A VIRTUAL TEST BED FOR PEBB-BASED SHIP POWER SYSTEMS

ANNUAL TECHNICAL REPORT

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Submitted

by

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on behalf of the project team

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Volume II

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PREFACE

This technical report is primarily a compilation of presentations made at the annual project review meeting held on June 3-4, 1997 at the University of South Carolina. Additionally, this report includes an introduction to the project, and copies of papers that were written under the sponsorship of this grant during the past year.

Any questions regarding the content of this report or specifics of the project can be addressed to

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INDEX

PUBLICATIONS INDEX

Volume III

"A time domain model for flicker analysis", A.P. Sakis Meliopoulos and G. J. Cokkinides, IPST '97, October 1997.

"Wavelet-based transient analysis", A.P. Sakis Meliopoulos and Chien-Hsing Lee, 29th North American Power Symposium, Oct 13-14, 1997.

"An efficient and accurate method of incorporating magnetic saturation in the physical-variable models of synchronous machines" S. D. Pekarek and E.A. Walters,

"A fast and efficient multi-rate technique for detailed simulation of AC/DC power systems", S. D. Pekarek, O. Wasynczuk, H.J. Hegner,

"Digital tracking control for PWM systems with unacceptable zeros", M. Al-Numay and D. Taylor, submitted to IEEE Trans. on Circuits and Systems - special issue on Simulation, Theory, and Design of Switched-analog Networks.

"Adaptive control of DC motor drives with converter nonlinearities" W. Khan and D. Taylor, submitted to Intern. Journal of Control

"Adaptive control of DC motor drives with inverter nonlinearities" W. Khan and D. Taylor, submitted to Intern. Journal of Control

"Modeling and control of digital PWM systems using averaging" M. Al-Numay and D. Taylor, submitted to IEEE Trans. on Control Systems Technology

"Polymer current limiters for low-voltage power distribution systems", M. H. McKinney, C.W. Brice, and R.A. Dougal, IEEE Conf on Industrial and Commercial Power Systems, May 1997, Philadelphia, PA.

"Global Asymptotic stability of indirect field-oriented speed control of induction motors", L. Gokdere, M. A. Simaan, and C. W. Brice, submitted to Automatica

"A passivity-based controller for saturated induction motors" L. Gokdere, M. A. Simaan, and C. W. Brice, submitted to IEEE Trans on Control Sys Tech

"Incorporation of magnetic saturation effects into passivity-based control of induction motors", L. Gokdere, M. A. Simaan, and C. W. Brice, submitted to IEEE Trans. on Industrial Electronics

"A comparison of passivity-based and input-output linearization controllers for induction motors" L. Gokdere, M. A. Simaan, and C. W. Brice, accepted for presentation at IEEE Emerging Technologies and Factory Automation Conf., Sept. 9-12, 1997, Los Angeles, CA.

"Speed estimators for indirect field-oriented control of induction motors" L. Gokdere, M.A. Simaan, and C.W. Brice, accepted for IEEE Emerging Tech and Factory Automation Conf., Sept. 9-12, 1997, Los Angeles, CA.

"A passivity-based controller for high-performance motion control of induction motors", L. Gokdere, M. A. Simaan, and C. W. Brice, accepted for presentation at IEEE Power Electronics Specialists Conf, June 22-2- St. Louis, MO.

INTRODUCTION

The Power Electronic Building Block (PEBB) will enable the Navy to meet DOD and Navy goals of reduced manning, reduced cost, increased effectiveness and enhanced survivability by allowing radically new architectures for shipboard power systems. Since these new architectures cannot be based on historic design precedents and time-and-field-tested design rules, extensive prototyping and testing are necessary. These prototypes are used to validate the designs and to define the operational envelope, in both intact and damaged conditions. The use of virtual prototypes, rather than hardware prototypes, allows the US Navy to maintain its technological superiority by exploiting its dominant position with respect to information technologies.

The Virtual Test Bed (VTB) provides a unique capability for virtual prototyping of PEBB devices and of PEBB-based electric power systems by integrating into a single simulation environment models that have been produced in a variety of simulation languages by a diversified and multi-technical design team.

Those who develop new pieces of the shipboard power system often (and for good reasons) use different software tools for different modeling tasks. Since a system is composed of many such entities, and the system must be tested as a whole, one encounters the need to compute the performance of a system described by a heterogeneous collection of models. The primary objective of the VTB project is to create the virtual prototyping environment that accepts this heterogeneous collection of models and integrates them into a single simulation so that a design engineer can evaluate and understand the dynamic performance of the entire system. The VTB

- allows closer collaboration amongst experts in different fields
- allows each expert to use the best design tools and best design practices within their own area of expertise
- allows integration of more aspects of the design, including physical configuration, electrical configuration, thermal configuration, etc., into a single virtual prototype
- eliminates the need for manual translations of models while exploring system response
- allows more rapid exploration of a larger design space to yield more optimal designs
- provides more advanced visualizations of system performance to help build an intuitive understanding of the influence of controllable parameters

The approach chosen for creating the VTB's mixed-language virtual prototyping environment involves *translation* of the source models into the VTB internal language. This provides a flexible, powerful, robust, and extensible means for integrating models into a unified simulation environment. In addition to developing the model translation technologies, the VTB project also advances other technologies associated with virtual prototyping, including user interfaces, model libraries, execution environments, and visualization tools. These technical advances allow the VTB to fully support development and application of the PEBB.

A secondary objective of the VTB project is to develop a base library of models that can be used in the Virtual Test Bed. These models should execute rapidly, be constructed in such a way that they can be connected to other models, and yet can be written in a variety of modeling/simulation languages. Particularly important to the study of PEBB-based power systems is an accurate model of a PEBB.

The third and final objective of this project is to support development and applications of PEBBs by using existing modeling tools and existing components of the VTB for virtual prototyping of the PEBB before the VTB is fully developed.

The presentation materials that follow describe a majority of the technical work that was performed under the auspices of this grant during the past year. Time constraints during the meeting prevented the presentation of all aspects of all work that was performed, but this report provides a fair cross section and a useful summary.

Somewhat arbitrarily, the report is organized according to the presentation scheme that was used at the annual review meeting. That is, items are arranged according to the site at which work was done, rather than by topic.

Virtual Test Bed

First Year Final Report
June 3-4, 1997

End of First Year Presentations

Faculty
George J. Cokkinides
Elias N. Glytsis
A. P. Sakis Meliopoulos
Andrew F. Peterson
David G. Taylor

Graduate Research Assistants
Mohammed Al-Numay
Milad Adel Badawi
Douglas Fulcher
Chien-Hsing Lee
Song Li
Charles Thorpe
Karim Wassef

School of Electrical and Computer Engineering
Georgia Institute of Technology
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Virtual Test Bed

Podium Presentations

Network Solver

Approximate Analysis of Permeable Material Power Lines

Rigorous Transient Modelling of Permeable Material Transmission Lines

Modeling and Control of Pulse Modulated Circuits & Systems

Wavelet Based Transient Analysis

Poster Presentations

Analog and Digital Tracking Control of PWM Systems

Adaptive Feedforward Control of PWM Power Converters

Six Pulse Converter Model

Network Solver

Approximate Analysis of Permeable Material Power Lines

Rigorous Transient Modelling of Permeable Material Power Lines

Wavelet Based Transient Analysis

Summary of Activities

Research Activity	Individuals Involved
Transient Modeling of Permeable Material Transmission Lines	Peterson, Prof. Karim Wassef, GRA
Modeling of Permeable Material Conduit Systems Using Quasi-Static Methods	Glytsis, Prof. Meliopoulos, Prof. Douglas Fulcher, GRA
Sampled Data Methods Modeling and Control of Pulse Modulated Circuits and Systems	Taylor, Prof. Mohammed Al-Numay, GRA Song Li, GRA
Network Solver PEBB and Component Modeling Transient Network Analysis via Wavelet Transforms	Meliopoulos, Prof. Lee, Chien-Hsing, GRA Charles Thorpe, GRA Milad Adel Badawi, GRA

Virtual Test Bed

Network Solver

Faculty
George J. Cokkinides
A. P. Sakis Meliopoulos

Properties of Network Solver
For
Virtual Test Bed Application

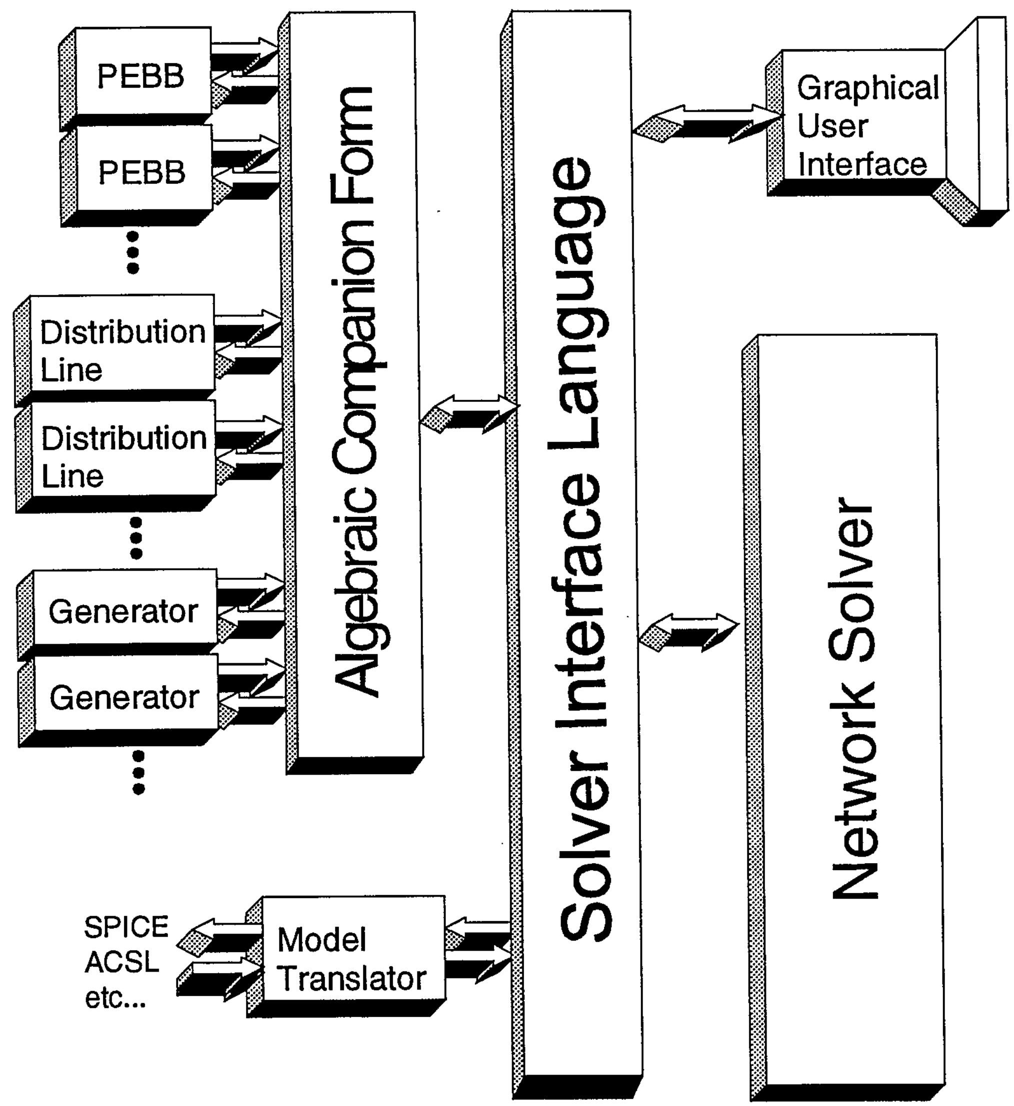
VTB Concept Requirements

Dynamic Range (System Stiffness)
Parameter Changes in Real Time
Real Time Animation and Visualization
Universal Model of Components

VTB Practice Requirements

Convergence
Simultaneous Solution

Network Solver Organizational



Network Solver Technologies

Indirect Methods

Coordinate Method (Gauss)
Annealing

Direct Methods

First Order

Resistive Companion Form
Method of Characteristics
Difference Equations

Second Order

Algebraic Companion Form

Universal Model of Components

Model Equations:

$$\begin{bmatrix} i \\ 0 \end{bmatrix} = \begin{bmatrix} f_1(\dot{v}, \dot{y}, v, y, u) \\ f_2(\dot{v}, \dot{y}, v, y, u) \end{bmatrix}$$

where: i : vector of *interface through* variables,
v : vector of *interface across* variables,
y : vector of device internal state variables
u : vector of independent controls.

Above Equations are integrated to provide:

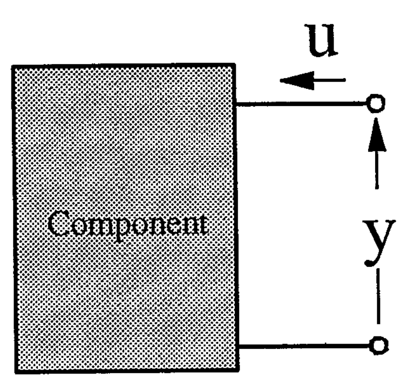
Algebraic Companion Equations:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \frac{1}{2} \mathrm{diag}(v(t), y(t)) \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix}$$
$$+ \frac{1}{2} \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} \mathrm{diag}(v(t), y(t)) \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix}$$

where:
$b_1(t\text{-}h)$, $b_2(t\text{-}h)$ are past history functions.

Algebraic Companion Model

Linear Differential Equation Based Model Translation



Consider a two terminal device with interface variables u and v, specifically:

y is an "**across**" variable.
u is a "**through**" variable.

Equation derived from physical laws is:

$$a_0 y + a_1 y^{(1)} + \ldots + a_n y^{(n)} = c_0 u + c_1 u^{(1)} + \ldots$$

Algebraic Companion Form Modeling

Linear Differential Equation Based Model Translation (continued)

Convert to Canonical Form:

$$\dot{x} = Ax + Bu$$

where:

$x_1 = y - b_0 u$	$b_0 = c_0$
$x_2 = \dot{x}_1 - b_1 u$	$b_1 = c_1 - a_1 b_0$
$x_3 = \dot{x}_2 - b_2 u$	$b_2 = c_2 - a_1 b_1 - a_2 b_0$
...	...

Algebraic Companion Form Modeling

Linear Differential Equation Based Model Translation (continued)

Numerical Integration of Canonical Form (example: trapezoidal rule) yields:

$$x_{k+1} - x_k = \frac{h}{2}\{A(x_{k+1} + x_k) + B(u_{k+1} + u_k)\}$$

rearrange to:

$$x_{k+1} = Du_{k+1} + Cx_k + Du_k$$

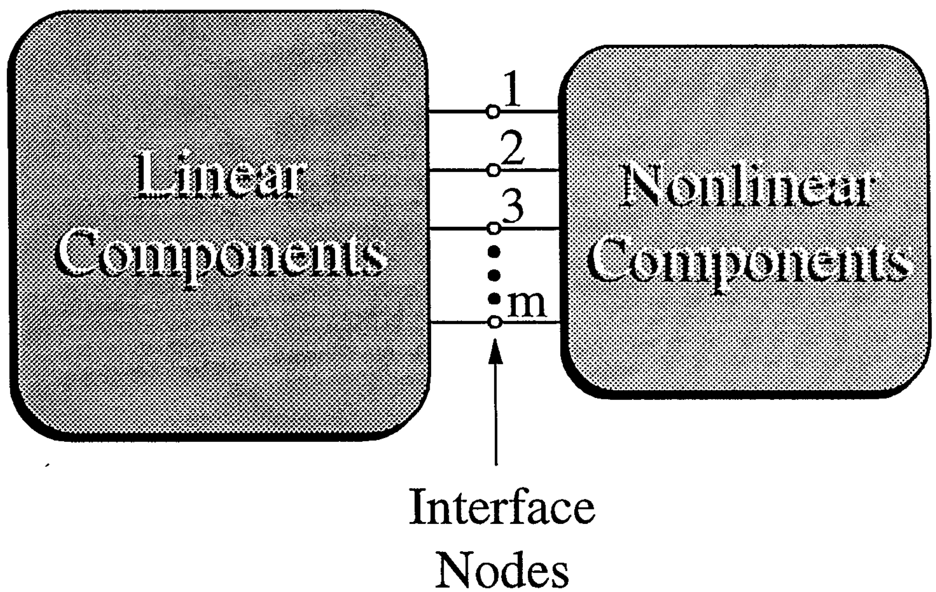
then:

- Identify resistive companion form conductance $\boldsymbol{g}$ by setting past history variables to zero, $\boldsymbol{u}$ = 1 and solving for $\boldsymbol{y}$.
- Derive past history equation by removing $(\boldsymbol{g} \cdot \boldsymbol{u})$ term from above equation.

Algebraic Companion Model

Universal Nonlinear Differential Equation Translation

Identify interface nodes between set of linear and nonlinear components.



Assume Linear Network has l internal states, and m interface nodes to the Nonlinear Network. Furthermore, the nonlinear network has n internal states.

Algebraic Companion Model (ACM)

Universal Nonlinear Differential Equation Translation (continued)

Linear Network **ACM** Equations:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \cdot \begin{bmatrix} v(t) \\ y_L(t) \end{bmatrix} + \begin{bmatrix} B_1(t-h) \\ B_2(t-h) \end{bmatrix}$$

Nonlinear Network **ACM** Equations:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} A_3(v(t), y_N(t)) \\ A_4(v(t), y_N(t)) \end{bmatrix} + \begin{bmatrix} B_3(t-h) \\ B_4(t-h) \end{bmatrix}$$

where $\boldsymbol{A_3}, \boldsymbol{A_4}$ are nonlinear functions.

