REAL TIME DYNAMIC SIMULATION OF POWER SYSTEM USING MULTIPLE MICROCOMPUTERS

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Abstract Recent developments in the design and manufacture of microcomputers together with improved simulation techniques make it possible to achieve the speed and accuracy required for the dynamic simulation of power systems in real time. This paper presents some experimental results and outlines new ideas on hardware architecture, mathematical algorithms and software development for this purpose. The results of power system studies are discussed, and a new system formulation is proposed in which the state equations and electrical network equations are partitioned; the network equations being solved separately on a host processor while the state equations of each generating unit are solved on slave units. A transputer based, parallel processing system connected to micro VAX computer is proposed for the simulation of the dynamics of a power system in real time. Such a simulator can be used for the evaluation of instability over a long period of time resulting from persisting faults and for the study of voltage collapse phenomena in power systems.

چکیده پیشرفتهای تازه در زمینهٔ طراحی و ساخت میکروکامپیوترها و تکنیکهای ریاضی برای شبیه‌سازی کامپیوتری امکان افزایش سرعت و دقت لازم را برای شبیه‌سازی دینامیکی رفتار سیستمهای قدرت تا حد ریل تایم (زمانی که واقعاً پدید در سیستم اتفاق می‌افتد) فراهم کرده است. این مقاله نتایج تجربیات عملی بدست آمده در این زمینه را ضمن ارائه خلاصه ایده‌های تازه برای ساختار سخت‌افزاری، نحوهٔ بیان مناسب معادلات حالت و نرم‌افزارهای مربوطه ارائه می‌دهد. نتایج حاصله از مطالعات سیستمهای قدرت مورد بحث قرار گرفته و فرم جدیدی برای بیان ریاضی معادلات سیستم پیشنهاد شده که در آن معادلات دیفرانسیل متغیرهای حالت و معادلات شبکه از هم جدا شده‌اند بطوریکه معادلات شبکه روی میکروکامپیوتر مادر و معادلات حالت جداگانه و همزمان روی میکروکامپیوترهای وابسته حل می‌شوند. یك سیستم ترانسپیوتری که قادر به انجام فرآیندهای موازی است متصل به یك کامپیوتر مایکرووکس بمنظور شبیه‌سازی دینامیکی سیستم بصورت ریل تایم پیشنهاد شده، یك چنین سیستمی می‌تواند برای مطالعات ناپایداری دینامیکی سیستم در نتیجهٔ خطاهای ماندگار و مطالعات پدیدهٔ کلپس ولتاژ در سیستمهای قدرت مورد استفاده قرار گیرد.

INTRODUCTION

The dynamic behaviour of power systems is now well documented. Mathematical models are available to represent different parts of the system: prime movers, generators, transformers, lines and loads in varying degrees of detail [1-3]. Software packages are now available to simulate system dynamics. They can evaluate and monitor state variations during any time interval due to different disturbances. They can also advise as to which mathematical models are appropriate for a particular type of study.

Generally, dynamic simulation requires solution of a set of nonlinear algebraic and differential equations which describes the dynamics of the power system [4]. Apart from input / output software that accompanies these software packages to facilitate man- machine interaction, the main feature of them is to solve these sets of differential and algebraic equations. An important feature of a dynamic simulator however, is the amount of computational effort required to simulate a particular dynamic problem in power system.

In modern control centres, there is an increasing interest in using real time simulators as a power system test bed for operational planning and for dispatcher training [5, 6]. With recent developments in the design of fast microcomputers as building blocks for parallel processing, and the use of improved techniques for simulation, the speed and accuracy required for real time simulation can be achieved for problems which require more detailed models for system representation [7, 8].

This paper outlines some of the efforts currently going on in this area in the Energy and Power Systems Group at Imperial College [9, 10]. In this work, a previously tested software package which was originally developed to simulate power system dynamics for real time control experiments, has been adapted to run on a microprocessor with available software support. Modifications are then implemented to achieve fast dynamic response by using the minimum number of states, to decompose the state equations of generating units from one another and from those of the network equations, and to facilitate the control of timing and input/output of the simulation to achieve the real time speed of simulation.

