$

This simple approach feeding the outputs from the previous iteration step as the inputs to the next iteration step, may be unstable in practical cases. Fig. 6 illustrates this for the simplest case where the vector of unknowns, x, consists of one variable. The process (4) projects the value of the function h from the previous iteration step to the value of x in the new iteration step. Depending on both the function h and the starting point $x^{(0)}$, the process is either numerically stable [Fig. 6(a)] or unstable [Fig. 6(b)]. The detailed analysis of this phenomenon may be found in [4].

From the application point of view, a special stabilizing procedure is, thus, needed for making the FM method practical. Section IV delivers such a practical algorithm.

IV. ITERATION PROCESS

As indicated by (1)–(3), each border signal between the adjacent subsystems is an input and an output at the same time. Therefore, the iteration process is stable if the difference between x^k and $h(x^k)$ converges to zero. It may be written as:

$$g(x^k) = h(x^k) - x^k \rightarrow 0, \qquad k = 0, 1, 2, \cdots. \tag{5}$$

In the proposed algorithm, iterations are performed as follows [5]:

1. Assume initial conditions ($k = 0$)

   $$x^0 = a, \quad \gamma^0 = 1, \quad g(x^0) = 0 \tag{6}$$

   where a is a value of x from the previous time step or a value supplied by a predictor, if used.
2. Solve the entire model with x^k as the input:

   $$g(x^k) = h(x^k) - x^k. \tag{7}$$

3. Determine the corrected input vectory for the next iteration step (first correction of unknowns). The vectory is a new value of the vector of unknowns x calculated using

the linear approximation of the function g and applying, in addition, a stabilizing factor γ:

$$y^k = x^k - \frac{1}{2}\left(\frac{x^k - x^{k-1}}{g(x^k) - g(x^{k-1})} - \gamma^k\right). \tag{8}$$

4. Solve the entire model with y^k as the input:

$$g(y^k) = h(y^k) - y^k. \tag{9}$$

5. Calculate the auxiliary coefficients and correct unknowns:

$$\gamma^k = \frac{\gamma^{k-1} g(x^k)}{g(y^k) - g(x^k)}. \tag{10}$$

The variable γ stands for an adaptive stabilizing factor that controls the stability/speed balance of the algorithm (if γ is close to 1, the algorithm is faster; if γ is close to 0, the algorithm is deeply stable).

6.

$$\Delta^k = \gamma^k g(x^k). \tag{11}$$

7.

$$x^{k+1} = x^k - \Delta^k. \tag{12}$$

The variable Δ is an additive correcting factor for the unknowns x. Normally, Δ decreases as the iterations progress. When Δ reaches its minimum, then the iteration process should be stopped. Therefore, the "stop" criterion is written as:

8.

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if abs($\Delta^k$) < $\varepsilon$ then
  if abs($\Delta^k$) > abs($\Delta^{k-1}$) then
    stop and go the next time step
  else $k = k + 1$ and go to step 2.
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The algorithm (6)–(12) proves to be very efficient [5]. In practical situations it needs one or two iterations to find a solution (i.e., the submodels are typically called two or four times).

V. LINKING DIFFERENT SIMULATION TECHNIQUES

Assume, some of the submodels in a complete system are accomplished as phasor-type solutions with the rest of them as waveform-type solutions. To connect these two "genders" one needs two extra blocks: phasor-to-waveform and wave-form-to-phasor converters (Fig. 7). The phasor-to-waveform converting block is a trivial signal generator controlled by the triple: amplitude, phase, and frequency. The waveform-to-phasor converter may employ any digital signal processing technique such as Discrete Fourier Transform (DFT). Again, by a phasor we mean the triple: amplitude, phase and frequency.

Having the two types of models connected via the appropriate converters, the solution of the complete system involving both types of models is supported by the iteration algorithm (6)–(12).