Algebraic Companion Model (ACM)

Universal Nonlinear Differential Equation Translation

Elimination of the second block row of the Linear Network **ACM** Equations yields:

$$i(t) = D \cdot v(t) + E(t-h)$$

Substitution in the nonlinear network equation yields an equation of the form:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} A_3'(v(t), y_N(t)) \\ A_4(v(t), y_N(t)) \end{bmatrix} + \begin{bmatrix} B_3'(t-h) \\ B_4(t-h) \end{bmatrix}$$

Note that the dimension of the resulting system in only $m+n$.

Algebraic Companion Model (ACM)

Universal Nonlinear Differential Equation Solution **- Newton's Method**

Nonlinear equations are approximated by the following quadratic form:

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = Ax(t) + \tfrac{1}{2}\langle x(t)\rangle Bx(t) + \tfrac{1}{2}C\langle x(t)\rangle x(t) + D(t-h)$$

where the notation $\langle x(t)\rangle$ represents a diagonal matrix whose diagonal entries are the entries of the vector $x(t)$, and:

$$x(t) = \begin{bmatrix} v(t) \\ y(t) \end{bmatrix}$$

Algebraic Companion Model (ACM)

Universal Nonlinear Differential Equation Solution

Using Kirchoff's current law, the currents are eliminated, resulting in the following equation for the entire nonlinear network:

$$0 = Ax(t) + \tfrac{1}{2}\langle x(t)\rangle Bx(t) + \tfrac{1}{2}C\langle x(t)\rangle x(t) + D(t-h)$$

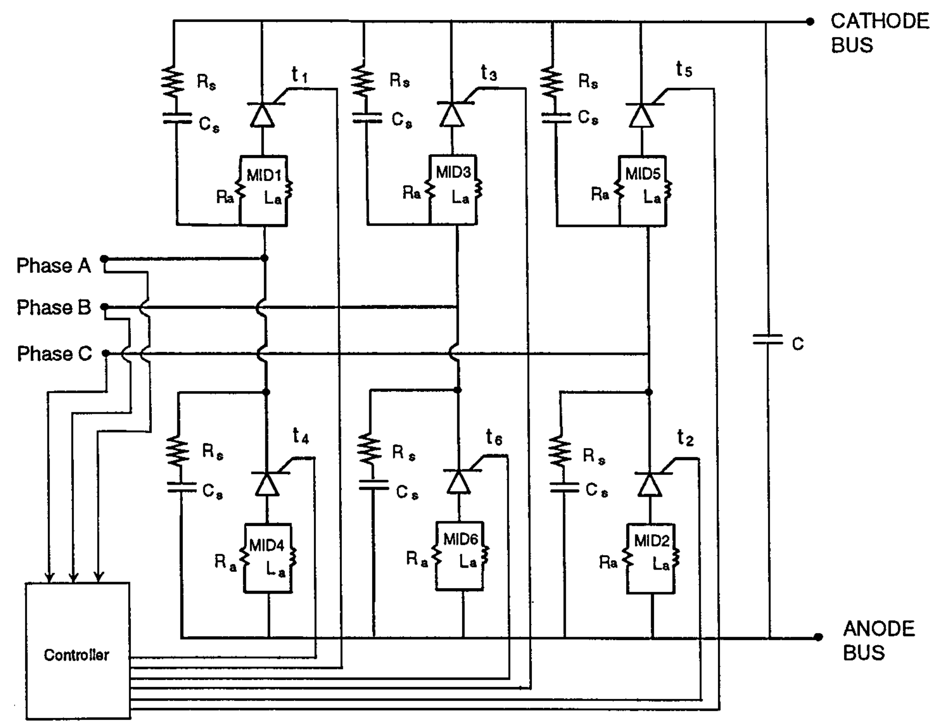
This equation system is solved using Newton's method:

$$x_{k+1} = x_k - \left\{A + \tfrac{1}{2}\langle Bx_k \mathbf{1}\rangle + \tfrac{1}{2}\langle x_k\rangle B + C\langle x_k\rangle\right\}^{-1} E_k$$

where:

- k is the Newton's iteration count.
- E is the mismatch of the previous iteration
- $\mathbf{1}$ is a vector with all entries equal to 1.

Universal Model of Components
Procedural Models – Example

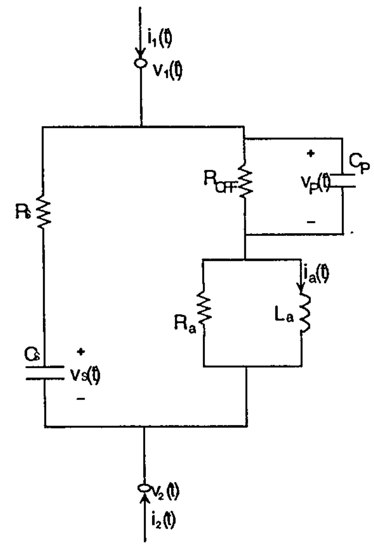


Controller: EquiDistant Control

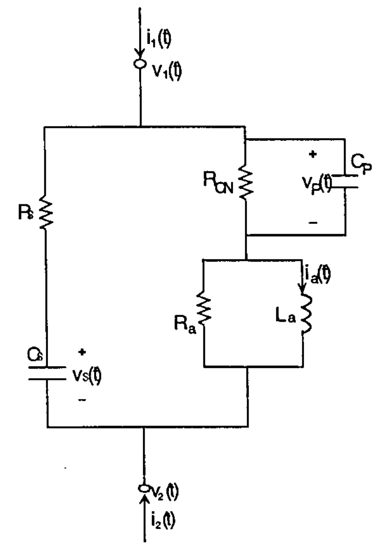
Turn-ON: EquiDistant Control

Turn-OFF: Zero Current Crossing

Universal Model of Components
Procedural Models – Example



VALVE IS OFF



VALVE IS ON

If in OFF-State and Turn-On Condition is Met

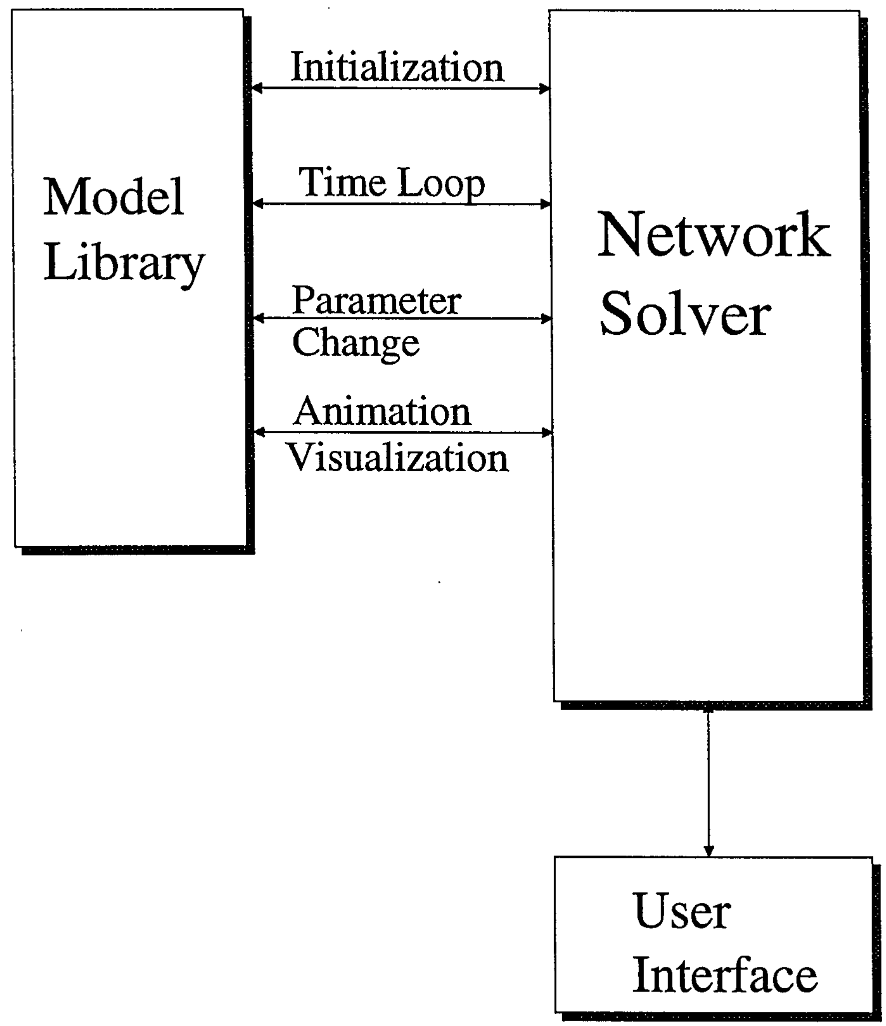
Switch to Model 1

If in ON-State and Zero Current Crossing Occurred

Switch to Model 2

End

Network Solver – Virtual TestBed Interface



Implementation Issues

Unified Model Representation

Algebraic Companion Form

Quadratic Convergence

Support of Other Forms

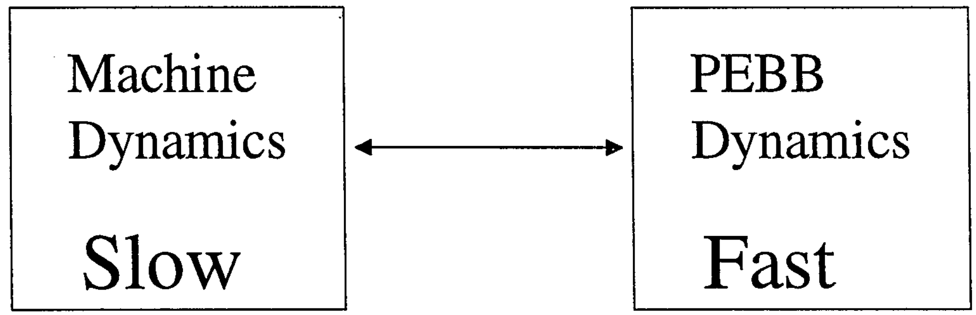
Resistive Companion

Non-Parametric Forms

Block Matrix Based Sparsity Methods (Matrix Topology vs Network Topology)

Proven Minimization of Multiply Adds

Dynamic Range (System Stiffness)



Issues

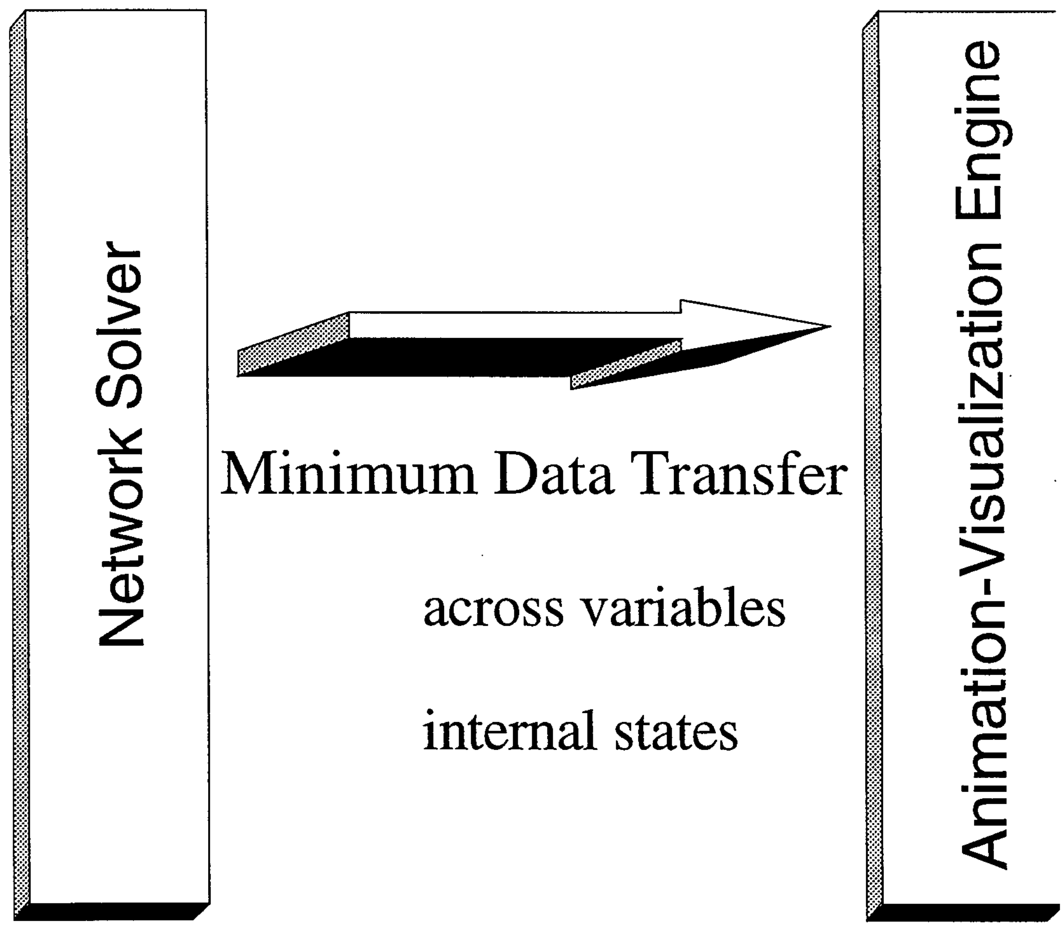
Simultaneous Solution versus Decomposition

Analytic Approach

Hybrid Approach

Adaptive Averaging PEBB Model – Independent Time Step

Network Solver – Animation/Visualization Engine Interface



Network Solver

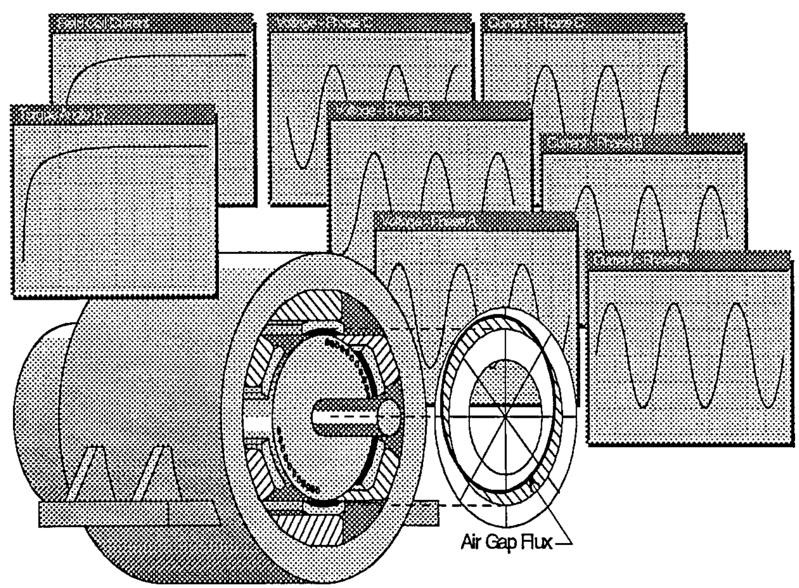
Animation/Visualization Engine Interface

Example

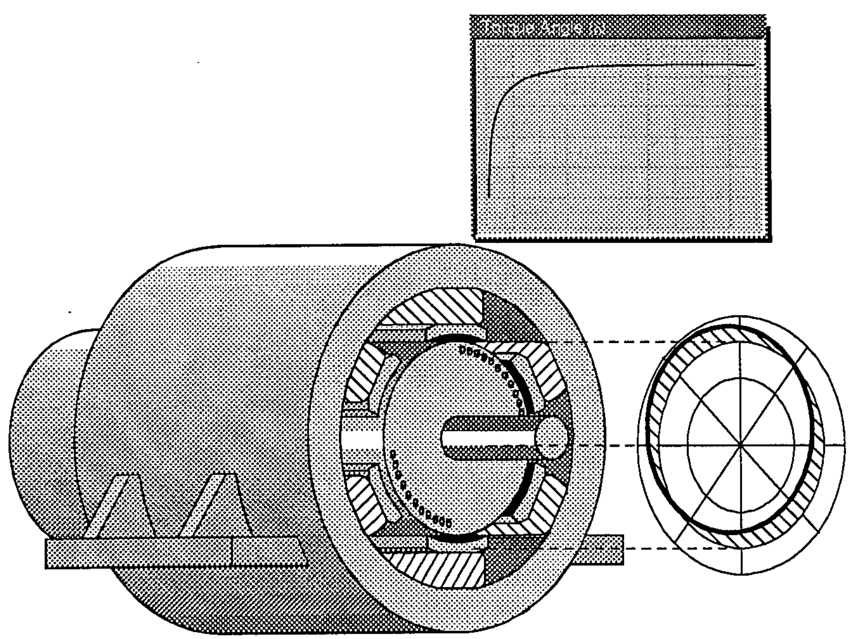
Network Solver Passes the Following Information