The main difficulty in achieving a real time speed of simulation being the number of state equations in each generating unit. The simulation is limited to those dynamic behaviours of the system which are within the proposed time range for a reasonable degree of accuracy.

SYSTEM MODELLING

A classification of dynamic problems in power system studies and appropriate component representation is evaluated and given in reference 27. The mathematical model has been selected such that simulation can be made of power system problems in the time range of one tenth of a second to several minutes of real time after a disturbance, thus making it possible to simulate major disturbances in power systems such as:

- a major loss of generation, leading to large power flow changes and operation of protective relays
- a series of faults and / or protective gear failures resulting in a system split, with major imbalances of generation
- steady state instability e. g., low frequency power oscillations over weak tie lines coupling pools and utilities.

In general a state space representation is used for generating units consisting of generator electrical equations, AVR and excitation system, turbine and generator inertia, turbine and boilers, governor and speed control and power stabiliser. Non-linearities are taken into account, and the state equations are partitioned in different groups, where each group consists of a set of linear state equations which can be treated independently and separately from algebraic equations which represent at network frequency and voltage dependant loads in each time step. Automatic protective gear operations are also modelled both for generator and transmission plant.

GENERATING UNITS

The state equations of each generating unit can be considered as follows:

$$\begin{aligned} \dot{X}_1 &= f_1 (X_1, V_{g1}, I_{g1}, U_1) \text{ with: } \dot{X}_{min} \leqslant \dot{X} \leqslant \dot{X}_{max} \\ \dot{X}_2 &= f_2(X_2, V_{g2}, I_{g2}, U_2) \qquad X_{min} \leqslant X \leqslant X_{max} \end{aligned} \quad (1)$$

. . . .

where X is an n vector denoting states of generating unit 1, f_1 is an n vector of nonlinear functions, V_{g1} and I_{g1} are output voltage and current components and U_1 is the vector of controllable set points at each generating unit. The initial condition of the system $X(t_o)=X_o$ is evaluated after a simple load flow and using the predisturbed condition of the system. The state equations are solved simultaneously at each time step using a trapezoidal integration routine.

Apart from the limits applied on the states and rate of changes, each set of state equations is independent and linear, assuming V_g and I_g are constant in each iteration during one time step. These equations can be solved and new values of voltage components evaluated for each generator at the end of each iteration in one time step. It can be shown that these state equations are linked together by the algebraic equations (2) which represent the rest of the system.

$$g(X, V_g, I_g) = 0 \quad (2)$$

where g is an n vector of complex functions, X is an m = n. k, vector denoting all the states of the system, m is the number of generating units, and k is the number of states in each generating unit.

At least nine state equations are required to simulate the dynamics of each generating unit: two for inertial equations three to represent the AVR and excitation system, one for the governor, two for a reheated steam turbine and one for the generator with its rotor open loop time constant when represented by a voltage source $\acute{E}$ behind transient reactance $\acute{X}_d$, when saliency and short term transient effects are not simulated.

The number of states can be increased to seventeen for each generating unit [11] taking into account the effect of a power stabilizer or detailed turbine model, speed control system and generator by increasing the simulation response. The number of generating