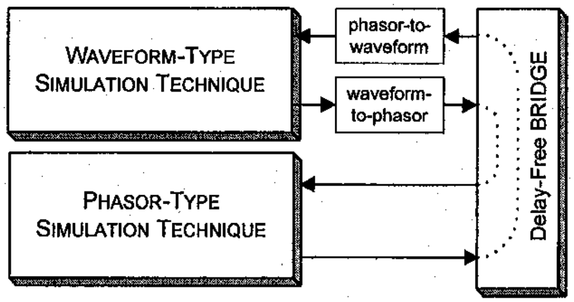

Fig. 7. Linking waveform-type and phasor-type simulation techniques.

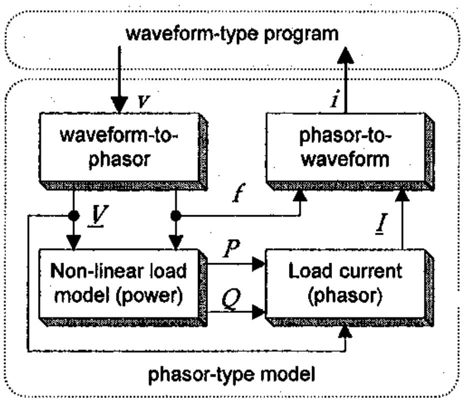

Fig. 8. Linking a phasor-type nonlinear load model with a waveform-type program.

In order to illustrate this approach let us present the practical example. Assume one needs to include the following commonly accepted load model [6]:

$$P = P_0\left(\frac{V}{V_0}\right)^{\alpha}\left(1 + k_P\frac{f - f_0}{f_0}\right),$$
$$Q = Q_0\left(\frac{V}{V_0}\right)^{\beta}\left(1 + k_Q\frac{f - f_0}{f_0}\right) \tag{13}$$

into a waveform-type program. In (13), P and Q stand for active and reactive powers, respectively; V denotes the voltage amplitude; f—the frequency; while the index 0 refers to the rated values; α, β, k_P and k_Q are coefficients. Fig. 8 shows the implementation of the explicit load model (13) as a phasor-type subsystem inserted into a waveform-type transient program.

Generally, the waveform-to-phasor and phasor-to-waveform conversions may be referred to as "analysis" and (12) "synthesis" operations, respectively. The analysis module providing a connection between the waveform-type model and the phasor-type model may extract more information from the waveform, than just the fundamental frequency phasor. This may include the amplitudes and phases of harmonics and subharmonics as well as parameters of decaying d.c. components (Fig. 9). If a given harmonic is present in the waveform-type part and is not represented in the phasor-type part, then either an open- or short-circuit is virtually seen from the waveform-type part depending on the nature of the boundary signals. If current is the output from the waveform-type part, and voltage is the input, then the phasor-type part is seen as a short-circuit (zero

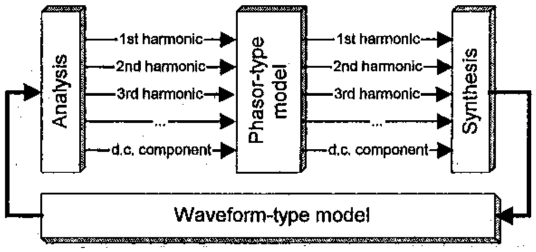

Fig. 9. General linkage between the phasor-type and waveform-type models.

voltage and non-zero current of a given harmonic). For the voltage (output from the waveform-type part)—current (input) arrangement, the phasor-type part neglecting a given harmonic is seen as an open circuit for this harmonic (zero current under non-zero voltage).

The phasor-type model may be solved consecutively for each component of its input signals (i.e., for the fundamental frequency component, given harmonics and subharmonics, etc.). The selection of the signal components taken into account when linking the waveform-type and phasor-type models should be driven by the nature of the modeled elements and the purpose of simulation. For example, for the static VAR compensator, it may be justified to provide the characteristic of the device not only for the fundamental frequency, but for higher harmonics as well.

Once the phasor-type model is solved (for each signal component), its waveform-type response is synthesized as shown in Fig. 9.

The outlined mode of simulation centers itself between two extremes. The complete waveform-type model of a given element is one of them. The simplified fundamental frequency based characteristic of the element is the opposite extreme. Depending on the purpose of simulation and the available data, the proposed approach may be a vital alternative to both the complete and simplified models.