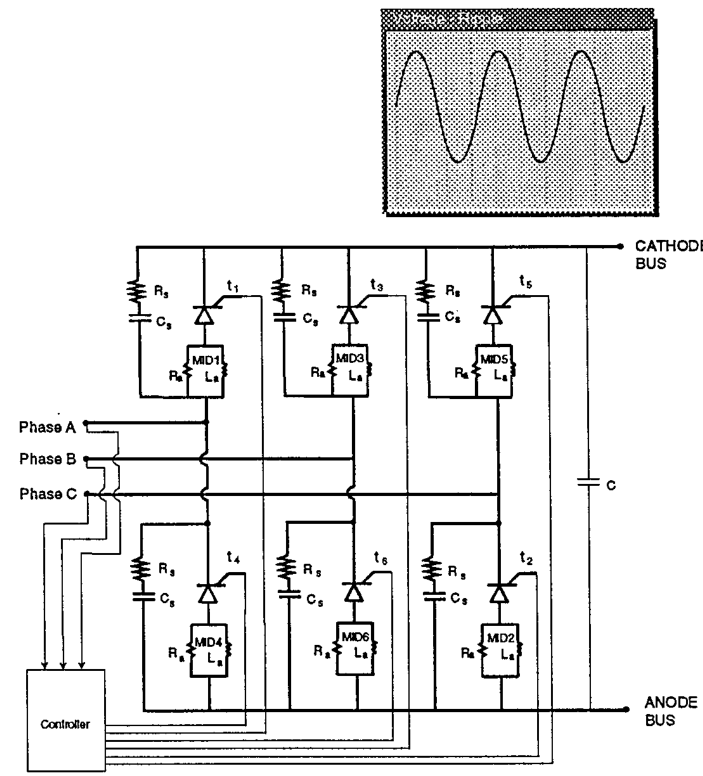
Across Variables:	Phase Voltages
Internal States:	Speed, Torque Angle, Mechanical Power, Other

Animation/Visualization Engine Produces:



Demonstration
Animation – System Stiffness





Future Work

Alternate Network Solvers

Periodic Steady State – Network Solver
Wavelet Based Approach
Small Signal Stability Analysis

SIL Compliance

Completion of Model Library

Animation and Visualization

Reliability Analysis

Approximate Analysis of Permeable Material Transmission Lines

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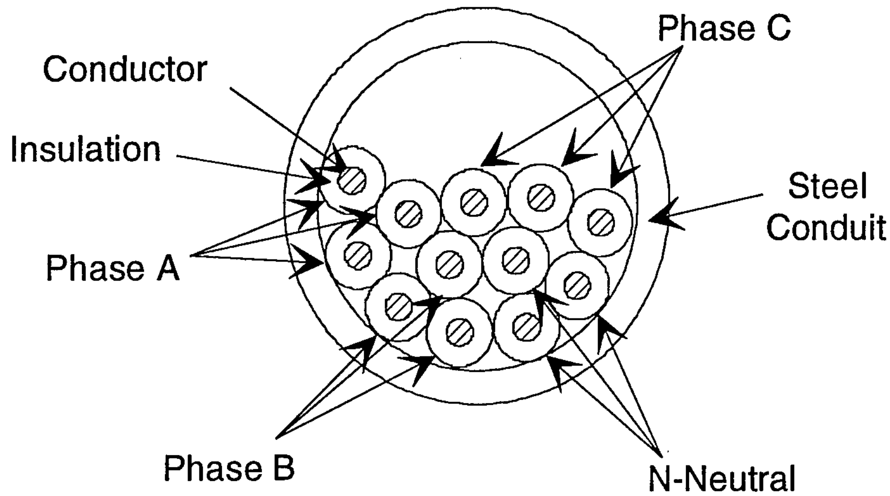
OUTLINE

- Importance of Modeling of Permeable Materials
- Model Description
- Example Cases
- Summary and Future Work

Importance of Modeling Permeable Materials

- Existence of Permeable Materials in a Ship Environment
- Nonlinear Effects on Transmission Lines
- Magnetic Field Shielding
- Dependence of Series Impedance on Electric Load
- Modeling is Necessary
  - Safe and Stable Electric Power System
  - Accurate Control of Electrical Equipment

Model Description



- Transmission Line Equations

$$\frac{\partial[v]}{\partial z} = [r][i] + [\ell]\frac{\partial[i]}{\partial t}$$

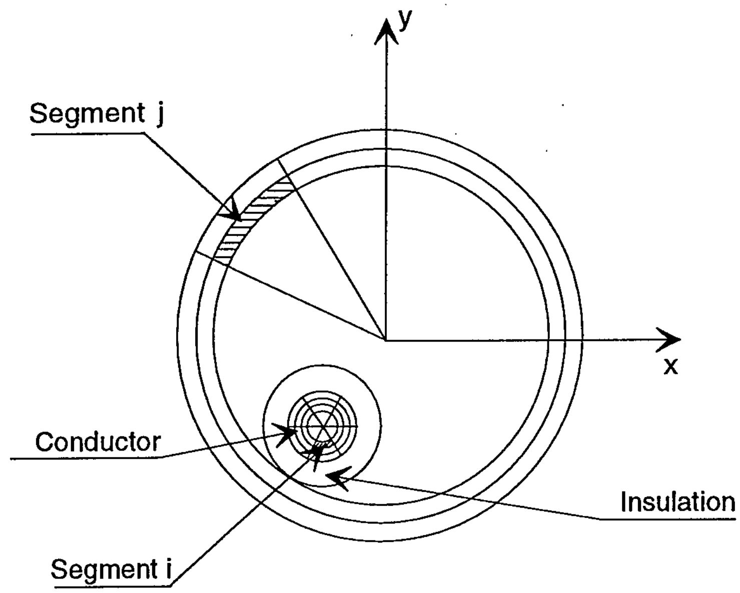
$$\frac{\partial[i]}{\partial z} = [c]\frac{\partial[v]}{\partial t}$$

- Lumped Element Equivalent Circuit

$$[v] = \Delta z[r][i] + \Delta z[\ell]\frac{\partial[i]}{\partial t} = [R][i] + [L]\frac{\partial[i]}{\partial t}$$

$$[i] = \Delta z[c]\frac{\partial[v]}{\partial t} = [C]\frac{\partial[v]}{\partial t}$$

Method of Conductor Subdivision



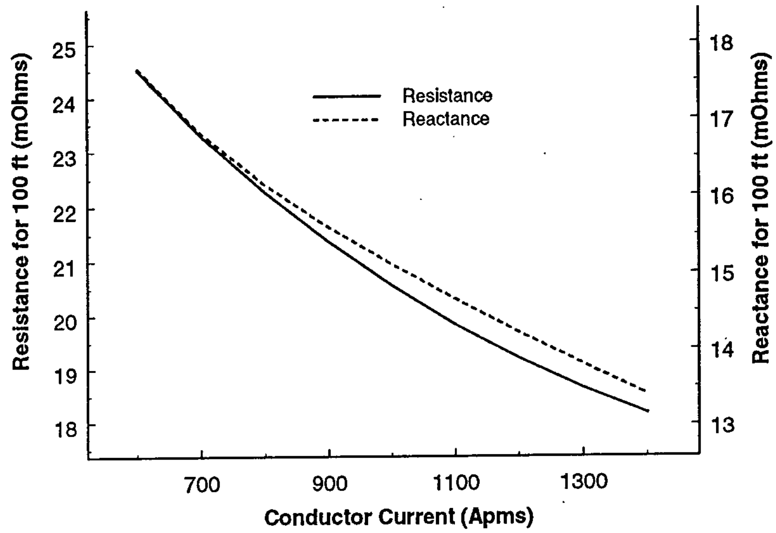
- Subdivide Conductors Into Segments
- Calculate Geometric Mean Radii
- Calculate Geometric Mean Distances
- Transmission Line Equations

$$\tilde{V}_i = \sum_j (r_{ij} + x_{ij})\tilde{I}_j$$

- Combine Segment Equations to Calculate [R] and [L] Matrices
- Self-Consistency (iterative)

Example Case

Copper 3/0 - GRC 2"



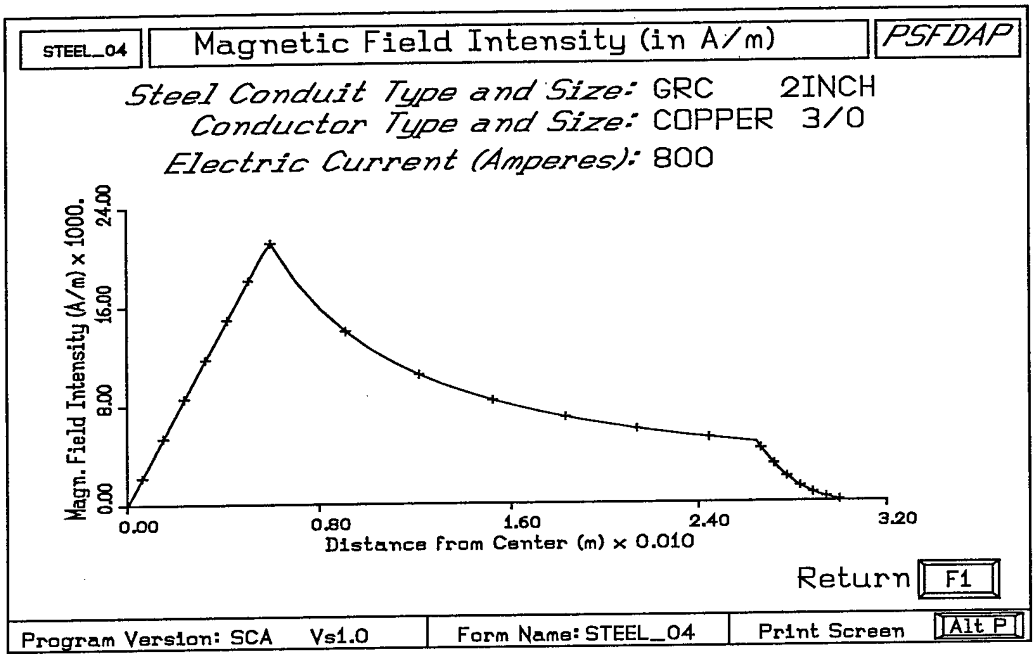
Resistance and Reactance Table

Electric Current (Amp)	R for 100 ft (mOhms)	X=ωL for 100ft (mOhms)
600	24.5232	17.6632
700	23.2944	16.8022
800	22.2744	16.1369
900	21.3782	15.5949
1000	20.5686	15.1151
1100	19.8437	14.6607
1200	19.2060	14.2217
1300	18.6524	13.7980
1400	18.1744	13.3930

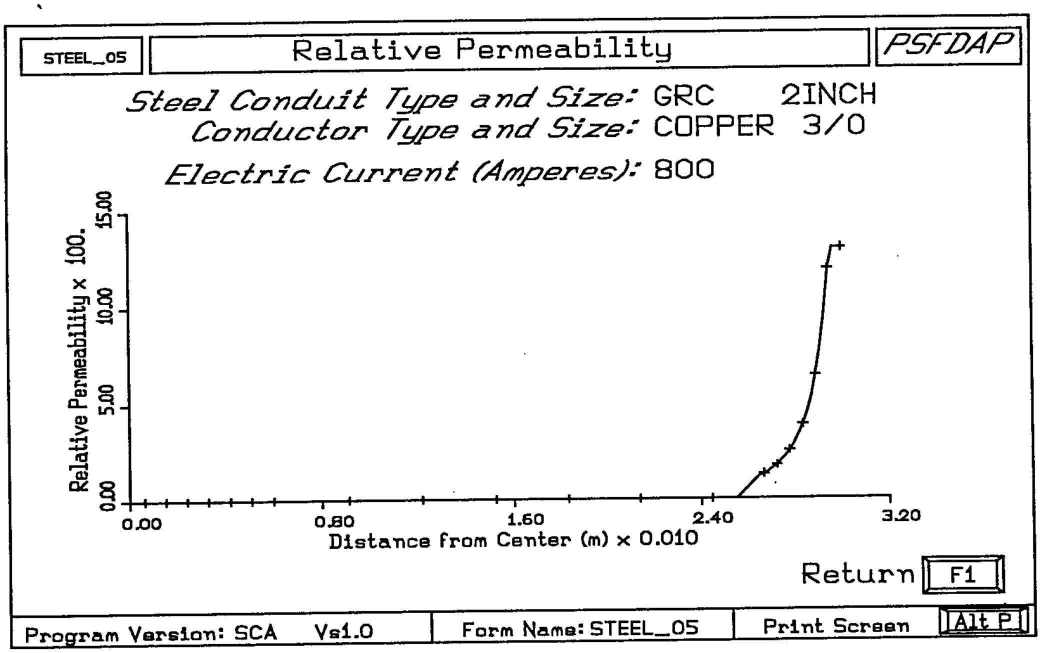
Example Case

Copper 3/0 - GRC 2"

Magnetic Field



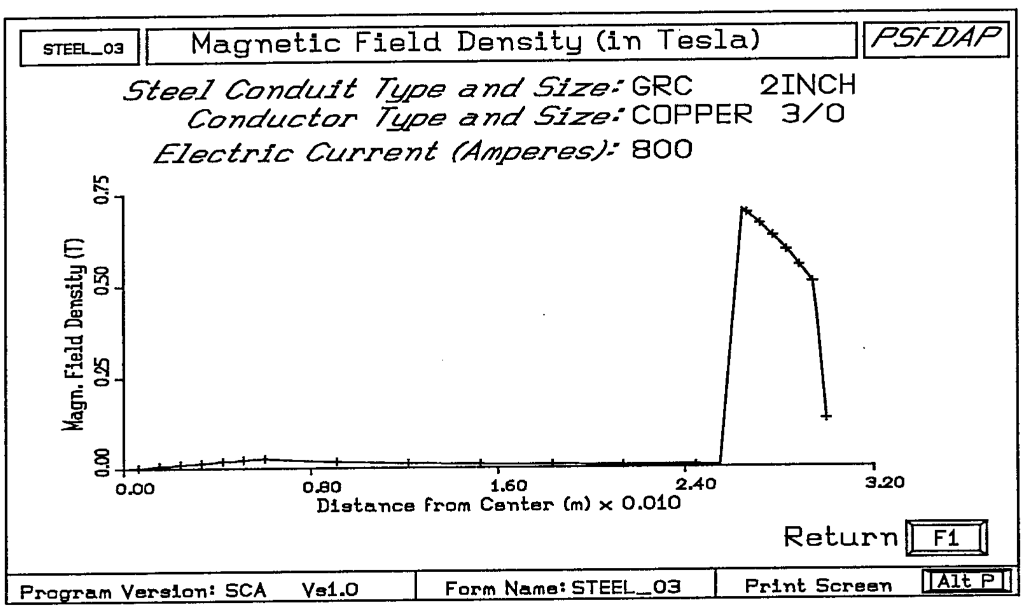
Relative Permeability



Example Case

Copper 3/0 - GRC 2"

Magnetic Field Density



Summary

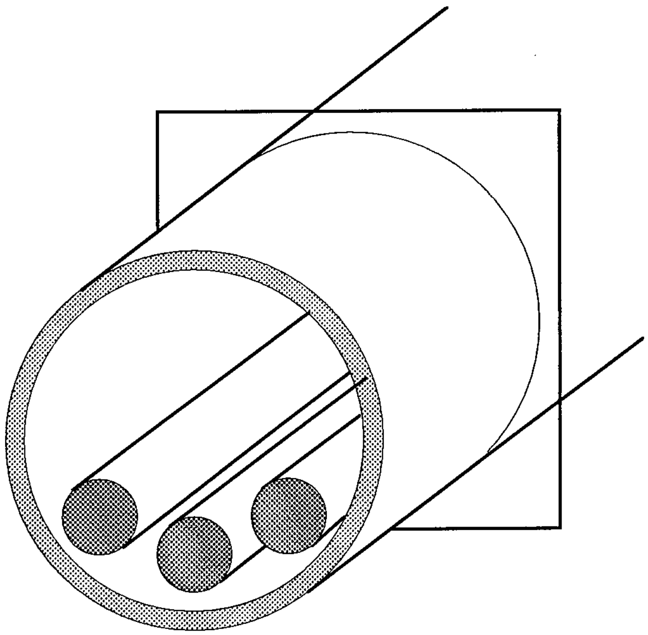
- Importance of Modeling Transmission Lines in the Presence of Permeable Materials
- Model Description Based on Conductor Subdivision and GMR, GMD
- Example Cases

Future Work

- Calculation of Capacitance Matrix
- Interface Transmission Line Model with Network Solver
- Improvement in the Calculation of Magnetic Field
- Comparison of the Model with the Rigorous Model Based on Finite Element Method

Virtual Test bed Project

RIGOROUS TRANSIENT MODELING OF PERMEABLE MATERIAL TRANSMISSION LINES



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Introduction

- *Why* pursue this study?

  The need to simulate signal propagation in transmission lines between the various components of the Network Solver.

- *What* is expected of the model?

  The model should be capable of modeling currents and voltages propagating through any geometry (expected to consist of multiple conductors in a permeable steel conduit)

- *How* is this done?

  This will be achieved using a combination of the Finite Element and Transmission Line Matrix methods in a Time Domain formulation.

Contents

The Transmission Line Matrix

The basic equations:

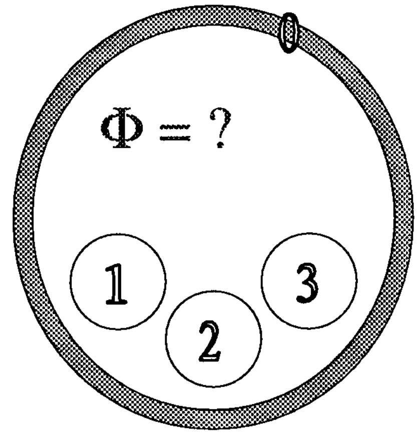
$$\frac{\partial}{\partial z}\vec{V} = -\vec{\vec{R}}\vec{I} - \vec{\vec{L}}\frac{\partial}{\partial t}\vec{I}$$

$$\frac{\partial}{\partial z}\vec{I} = -\vec{\vec{G}}\vec{V} - \vec{\vec{C}}\frac{\partial}{\partial t}\vec{V}$$

{V}	Voltage in each of the conductors
{I}	Current in each of the conductors
[R]	Line Resistance
[L]	Self and Mutual Inductance
[C]	Self and Mutual Capacitance
[G]	Line Trans-conductance

All terms are **per unit length** and vary as a function of both **location and time**. The formulation uses **a Finite Differencing** Scheme (in both time and space).