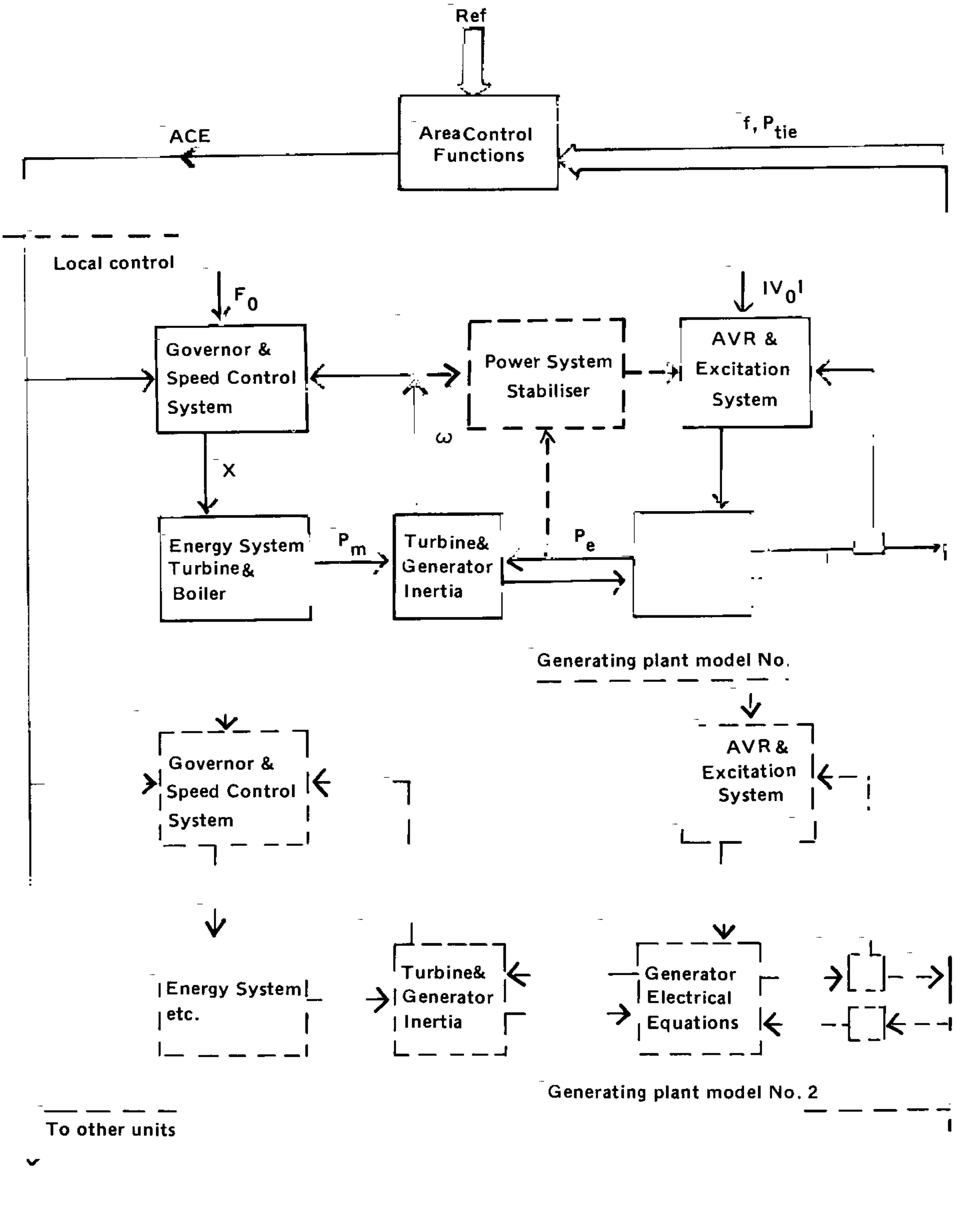

Figure 1. Interdependencies of state variables in one generating unit and with network equations

units however has little if any effect on the speed of simulation due to hardware design.

LOADS, LINES AND TRANSFORMERS

Interconnecting lines and transformers are considered as an n2 port ac network using complex single phase per unit values. A nodal admittance matrix method is applied, thus imbalances and short term transient effects are neglected. In practice the equivalent network of long transmission lines can be used and many lines can be lumped into their electrically nearest bus.