Another interesting issue is the presence of the "analysis" and "synthesis" operations within the iteration loop and their impact on numerical stability.

The analysis block needs the present sample of the waveform as well as certain number of back (historical) samples (typically stretched over one full cycle of the fundamental frequency). As illustrated in Fig. 10 the back samples are fixed since they were computed in the previous time steps. The present sample, though, is still under iterations since the solution for the present time step is just being sought. Certainly, the values returned by the waveform-type model in consecutive iteration steps affect the estimate of the phasor. However, the procedures for extracting a phasor such as DFT provide a kind of averaging and the present sample (being iterated) is weighted with the back samples (fixed). This takes a positive effect on the numerical stability of the iteration process.

With reference to Fig. 10, the phasor-type model is fed with a phasor from the analysis block and responds with an output phasor. This phasor is next synthesized into a corresponding waveform and the waveform is fed back into the waveform-type model. The value of the variable at the present time step is required only. However, the phasor may be represented by a waveform for the back samples as well. But the historical samples (black marks in Fig. 10) are already solved and there is no way to correct their values to reflect the newly computed phasor (white marks in Fig. 10).

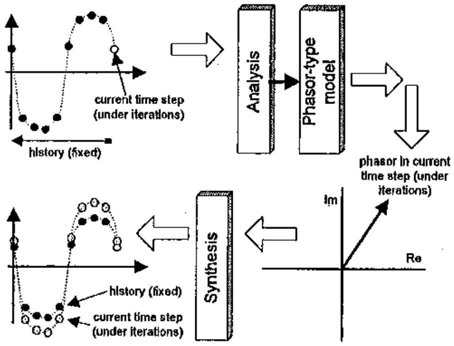

Fig. 10. Illustration of the analysis and synthesis blocks in the iteration process.

This phenomenon is a source of some error and takes certain negative effect on the numerical stability of the iteration process.

Consequently, the cuts between the waveform-type and phasor-type models are recommended to be done across signals that do not vary much from sinusoids during simulated events, and when in addition, the changes in the amplitude and phase of such signals are not abrupt.

VI. SIMULATION EXAMPLE

The system shown in Fig. 3 has been used as a numerical example. For the illustration purpose various representation techniques are used in this simple system:

- The 819 MVA, 26 kV, 60 Hz generator, G, is modeled using the internal FM approach as a connection of the turbine, the excitation system and the SM itself (Fig. 5). The latter is represented by the Park's equations and solved with 5 μs time step. The turbine equation is solved with a 10 ms time step.
- The transformer, T, is modeled as coupled RL coils with the saturation branch included.
- The parallel transmission line, L, is represented by a series of π-sections.
- The **Load** is modeled in the phasor-domain (Fig. 8).
- The system, S, is also modeled in the phasor-domain and includes representation of an equivalent machine [6].

A line-to-line-to-ground fault occurs at the generator's terminals at $t = 0.1$ s and gets cleared at $t = 0.35$ s. Fig. 11 presents the generator's terminal currents. Fig. 12 displays the signals between the turbine, the excitation system and the SM (see Fig. 5). Fig. 13 shows the selected internal variables of the Park's model of the SM.

This simple model has been investigated from the numerical point of view. The main conclusions are:

- The algorithm (6)–(12) ensures good convergence.
- The average number of iterations (6)–(12) needed to find a global solution is below two per time step.
- Prediction, (6), improves convergence. The optimal order of a predictor is two regardless of the type of a predictor.

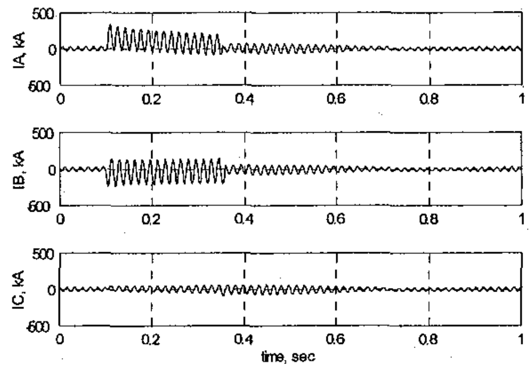

Fig. 11. Generator's currents.