The TLM Matrices



[L]: per-unit-length Inductance Matrix:

$$L_{ij} = \frac{\phi_{j0}}{I_i}\bigg|_{I_1=I_2=I_3\ldots=I_{i-1}=I_{i+1}=\ldots=I_n=0}$$

[R]: per-unit-length Resistance Matrix:

$$R_i = \frac{1}{\sigma_i A_i}$$

[C]: per-unit-length Capacitance Matrix:

$$[C]=[P]^{-1}$$

$$P_{ij} = \frac{V_i}{Q_j}\bigg|_{Q_1=Q_2=Q_3\ldots=Q_{i-1}=Q_{i+1}=\ldots=Q_n=0}$$

The Finite Element Method

The equation to be solved:

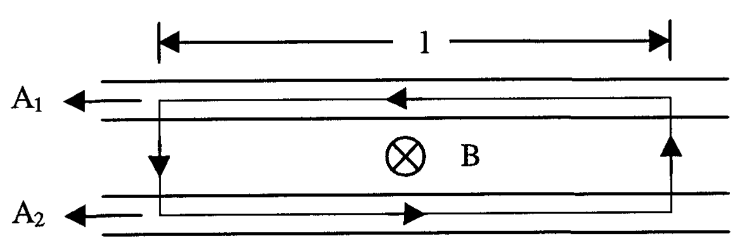
$$\nabla \cdot \left(\frac{1}{\mu} \nabla A \right) = \vec{J}_s - \sigma \frac{\partial \vec{A}}{\partial t}$$

where A is the magnetic vector potential and Js is the forced current density. The material properties are:

σ: conductivity

μ: permeability

The magnetic field vector B and flux Φ can be determined as functions of A:



$$\frac{\phi_{12}}{l} = A_2 - A_1$$

Illustration: Copper Lines in a Steel Conduit

Conduit:(Steel)

Relative Magnetic permeability	$\mu_r = 1000$
Conductivity	$\sigma = 8.3334E+06$ S/m

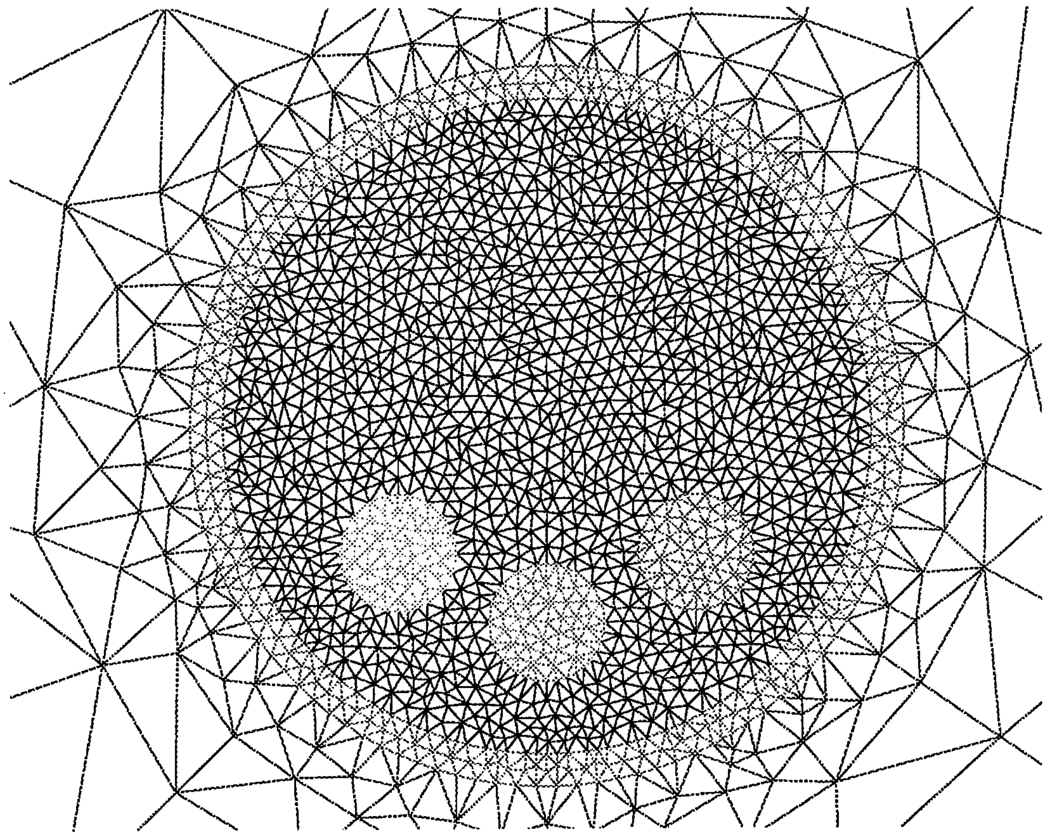
Conductors: (Copper)

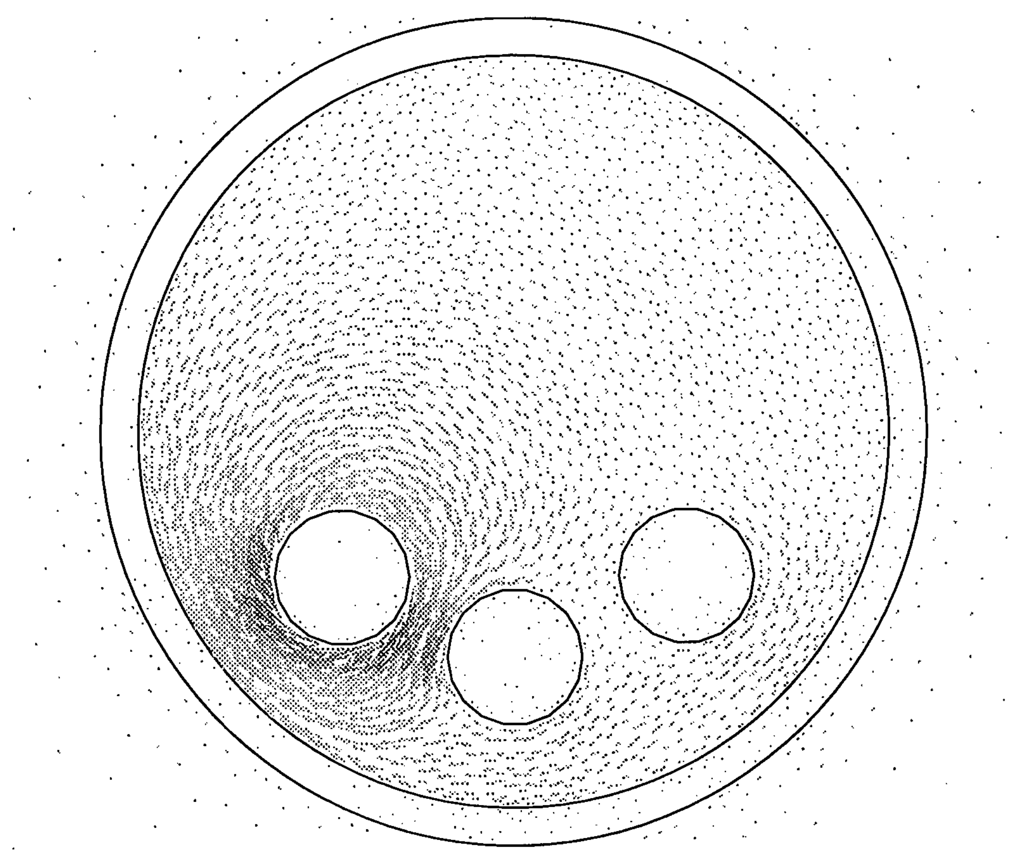
Relative Magnetic permeability	$\mu_r = 1$
Conductivity	$\sigma = 5.9595E+07$ S/m

Excitation: (Current)

Number of Conductors:	3
Amplitude:	1 Amp
Frequency:	50 kHz
Phase:	3 Phase

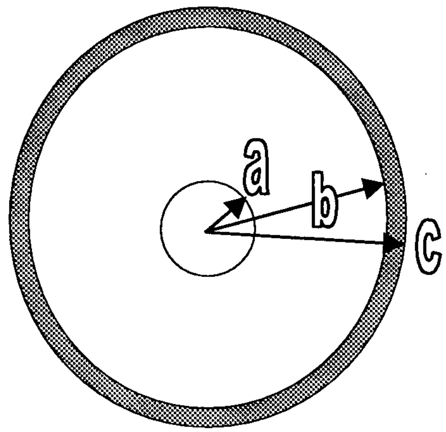
Illustration: Mesh and Magnetic Field Vector Snapshot





Analytical Verification

Coaxial line:



$$\frac{L}{\ell} = \frac{\mu_o}{2\pi}\left\{\ln\left(\frac{c}{a}\right) + \frac{b^2}{c^2 - b^2}\ln\left(\frac{c}{b}\right)\right\}$$

For a=50 , b=100, c=110 mm.

Analytical: $L/\ell = 2.4846\times10^{-7}\,H/\ell$

Finite Element: $L/\ell = 2.4768\times10^{-7}\,H/\ell$

Future Work

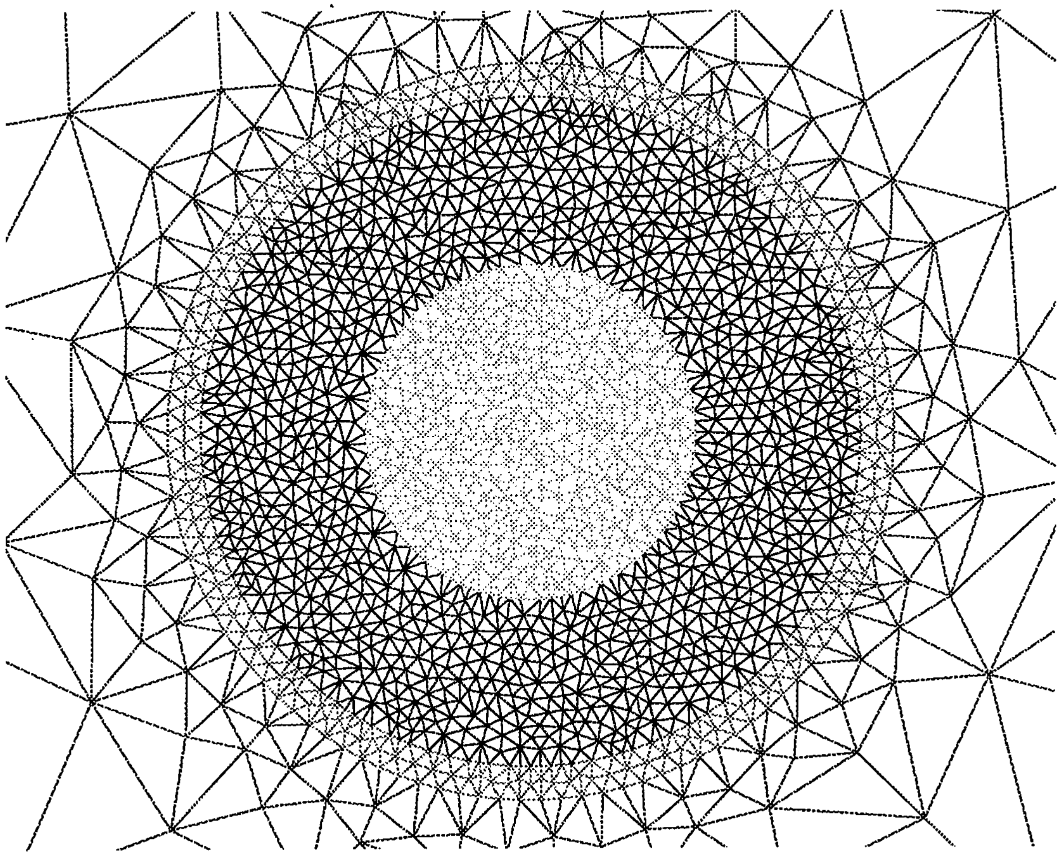
- *Alternative Vector Formulation.*

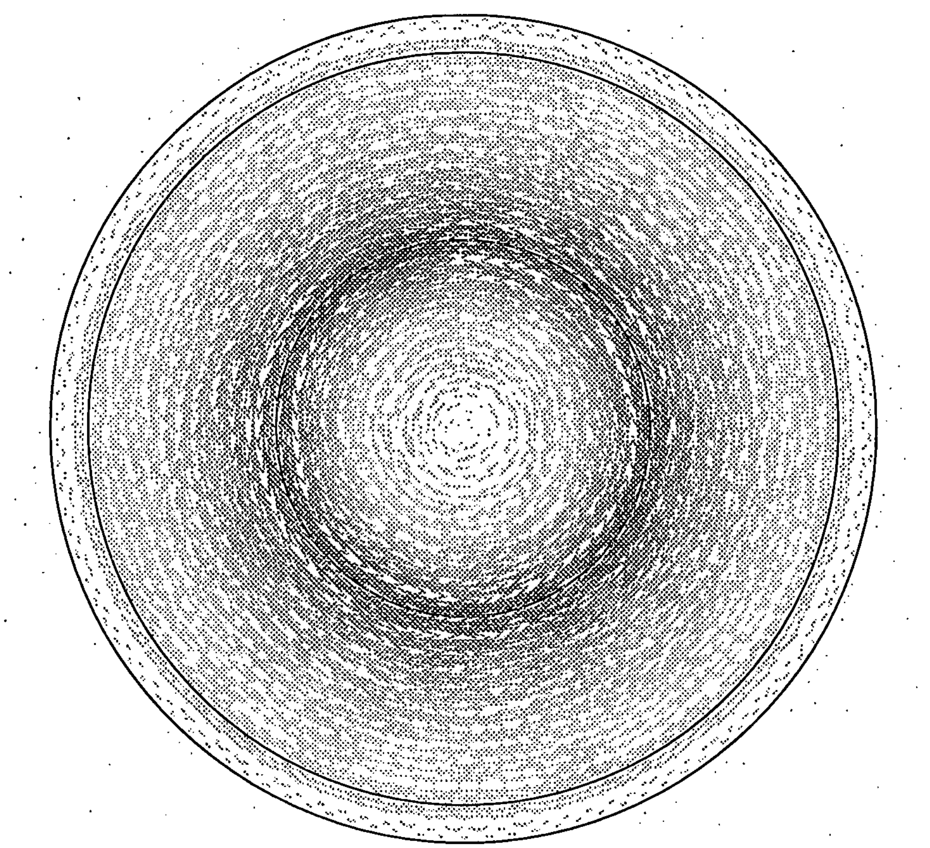
- *Adaptive Gridding Algorithms.*

- *Model Parameter Interpolation.*

- *Methods for rapid solution of non-linear equations.*

Verification: Mesh and Magnetic Field Vector Snapshot





Graphical User Interface

- *Mesh*
- *Magnetic Vector Potential (A)*
- *Magnetic Flux Lines (A contour)*
- *Magnetic Flux Density (|B|)*
- *Vector Magnetic Flux Density (B)*

Computational Requirements

- *Approximate number of unknowns:*

  ~ 2000 nodes (3500 elements)

- *Matrix density:*

  ~ 0.004 (highly sparse)

- *Number of iterations / time step:*

  n+1 (n is number of conductors)

- *Number of spatial iterations:*

$$m = \frac{\ell}{10\lambda_{\min}}$$

(ℓ is length of the transmission line)

Modeling and Control of Pulse Modulated Circuits and Systems

David G. Taylor

June 1997

Outline

- Relation of Work to VTB Project
- New Modeling Results
- New Control Design Results
- Future Work Planned

Relation of Work to VTB Project

- Pulse Modulated Circuits and Systems
  - Power Electronic Building Block (PEBB)
  - Power Converter
  - Motor Drive
- Common Features
  - High-Power Digital Switches
  - Digital Signal Processor

Relation of Work to VTB Project

- Modeling
  - Topology depends on switch positions
  - Direct simulation is time consuming
  - Simple averaging may not be accurate
  - Sampled-data method has advantages
    - Provides cycle-to-cycle response
    - Exploits symbolic or numerical off-line solution
    - Leads to fast and accurate on-line simulation