Loads are generally represented by their predisturbed equivalent admittance for short circuit and line outage studies, although there is the possibility of considering a more detailed model at some load busbars in this type of study. This makes it possible to represent the loads in the admittance bus matrix [12].

$$\begin{bmatrix} I_g \\ I_l \end{bmatrix} \begin{bmatrix} Y_{gg} & Y_{gl} \\ Y_{lg} & Y_{ll} \end{bmatrix} = \begin{bmatrix} V_g \\ V_l \end{bmatrix} \quad (3)$$

A nodal elimination can then be used for some of the loads to reduce the number of equations to a minimum possible. In its simplest form where all loads are represented by constant admittances, we have

$$I_g = (Y_{gg} - Y_{gl}.Y^{-1}_{ll}.Y_{gg})V_g \quad (4)$$

where subscripts g and l refer to quantities associated with generator and load busbars, respectively.

For loading disturbances however, or small perturbations in generating units, load bus bars are simulated as absorbing active and reactive power using a linear model for their voltage and frequency dependencies as follows:

$$\begin{aligned} P_l &= P_o(V/V_o)^{pv}.\ (f/f_o)^{pf} \\ Q_l &= Q_o(V/V_o)^{qv}.\ (f/f_o)^{qf} \end{aligned} \quad (5)$$

where P_l and Q_l are load active and reactive power p_v, p_f, q_v and q_f are their voltage and frequency dependencies. Linearising these equations:

$$\begin{aligned} \Delta P_l &= p_v \Delta V + p_f \Delta f \\ \Delta Q_l &= q_v \Delta V + q_f \Delta f \end{aligned} \quad (6)$$

These equations are added to the load flow equations and solved simultaneously with the network equations at each time step.

PROGRAM DEVELOPMENT

In the first stage a high level language program, previously developed for real time control experiments, was adapted and tested for fast dynamic simulation. System equations in this program are then modified to conform with the new decomposed representation.

The general construction of the program is also modified to run on a microcomputer under the DOS operating system. Two software packages have been added to the main package to facilitate input/output control during the simulation and to control the actual timing required at different stages of computation and data transfer. High level language was used in this stage with a fast compiler, on a conventional single processor equipped with a medium range coprocessor. In a later stage, PASCAL was used with a Turbo compiler which gave better results. This program is then modified for parallel processing using a parallel compiler and OCCAM as a harness language [14].

An implicit trapezoidal integration routine is used at this stage and the solution is converged for a reasonable degree of accuracy after about three iteration in average in each time step. Other integration methods have been tested and it appears that for a large number of generating units the amount of time spend for data transfer between different microprocessors must be taken into account for the best selection of the integration routine [15].

SOLUTION ALGORITHM

Figure 1 shows the dependencies of state variables of each generating unit on one another and on those of the network equations. The structure of the solution algorithm will be such that the state equations of the generating units will be solved in parallel. This conforms with the nature of the equations and will fit well [13] into the hardware architecture given in Figure 2.

When the state equations (1) are solved at the end of each time step, the values of v_d and v_q of each generating unit are sent to the host processor. The values of I_g are then calculated in the host by equation (3) for all the units. These values are each transferred to their appropriate processor used in equations (1) to find new state values and new V_g at the end of time step k+1. Other important states calculated at the end of each time step can be transferred for monitoring while the network equations are being solved.

A flow chart representing the general construction of the solution algorithm is given in Figure 3.