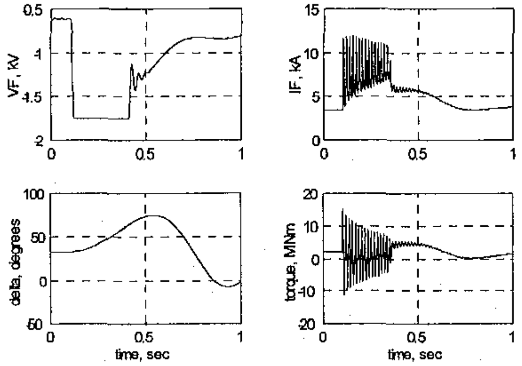

Fig. 12. Generator's boundary variables (see Fig. 5).

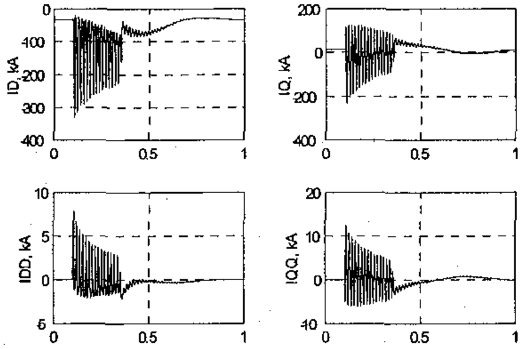

Fig. 13. Internal variables of the generator model.

The simulation results have been compared with EMTP. The FM algorithm facilitating flexible usage of various simulation techniques gives exactly the same solution as EMTP as long as the mathematical models of the simulated elements are the same. For this simple model the efficiency of the presented approach is similar to the EMTP performance. For larger networks with expansive equivalencing, the new method over performs the EMTP-type programs.

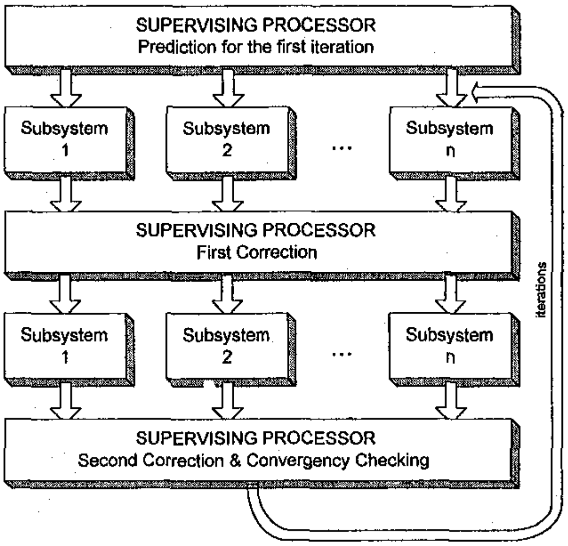

Fig. 14. The presented simulation method applied in the parallel processing environment.

VII. ADVANTAGES

The simulation method presented has numerous advantages and potential applications.

A. *Efficiency of Simulation (Speed versus Cost)*

The gained efficiency enabling faster simulation of larger systems with limited computational power results from the following:

- Each waveform-type model may be solved with its own time step using its own numerical integration method. The elements having long time constants could be solved with longer time steps saving considerable processing time (see the previous section for illustration).
- When a subsystem is an island detached by transmission lines (traditional decomposition), it is called only once in the presented iteration algorithm (6)–(12) because as decoupled, such a subsystem does not require any iterations. Naturally, this speeds-up computations.
- The models implemented in the phasor-domain or those implemented in the time domain but having longer time constants, may be called upon conditionally. If their inputs do not change significantly, those models are not executed and the previous time step values are assumed as their outputs saving considerable computational time.
- Closed loop testing of protective relays is a special mode of simulation. By their action, the relays can change the topology of the power system. The topology, however, in the presented approach is stored in the balance equations separately from the subsystems which suits very well this kind of modeling.