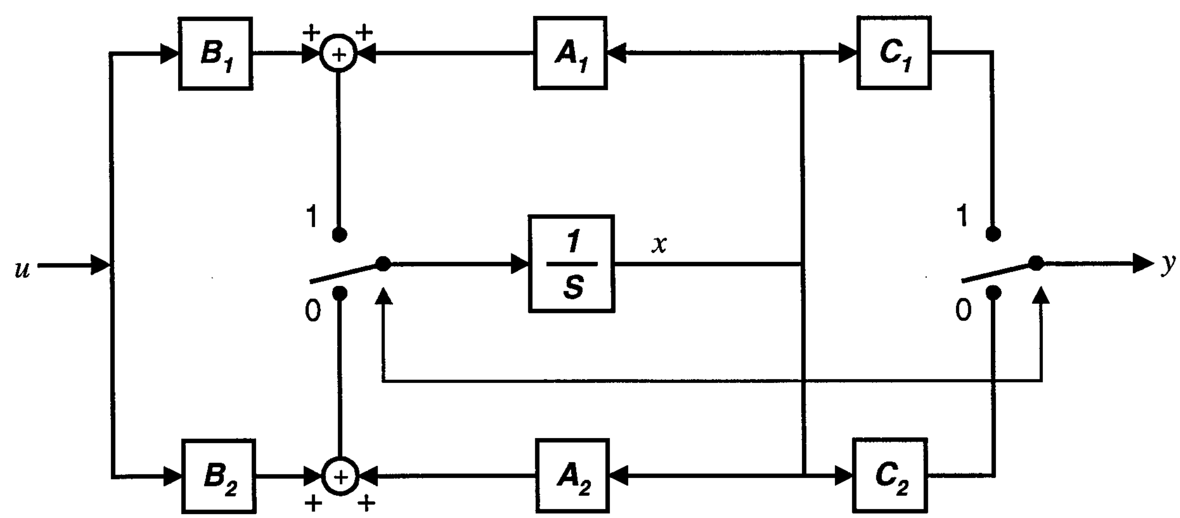
Relation of Work to VTB Project

- Control Design
  - Improve performance of existing systems
  - Optimally program future PEBB systems
  - Challenges
    - Nonlinearities
    - Unstable zeros
    - Unknown parameters
    - Computational efficiency

New Modeling Results

- Single-Switch Subsystem

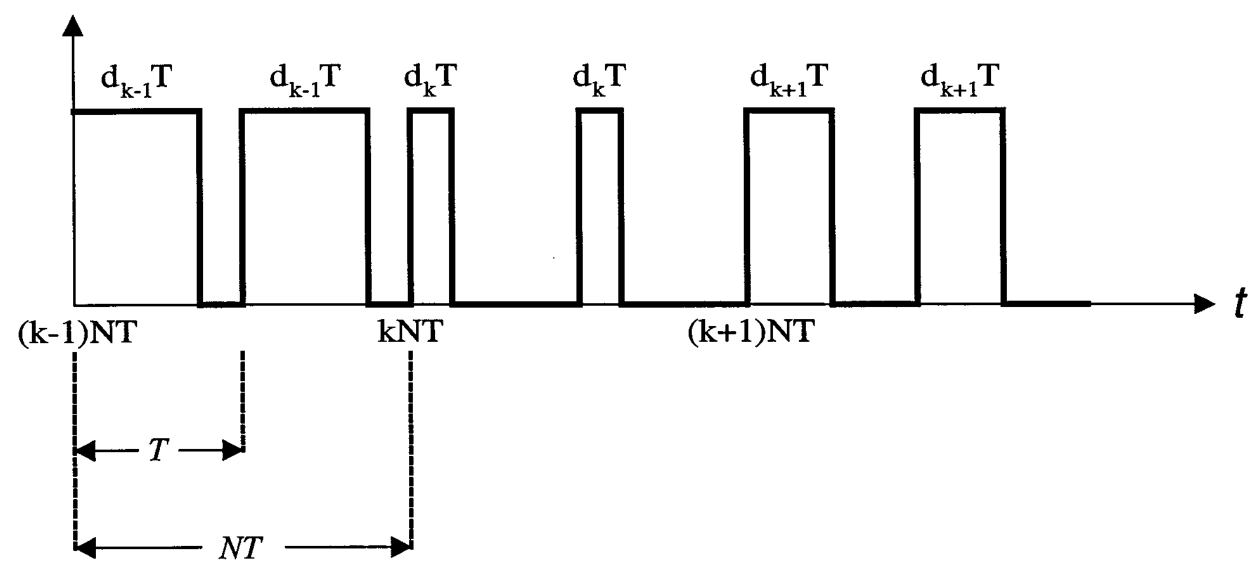
  u = source vector, x = state vector, y = output vector



New Modeling Results

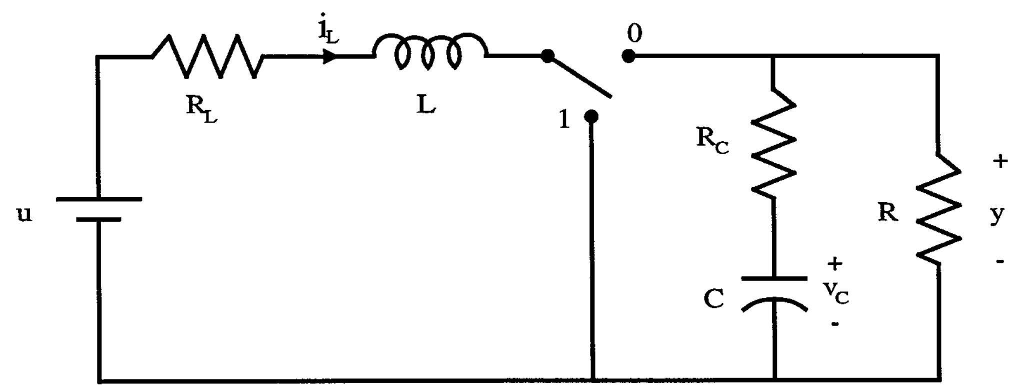
- Pulse Modulation Scheme

  T = switch period, NT = control period, d = duty ratio



New Modeling Results

- Boost Converter



$$A_1 = \begin{bmatrix} -\frac{R_L}{L} & 0 \\ 0 & -\frac{1}{(R+R_C)C} \end{bmatrix} \qquad B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \qquad C_1 = \begin{bmatrix} 0 & \frac{R}{R+R_C} \end{bmatrix}$$

$$A_2 = \begin{bmatrix} -\frac{RR_L + RR_C + R_L R_C}{(R+R_C)L} & -\frac{R}{(R+R_C)L} \\ \frac{R}{(R+R_C)C} & -\frac{1}{(R+R_C)C} \end{bmatrix} \qquad B_2 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \qquad C_2 = \begin{bmatrix} \frac{RR_C}{R+R_C} & \frac{R}{R+R_C} \end{bmatrix}$$

New Modeling Results

- One-Cycle-Average Output

$$y^*(t) := \frac{1}{NT}\int_{t-NT}^{t} y(\tau)\, d\tau$$

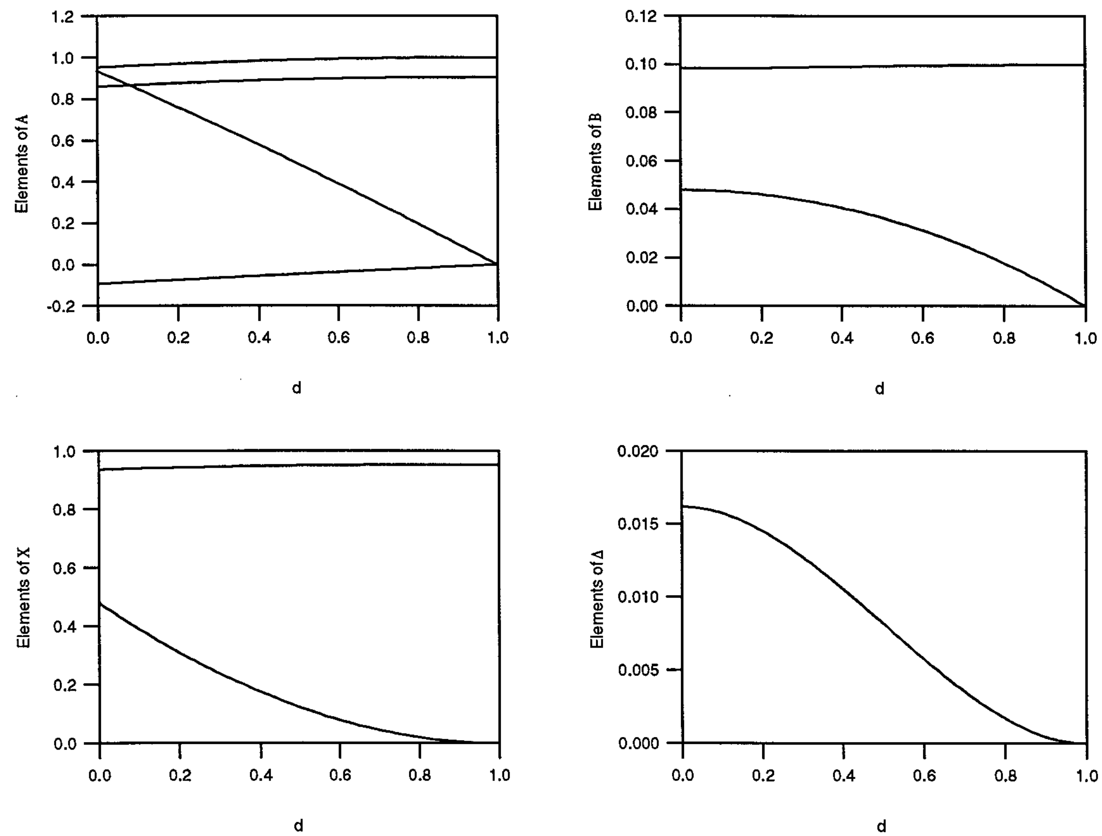
- Large-Signal Sampled-Data Model

$$x_{k+1} = A(d_k)x_k + B(d_k)u_k$$

$$y^*_{k+1} = C(d_k)x_k + D(d_k)u_k$$

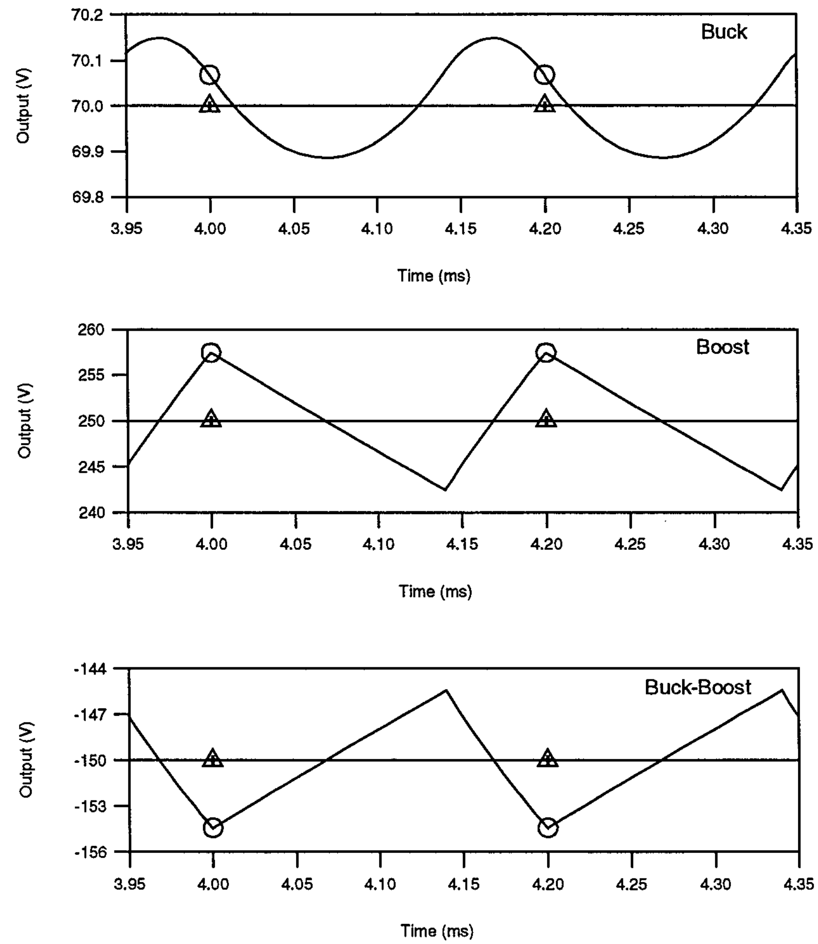
New Modeling Results

- Boost Converter Simulation Data



New Modeling Results

- Simulations
  - direct integration
  - traditional SD model
  - new SD model



New Control Design Results

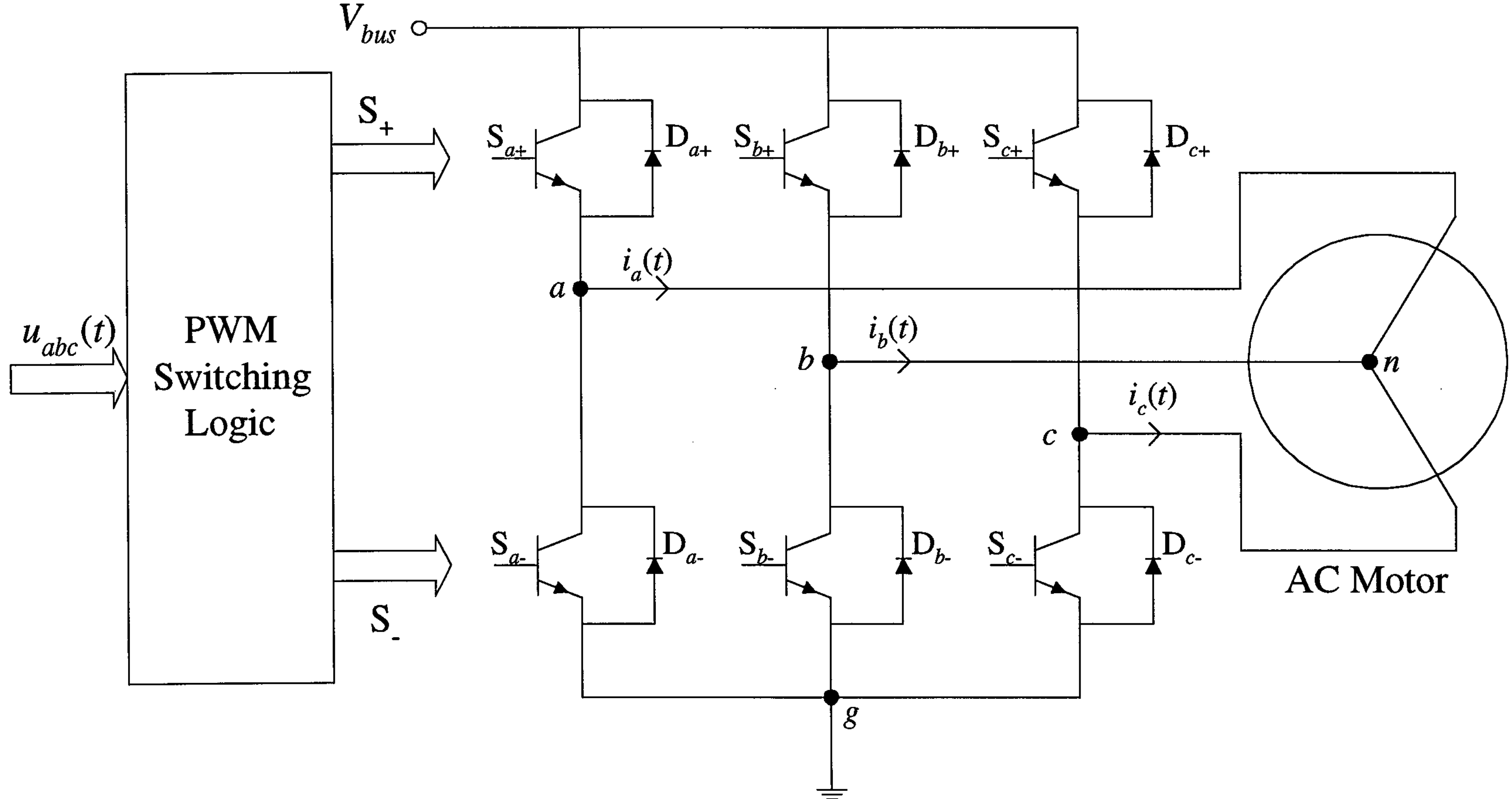
- Control of Non-Minimum-Phase Systems
  - Unstable zeros are common after discretization
  - Output redefinition eliminates unstable zeros
  - Nonlinear control design without adaptation
    - Mohammed Al-Numay (see poster)
  - Linear control design with adaptation
    - Song Li (see poster)

New Control Design Results

- Adaptive Control of AC Motor Drives
  - Input nonlinearities
    - deadtime, on/off delay, voltage drop
  - Output nonlinearities
    - friction, backlash
  - Parameters of inverter/motor/load unknown
  - Adaptive input-output linearizing controller
  - Globally stable with asymptotic tracking