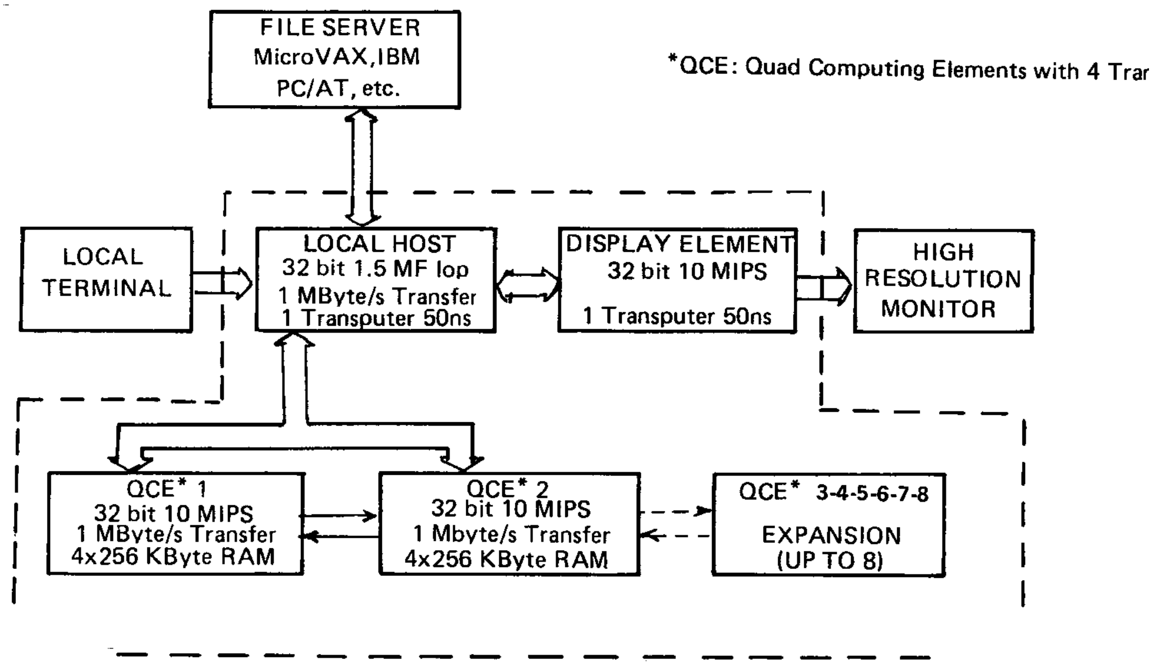

Figure 2. Basic hardware.