B. *Utilization of Parallel Processing*

The proposed simulation method suits very well parallel processing (Fig. 14). Each subsystem may be solved on separate

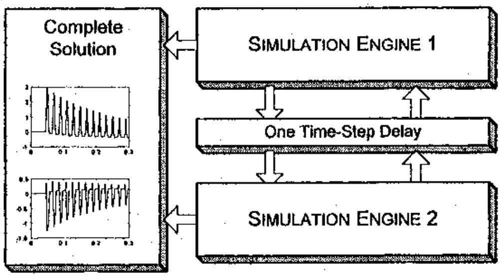

Fig. 15. Classical linking of two simulation engines (a typical example: EMTP and MATLAB).

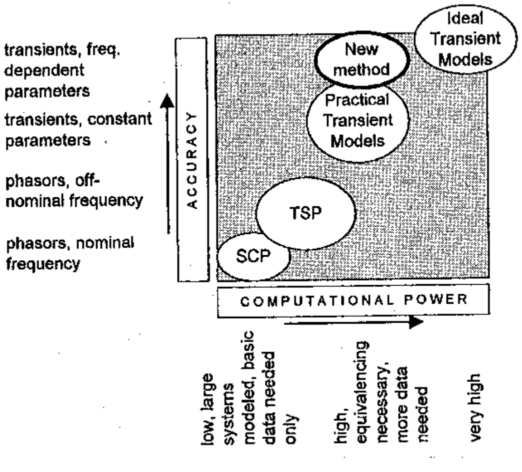

Fig. 16. Accuracy/efficiency map of various simulation techniques.

computational node (processor). The iteration process is controlled by an extra Supervising Processor (SP). Using such an organization, the data is exchanged only between the computational nodes and the SP. The SP also decides if and when to call a given model.

The presented approach enables efficient real-time simulation of large power systems. The subsystems may be implemented on separate microprocessors or, to accelerate the execution, using dedicated VLSI chips. A separate processor or programmable connection matrix implemented using VLSI would have access to present topology of the simulated power system and would establish a mirror connection between the subsystems in the model. The model developing and maintaining processes in this approach take advantage of the functional and hierarchical structure of the modeled power system.

C. Linking Separate Simulation Programs and Simulators

From the rigorous numerical point of view, diverse simulation engines such as EMTP and user written code such as MATLAB programs when linked together into one simulation application, provide approximate solution because they exchange their boundary signals with one time step delay (Fig. 15), [7], [8]. This is less important when considering simulation of controllers or relays where the reaction time of such elements is much longer than the simulation step. However, when one is simulating parts of a power system per se, such as surge arresters, using detailed models written outside the main simulation engine, one may face both the accuracy and numerical stability problems.

The iteration process proposed in Section IV is a remedy for this problem. The two or more simulation engines are treated as subsystems. The signals exchanged between them constitute the topology. The accurate delay-free solution of the entire simulated system is obtained by employing the procedure (6)–(12).

This approach may also be extended on two or more physical digital simulators developed and programmed separately. The algorithm (6)–(12) implemented on one of the simulators enables delay-free bridging between them.

D. Flexibility

The presented method enables flexible balance between the key issues of size, accuracy, speed and cost of simulation. Fig. 16 illustrates the relationship between the accuracy of simulation and the required computational power. Or, in other words, between the accuracy and the size of the system that can be simulated using given resources in given time.

The approach presented in this paper relaying on decomposition and combining diverse models, enables one to gain the efficiency of simulation without loss of accuracy. The latter is basically achieved by "zooming" in and out the models and the resulting accuracy depending on the purpose of simulation.

VIII. CONCLUSIONS

The paper presents the new approach to system decomposition and to accurate delay-free linking of diverse simulation techniques and engines. The method enables one to include different techniques such as waveform-type, phasor-type, and algebraic-type simulation techniques into one complete model. The rules of decomposition as well as the iteration process organizing the computations in different subsystems are presented. The proposed iteration algorithm ensures fast and stable solution of the complete system and suits very well parallel processing.

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