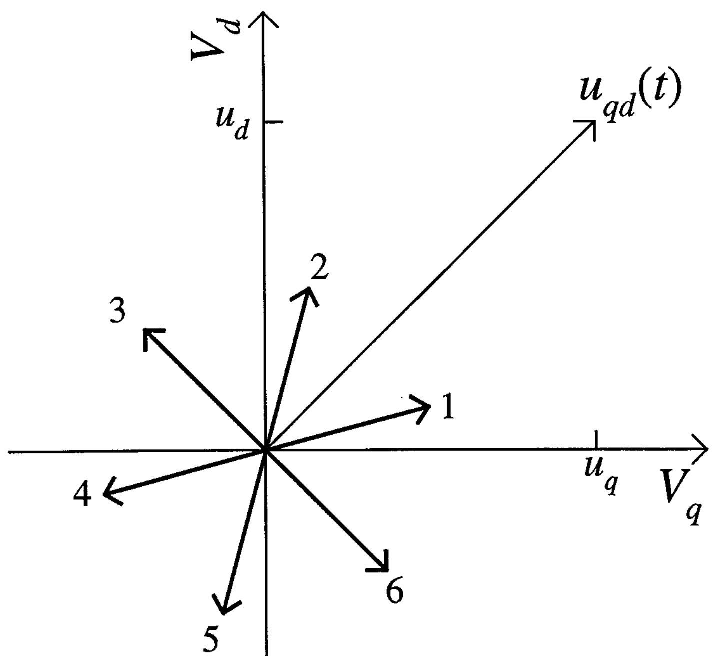
New Control Design Results

- Motor Drive

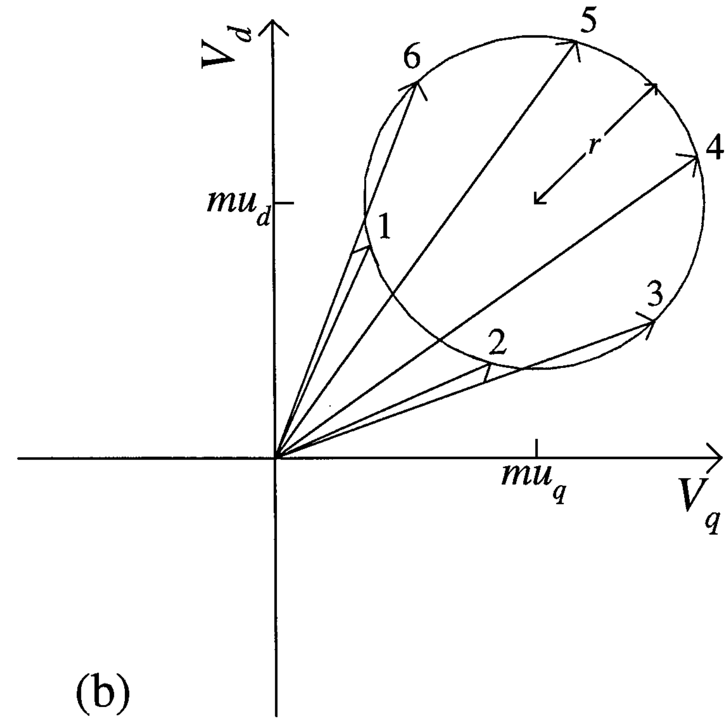


New Control Design Results

- Inverter Distortion



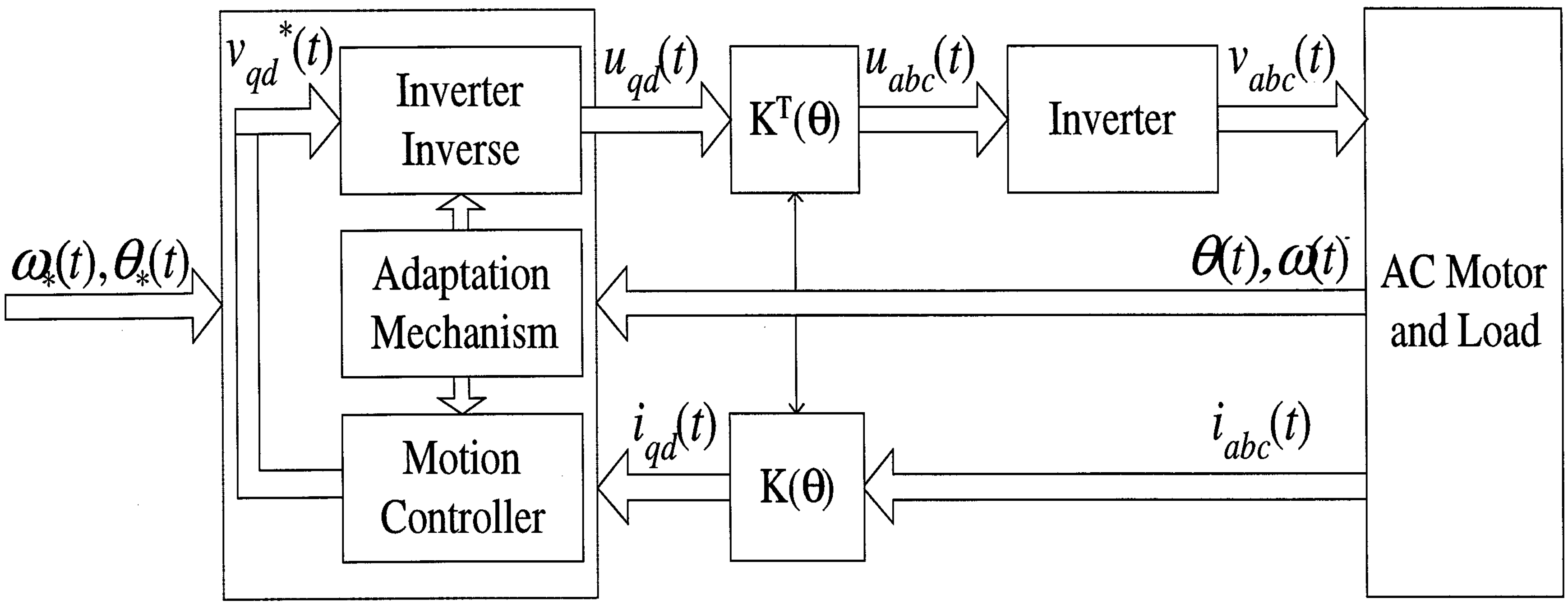
(a)



(b)