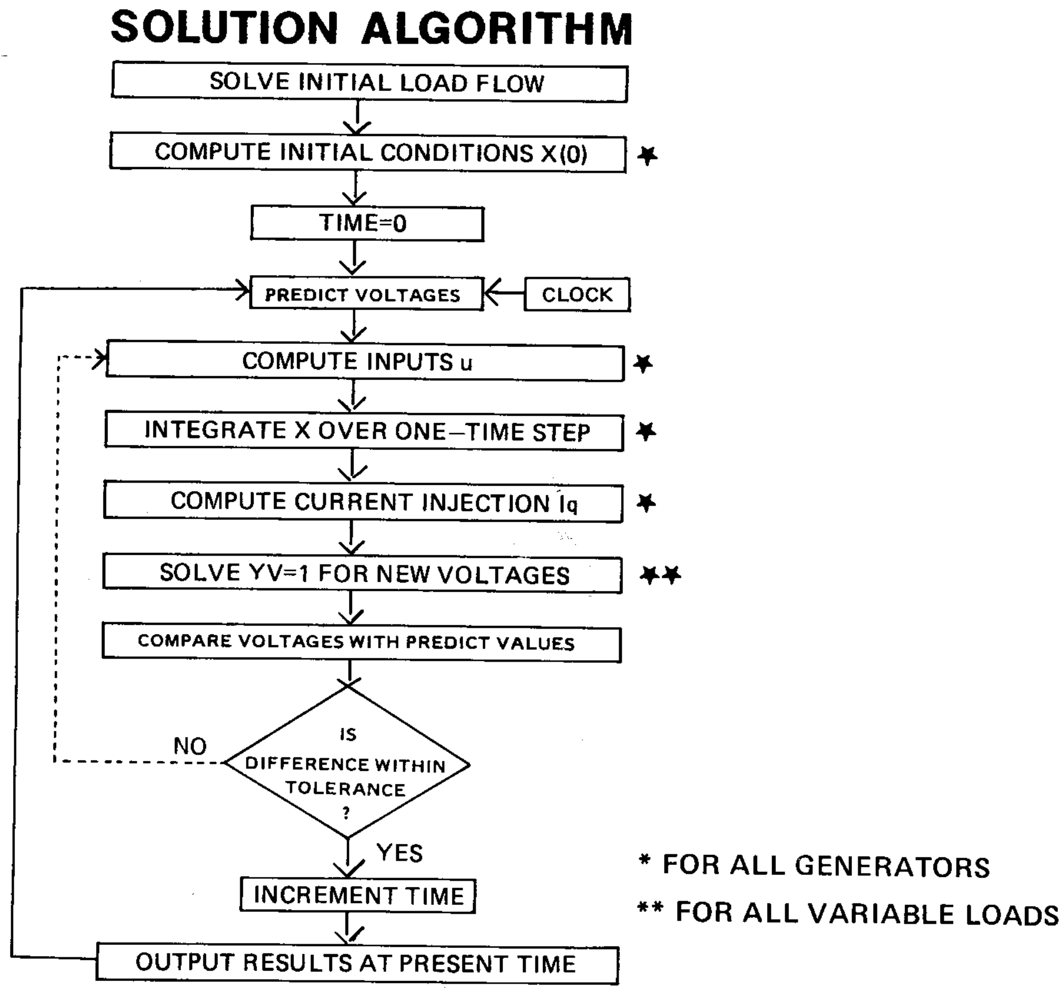

Figure 3

HARDWARE REQUIREMENTS

The state equations of the generating units are to be processed on a number of microcomputers in parallel. The required information in each processor at this stage includes the equations, intergration parameters values of I_g, values of states and derivatives of them at previous time steps, depending on the nature of the intergration routine. Each microcomputer should also be given the integration routine and input / output instruction routines. Routines with equations and integration parameters are filed at the start by the fileserver to the host and distributed among parallel units as appropriate. It is also required that each microcomputer communicates with the host to transfer state information from the host where a real time clock controls the whole process at the end of each time step.

Figure 2 shows the proposed basic hardware requirements using modules containing Transputers [14]. An IBM PC/AT, MicroVax or any similar system can be used as the fileserver connected to the host by a serial port.

A 32 bit, 20 MHZ processor is generally used with a speed of 1 Mbyte/s for data transfer. A high resolution TV monitor connected by a display processor to the system simulator will serve to display the different states or variables in the system. Other peripherals may be used to facilitate input/output transfer for various training procedures.

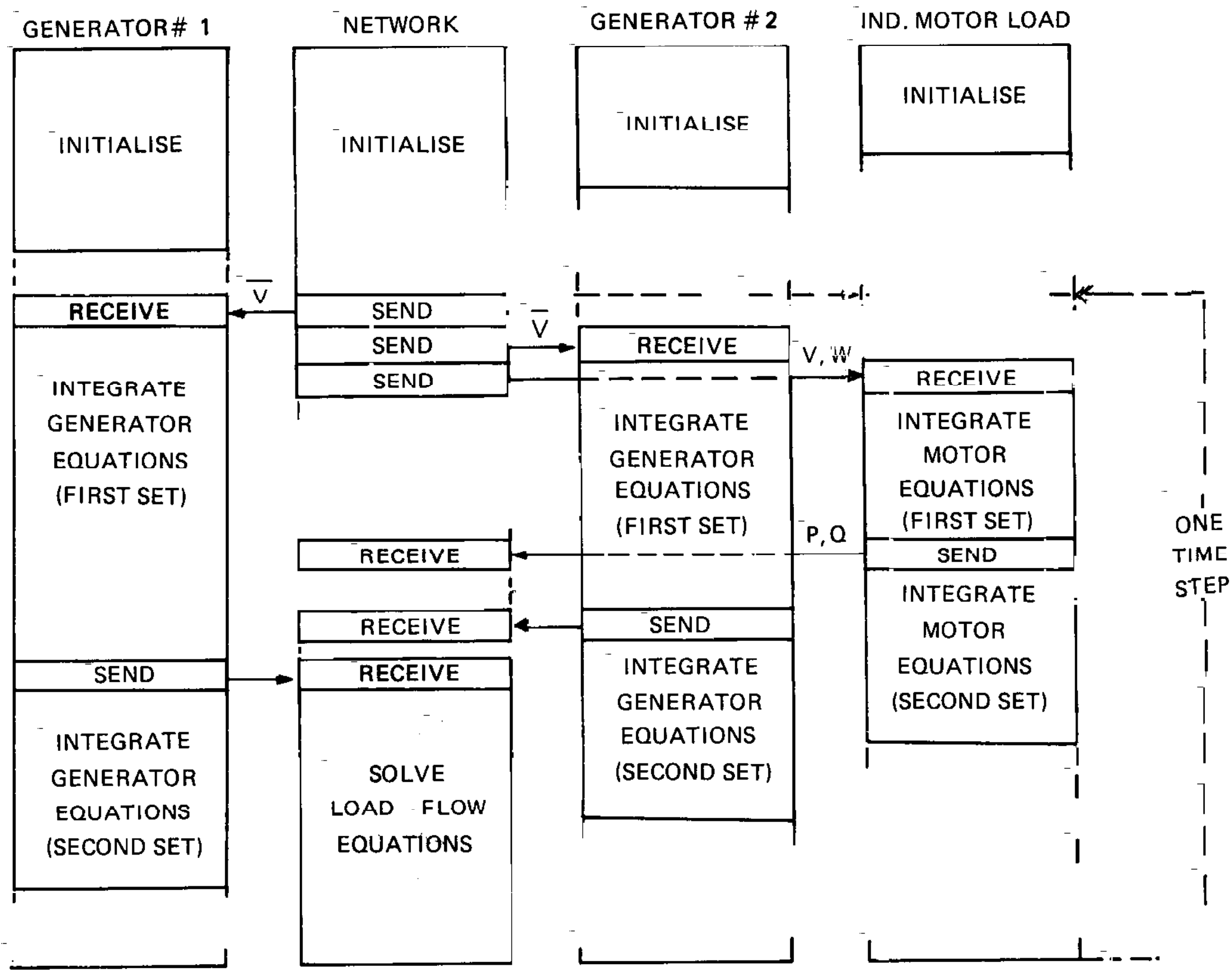

Figure 4. Parallel simulation of a transient study using four microprocessors.

CONCLUSION

Multi-microcompter simulation of power system dynamics produces a more economical solution when compared with conventional main frame, single processors or array processors computing system. The actual speed limit for simulation of dynamic stability for a system with few generating units using the conventional hardware structure at its best is less than one tenth of the real time for a reasonable degree of accuracy. Figure 4 represents a comparison of simulation time spend in one time step for transient stability using four microprocessors with the suggested method and conventional single processor simulation.

Simulation experiments using the decomposed model of the generating units, as explained in this paper, suggest that the algorithm can fit into a parallel hardware structure as defined in Figure 2. In this way, an increase in the number of generating units, as might occur in an industrial application has no effect on the total simulation time. In this way particular dynamic behaviour of power system can be simulated in real time, thus making it an innovative method for more accurate training simulator [16] in the future control centres.

A large proportion of the total processing time is spent on data transfer to save the states at the end of each time step and to retrieve the data for monitoring and solving network equations. It is essential, however, to keep the output information required to the minimum possible to avoid undue delays.

The processing time is normally longer in the initial period after a disturbance due to fast transient effects. This may be compensated for in later time steps. This is a price which has to be paid in some applications for more accurate simulation over a longer period of time.

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