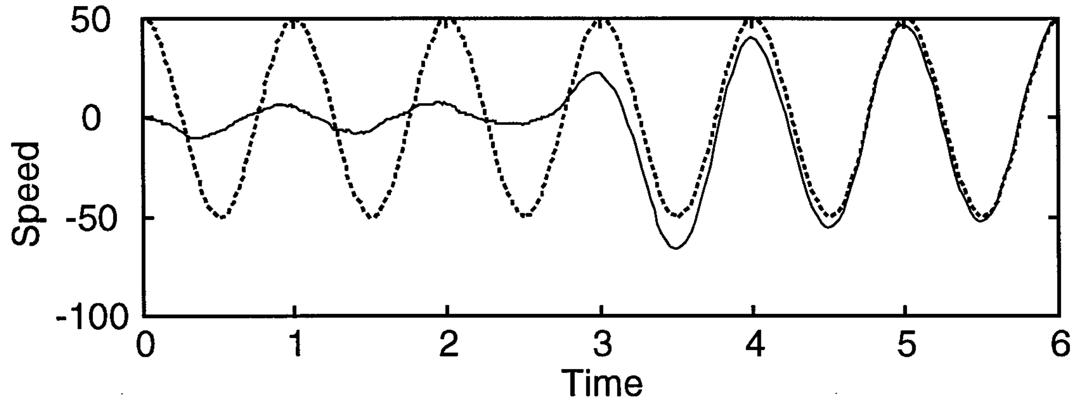
New Control Design Results

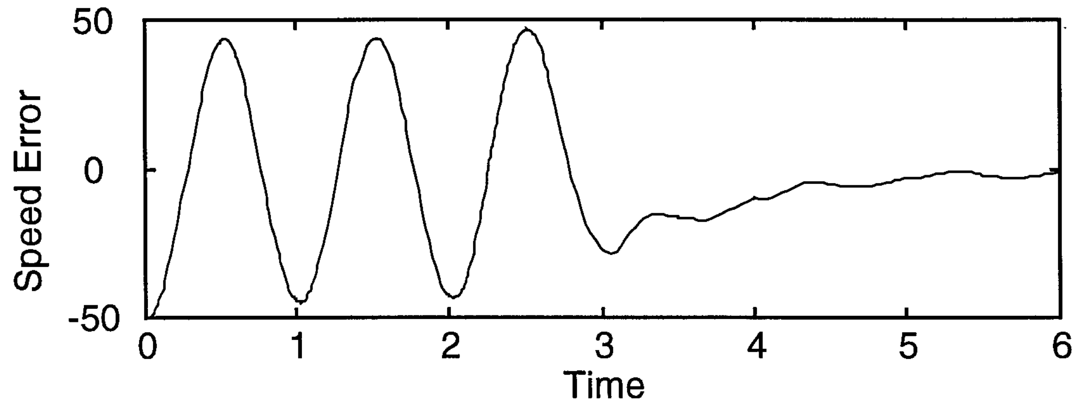
- Control System



New Control Design Results

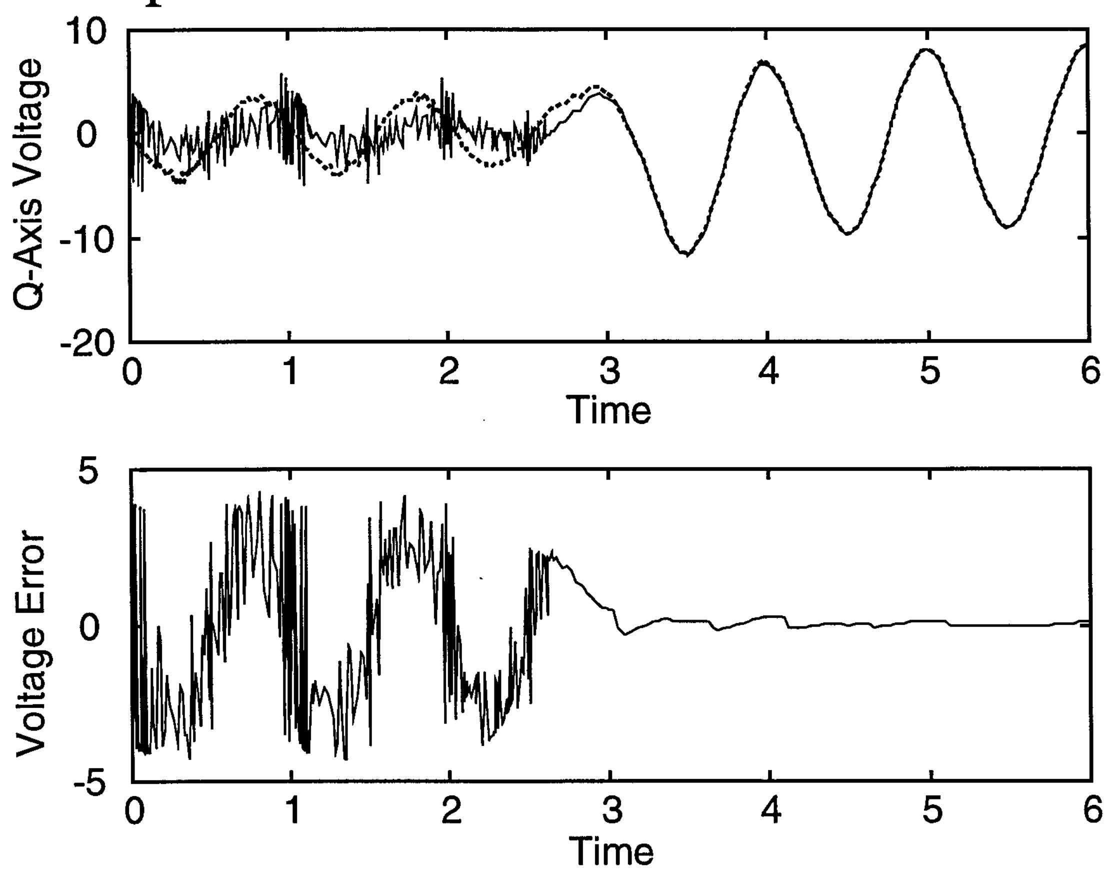
- Adaptive Speed Control





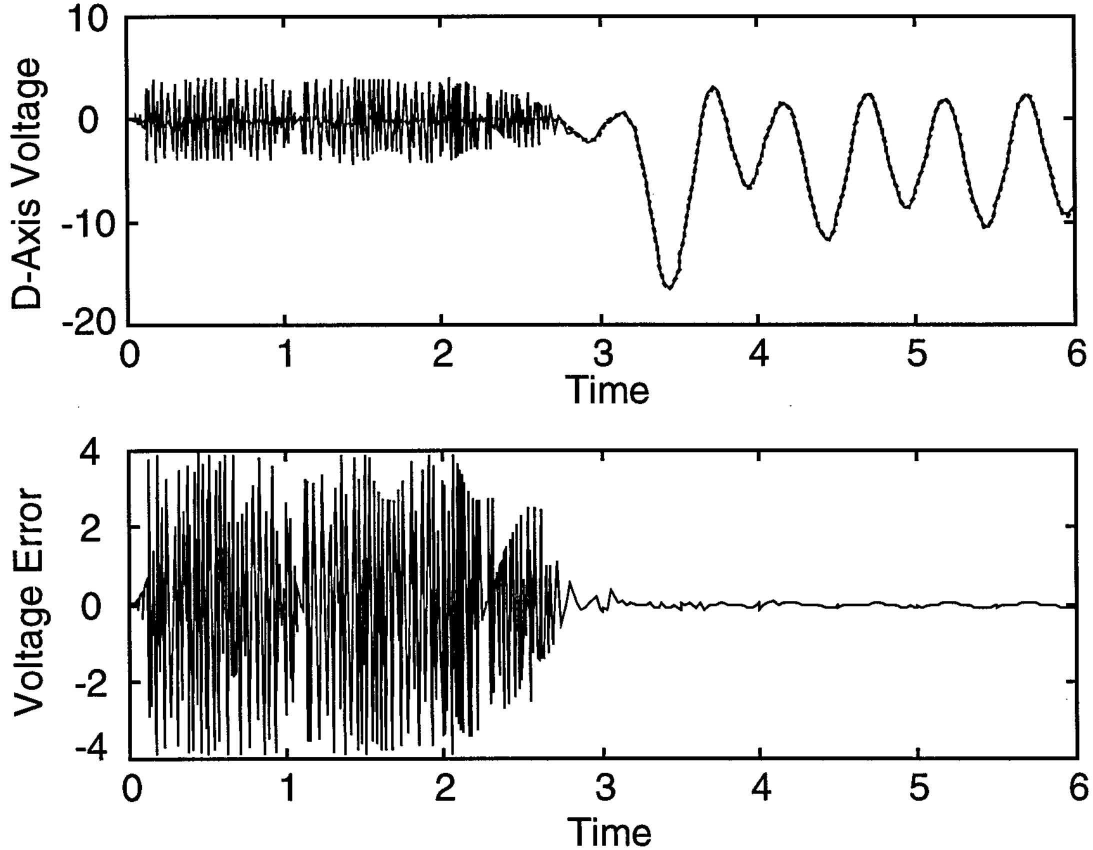
New Control Design Results

- Adaptive Speed Control



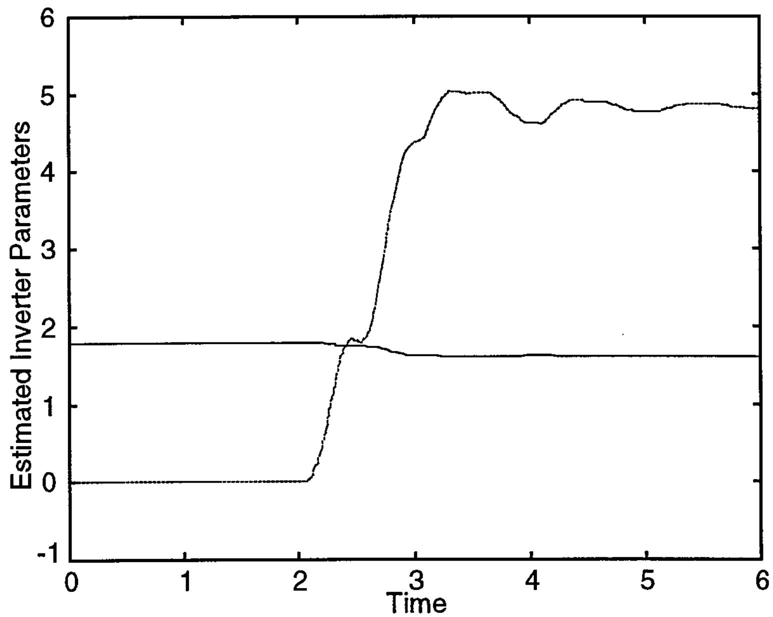
New Control Design Results

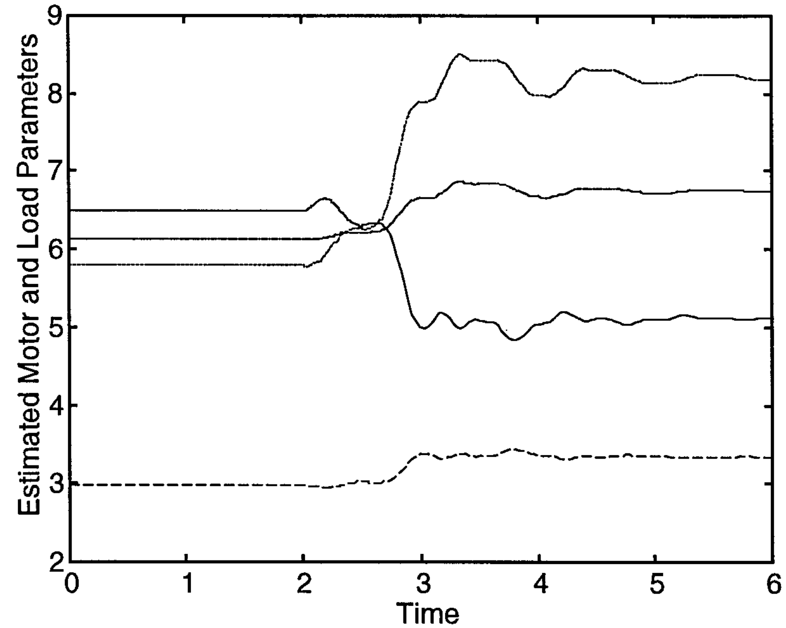
- Adaptive Speed Control



New Control Design Results

- Adaptive Speed Control



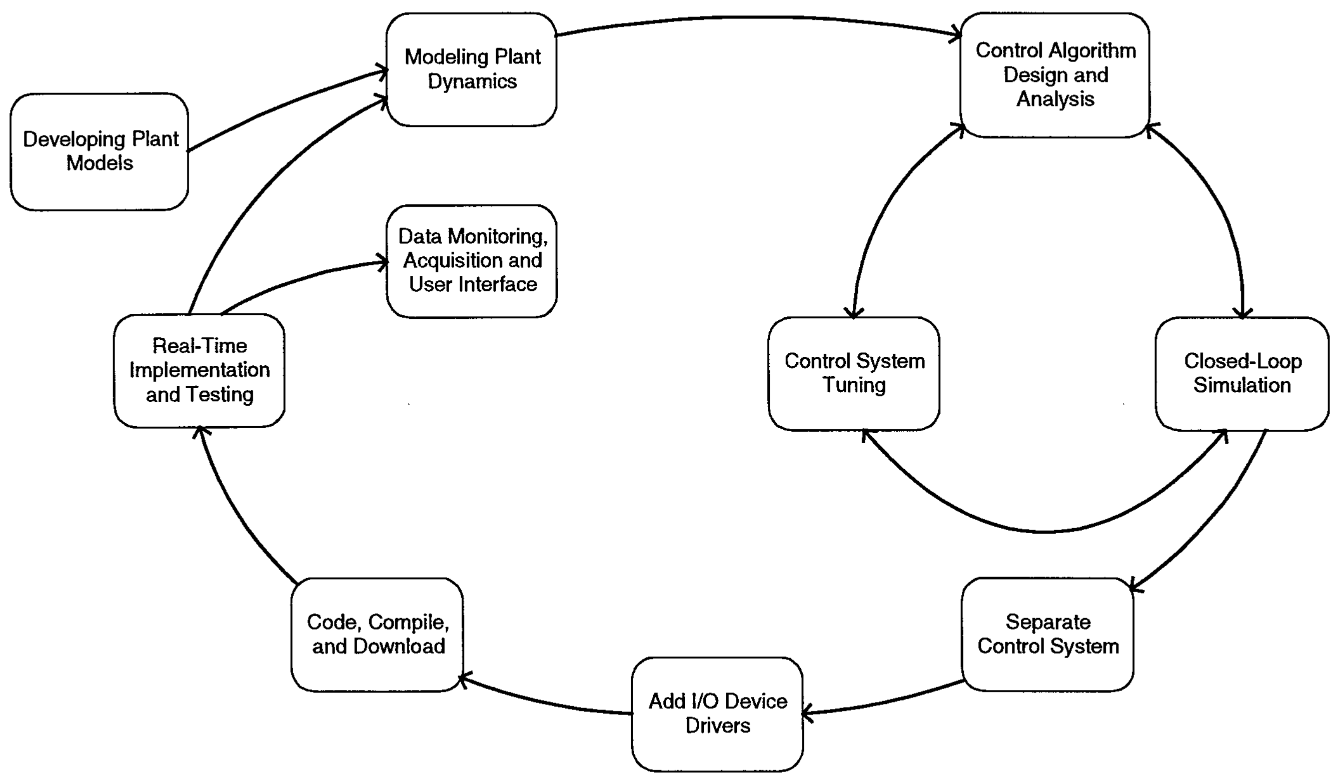


Future Work Planned

- Development of VTB Device Models
  - nonlinear components
  - uncontrolled switches
  - wider range of devices
- Development of PEBB Controllers
  - nonlinear adaptive control
  - nonlinear repetitive control
  - wider range of applications

Future Work Planned

- Rapid Prototyping



TAGANROG STATE UNIVERSITY OF RADIO ENGINEERING 1952

Virtual Test Bed

The city of Taganrog

- Population - close to 300'000.
- Founded in 1698.
- Two Universities.
- Biggest in the Europe Boiler Factory.

- Second in the country Harvester Combine Company.
- Two Aircraft Companies.
- Steel mill.
- Several electronic companies.

Taganrog State University of Radio Engineering

- Was chartered in 1952.
- Five colleges
  - *College of Radio Engineering.*
  - *College of Automation and Computer Engineering.*
  - *College of Electronics and Manufacturing Engineering.*
  - *College of Economics, Management and Law.*
  - *College of Natural Sciences.*

- Total Enrolment near 5000.
- About 600 faculty members and over 2500 staff members and research assistants.

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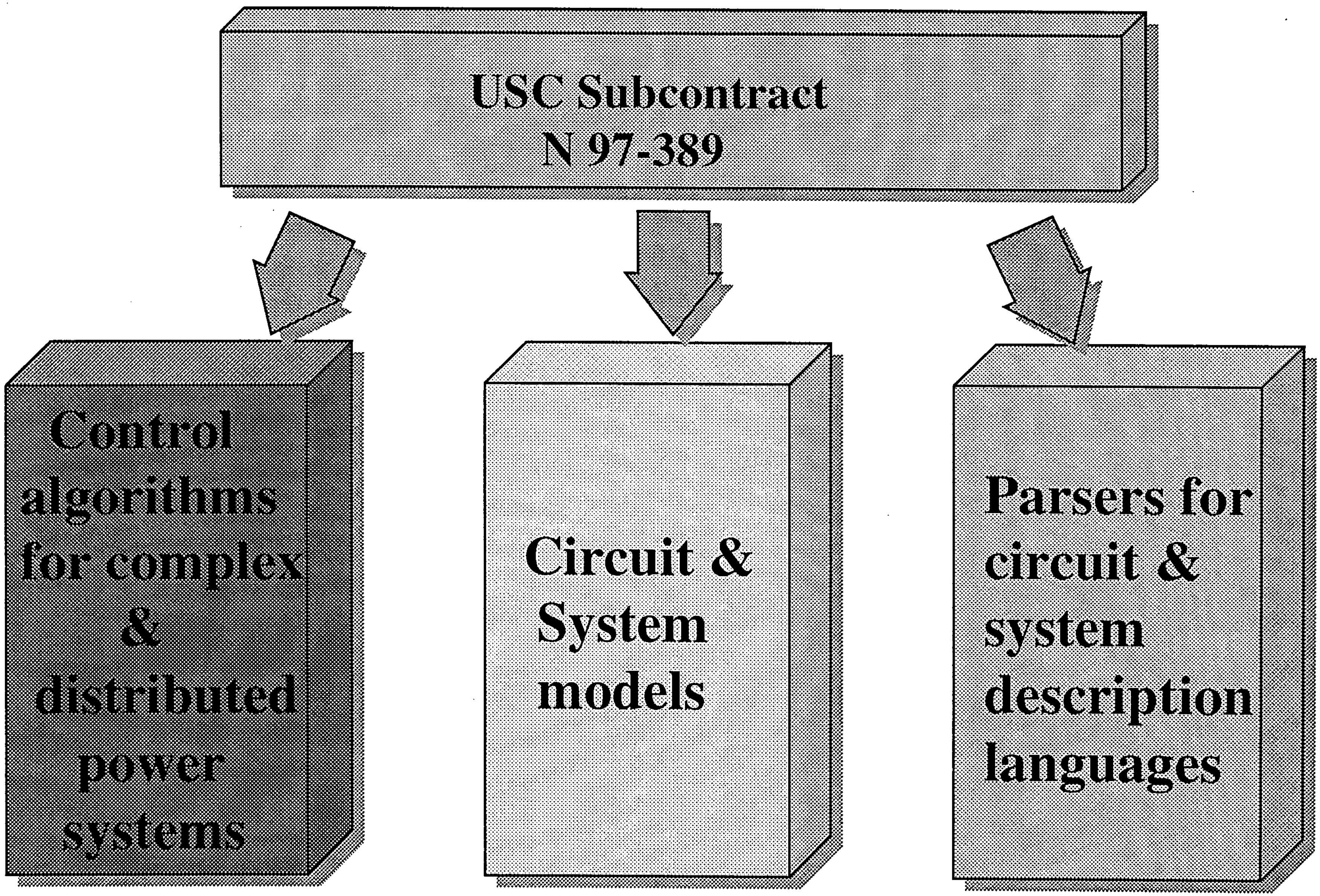

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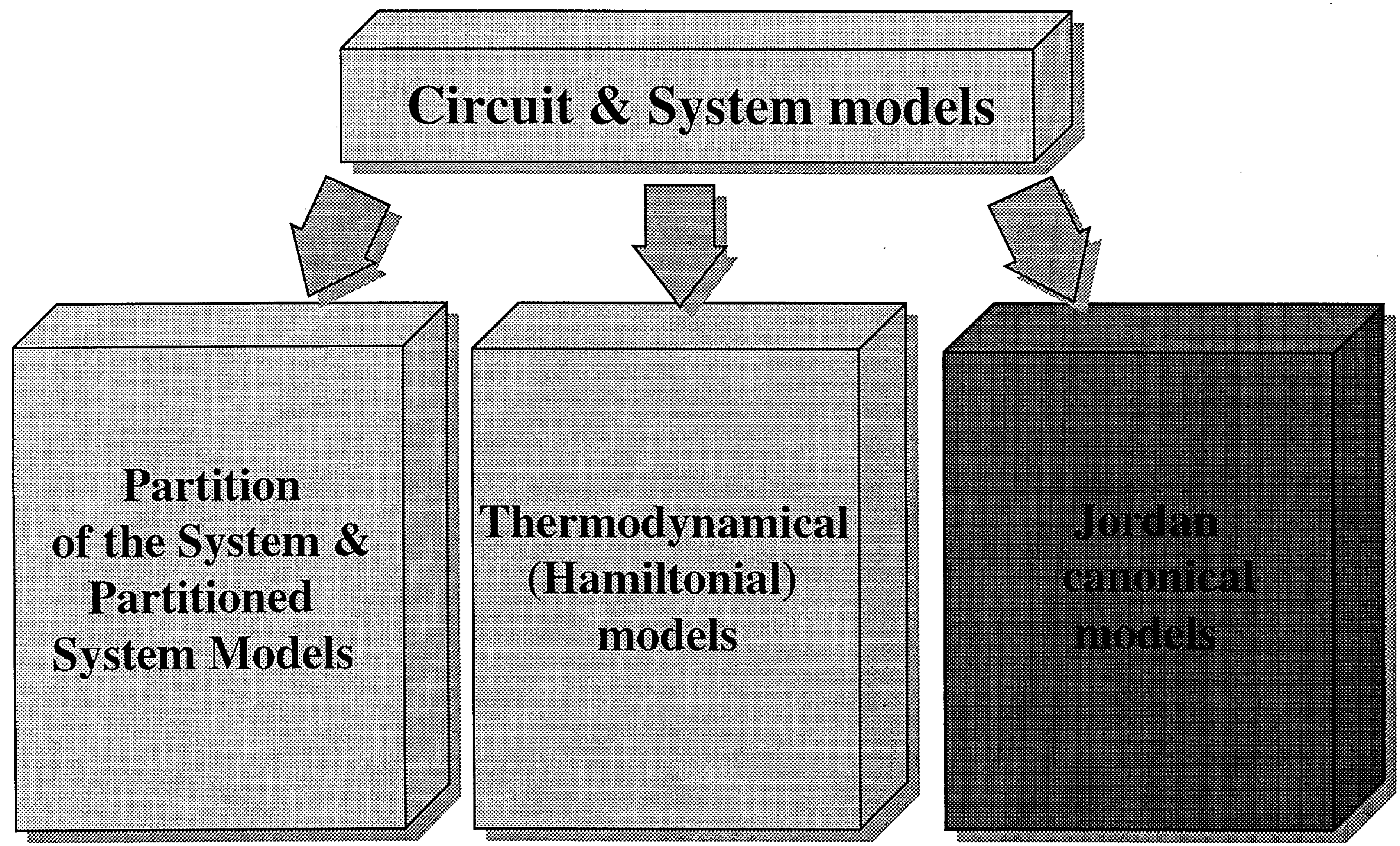


Virtual Test Bed

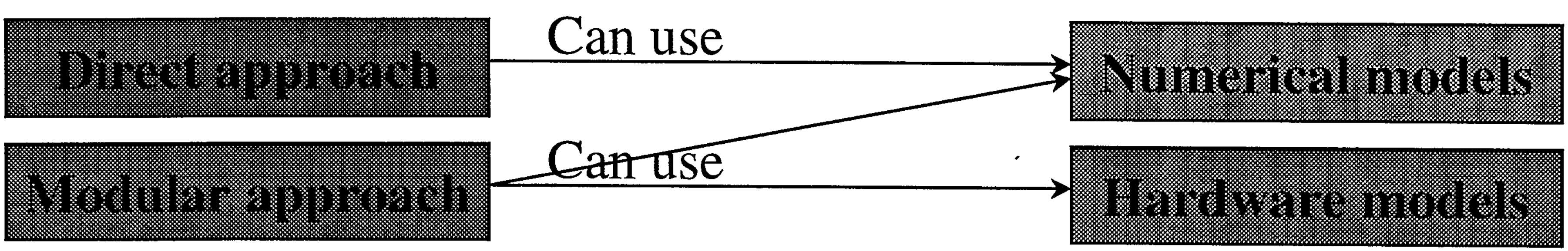
Partitioned System Models

VTB Philosophy:

submodels of a system are integrated into a single simulation platform; the individual parts of this model can be modeled by different tools or can be presented by real components.

Therefore, the models of power system components can be presented as numerical (mathematical) models and hardware (real device) models

Two approaches can be used: direct approach: each model is integrated and dissolved; modular approach: every model lives independently and exchanges with others at input-output level



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Advantages and Limitations
of a direct and modular approach (numerical aspects only)

Direct approach

Advantages:
- Well worked-up
- Accurate
- Robust
- No instability caused by decomposition

Limitations:
- Ineffective for large systems
- Timestep must be identical for all models
- Parallel processing hardly possible
- No hardware models
- Real time simulation is hardly possible

Modular approach

Advantages:
- Large system simulation possible
- Parallel processing easily possible
- Timestep may be independently chosen
- Hardware models available
- Real time simulation easily possible

Limitations:
- Stability or convergence problems for tightly coupled systems. (Unfortunately, as a rule, the parts in power system are tightly coupled.)

Conclusion: modular approach is more promising; if both can be used, the modular way is preferable

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•How strong are convergence problems in modular approach?

- Inconvergence completely destroys the simulation process

• When system is tightly-coupled?

- In low power circuit analysis

•Partitioning is made across signal flow paths with energy transmitting (bipolar technology)
•Partitioning is made across feedback paths
•Partitioning is made across power supply and ground bus

- In power system simulation

•Always, if energy is flowing between the parts separated
•Between neighboring parts (local feedback, acts instantly)
•Feedback loop embraces several parts separated (global feedback, delayed)

Conclusion: Unfortunately, as a rule, the parts in power system are tightly coupled. The use of modular approach may cause instability or non-convergence.

We are going to solve this problem.

Virtual Test Bed

What are ways to improve the convergence while solving the decomposed system? (mathematical approaches)

Polynomial acceleration methods

- Good for symmetrizable problems only
- Require estimation of relaxation parameters that is not possible

Conjugate gradient (direction) methods

- Based on the residual calculation, that is incompatible with black-box philosophy of the modular approach

Multigrid methods

- Also require residual calculation
- A system must have regular (meshwise) structure, that is impractical in our case

Conclusion: Unfortunately, we cannot apply these methods to improve the performance of modular approach

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Then, how to make tight coupling compatible with modular approach? Or, how to improve the convergence of decomposition-based simulation?

Neutralizing global feedback

- Time windowing: good, if delay is large enough;
- Step-size refinement: good, but needs some non-trivial algorithms;
- Ordering parts according to a signal-flow graph: very effective if signal flow graph is unidirectional, otherwise the convergence problem cannot be eliminated

We propose: multicycle concurrent and iterative approach (next reports);

Neutralizing local feedback

- Lumping tightly coupled parts together: this way kills all benefits of modular approach;
- Overlapping partitioning: improves convergence by the expense of complication the parts. The partitioning procedure is non-trivial

We propose: modified and generalized coupling approach;

Virtual Test Bed

- When modular approach is used, the solution process is always relaxation-based, in contrast to the direct approach, where the comprehensive model is solved simultaneously.
- In the relaxation-based analysis of dynamic systems the solution process always develops in two spaces: in the time space and in the relaxation space.
- The first kind of progress produces the time increment, while the second is responsible for the parts‘ interaction and updates the resulting iterates.
- Assuming that both these types of development may be either discrete or continuous, we can classify relaxation techniques in the form of a diagram (see next slide).

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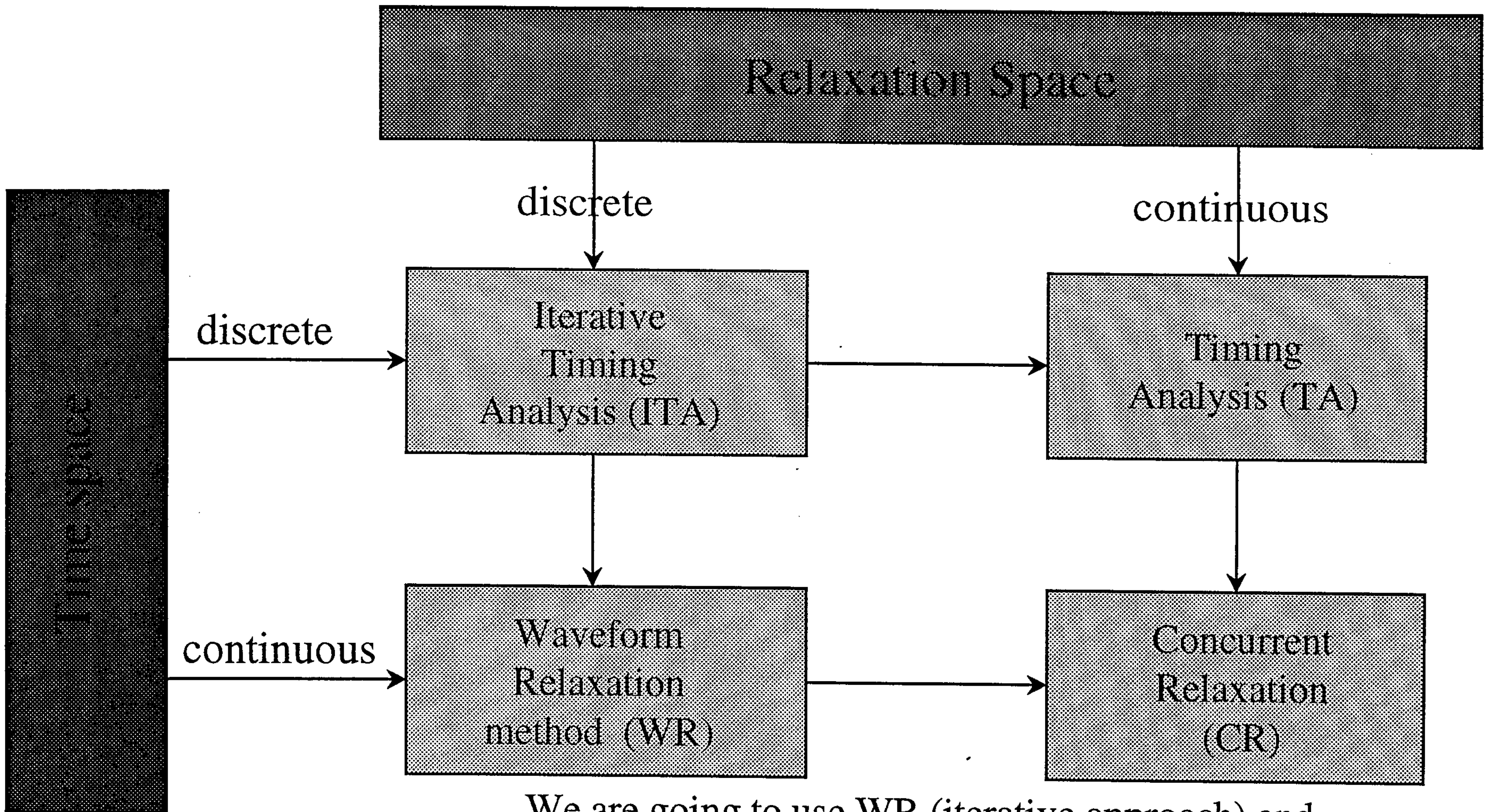
Decomposition-Based Methods for Dynamic System Analysis



We are going to use WR (iterative approach) and CR (one-sweep approach);

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- In VTB applications, the discrete-time methods, ITA and TA are not very advantageous, since they require that all models should be discretized identically, therefore, a severe synchronism is needed.
- The two approaches are promising: Waveform Relaxation and Concurrent Relaxation. They can incorporate both software and hardware models. They do not require internal synchronism in the solution process.
- WR is an iterative approach. Solution is reached after the system has repeatedly been recalculated (resimulated) several times. This is a limitation. But, instead, WR allows simulation of every part with its own speed (general clock mechanism is not needed). In the case of tight coupling WR iterations may diverge or converge very slowly.
- CR is a one-sweep simulation approach. This is an advantage. However, it requires that all processes operate in a common time space, concurrently. In case of tight coupling CR process may become unstable.

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Mathematical Model Representation

$$F_A[X_A(t), X_B(t), X_C(t)]=0$$
$$F_B[X_A(t), X_B(t), X_C(t)]=0$$
$$F_C[X_A(t), X_B(t), X_C(t)]=0$$

Original system consisting of parts A,B,C with state variables X_A, X_B, X_C

$$F_A[X_A^{i+1}(t), X_B^{i}(t), X_C^{i}(t)]=0$$
$$F_B[X_A^{i}(t), X_B^{i+1}(t), X_C^{i}(t)]=0$$
$$F_C[X_A^{i}(t), X_B^{i}(t), X_C^{i+1}(t)]=0$$

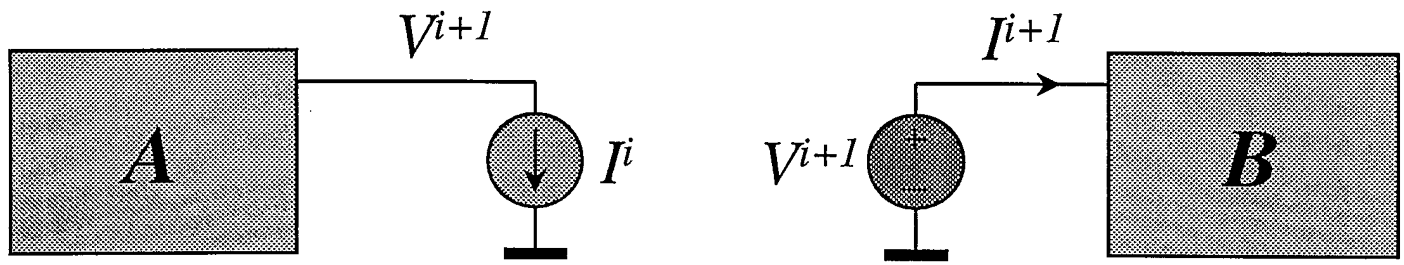
Decomposition by waveform relaxation method, i - iteration count

$$F_A[X_A(t), X_B(t-\tau), X_C(t-\tau)]=0$$
$$F_B[X_A(t-\tau), X_B(t), X_C(t-\tau)]=0$$
$$F_C[X_A(t-\tau), X_B(t-\tau), X_C(t)]=0$$

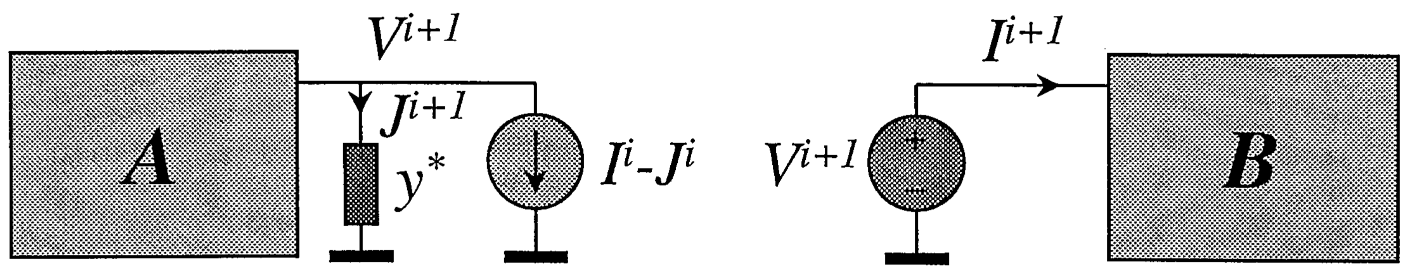
Decomposition by concurrent relaxation, τ - interaction delay

Virtual Test Bed

Modified coupling and Waveform Relaxation Method
(all iterates are time-dependent functions)



Basic coupling



Modified coupling

Virtual Test Bed

- Modified coupling is an approach to suppress an influence of the local feedback emerging in a decomposed circuit and thus to improve the convergence.
- The suppressing is deeper when the conductance y^* is closer to the input conductance of a corresponding adjacent part.
- Modified coupling can be used selectively, to suppress feedback in the particular parts separated.
- It is a very flexible approach, however, it requires some (at least approximate) information about the conductances.

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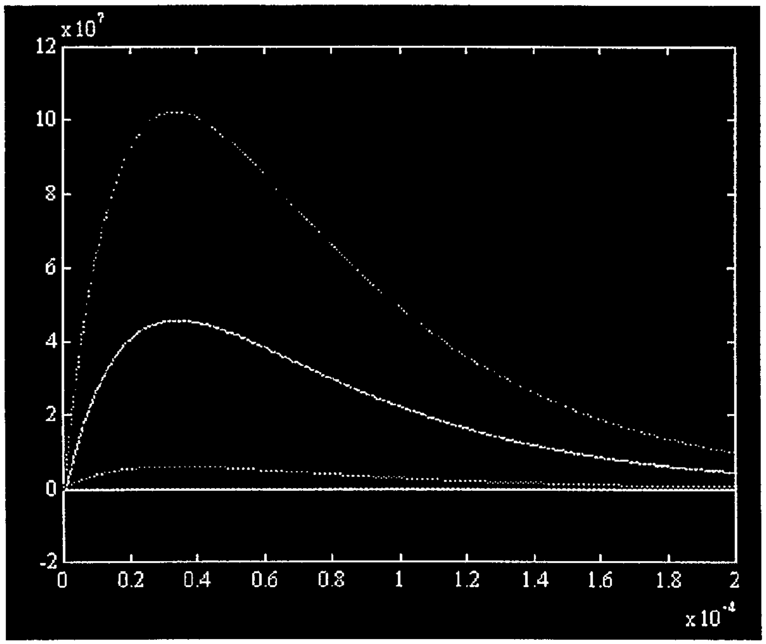
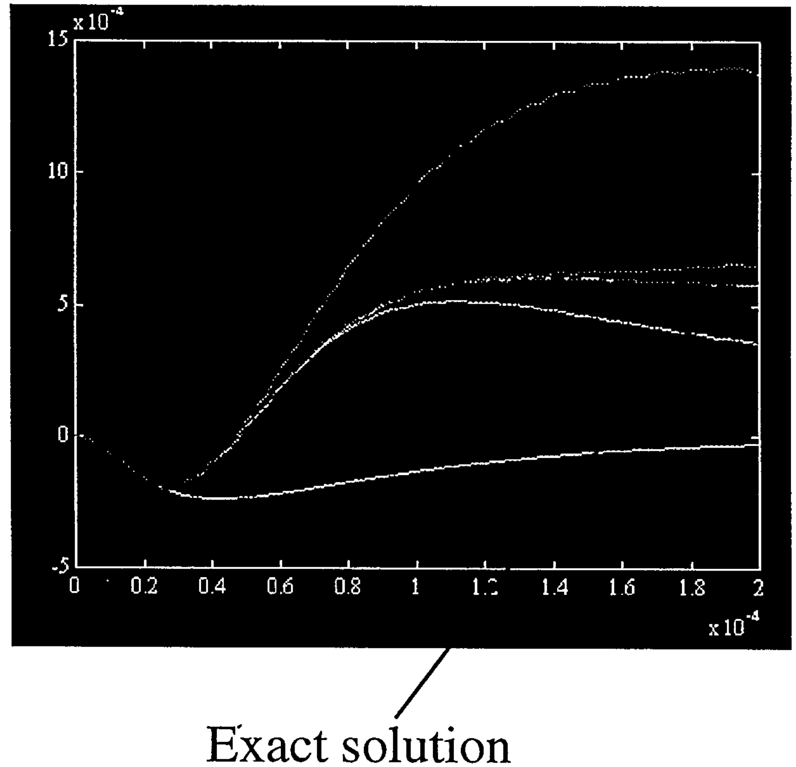
Modular approach: Simulation of tightly-coupled electro-acoustical system by waveform relaxation with two simulators: ANSYS (Swanson An. Inc.) and ELDO (ANACAD)



Basic coupling (divergence)



Modified coupling (convergence)

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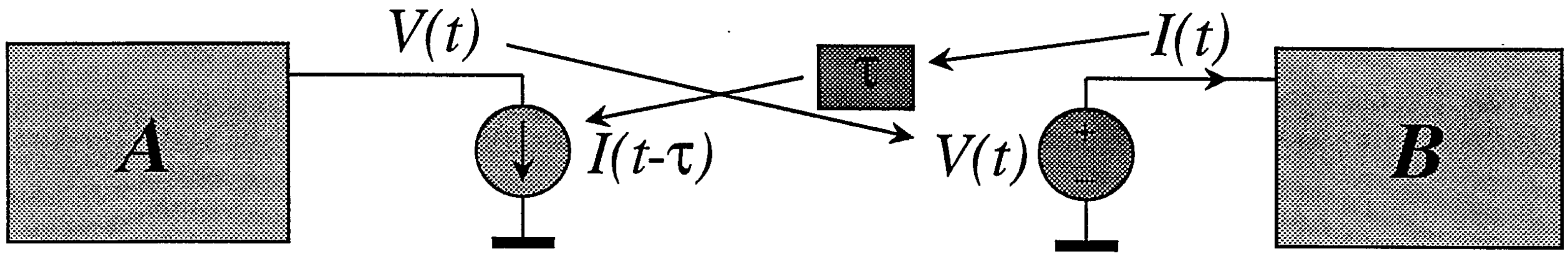
Simulation of the electro-acoustical system has been performed as follows:

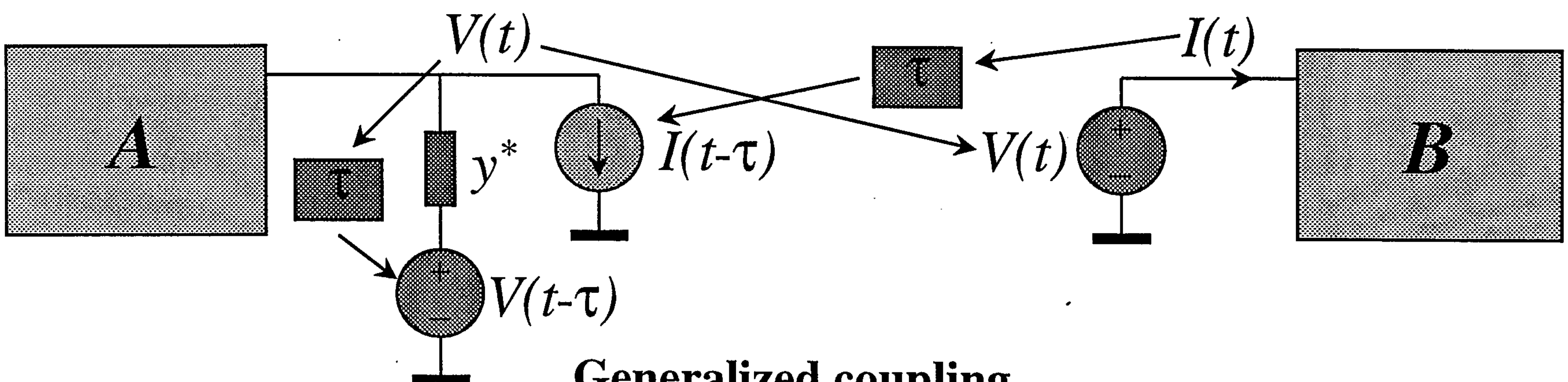
- First, we used 3-dimensional finite-element model of the ultrasonic element (in ANSYS, Solid5 model) to find its charge response on the unit voltage step.
- From this response we have derived a rough (simplified) equivalent circuit for the ultrasonic element. It contains a capacitor and an inductor connected in parallel.
- Then this rough model was used as an element y^* while simulating the whole system. The electrical part together with the element y^* was simulated by Eldo, the circuit analyzer, while the ultrasonic elements - by ANSYS.
- It was also proved that we cannot use this rough model instead of the detailed 3-dimensional ANSYS model and perform the whole analysis in Eldo only. If we do so, the results are completely different from the exact solution.
- Without using the modified coupling approach the resulting WR iterations diverge. Therefore, in a given situation the modified coupling approach has no alternative.

Virtual Test Bed

Generalized coupling and the Concurrent Relaxation Method



Basic coupling



Generalized coupling

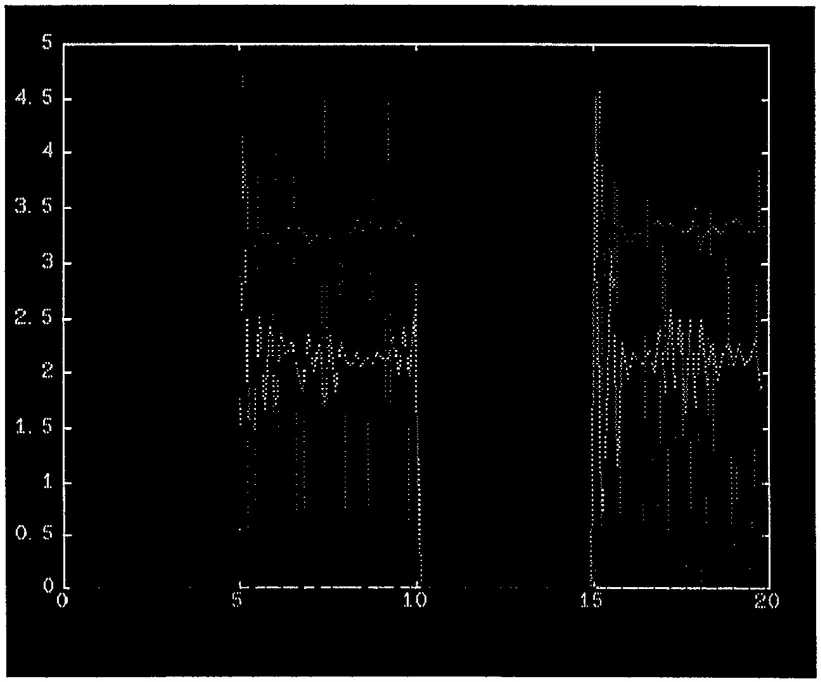
Virtual Test Bed

The generalized coupling can be considered as an extension of the modified coupling approach. The differences are:

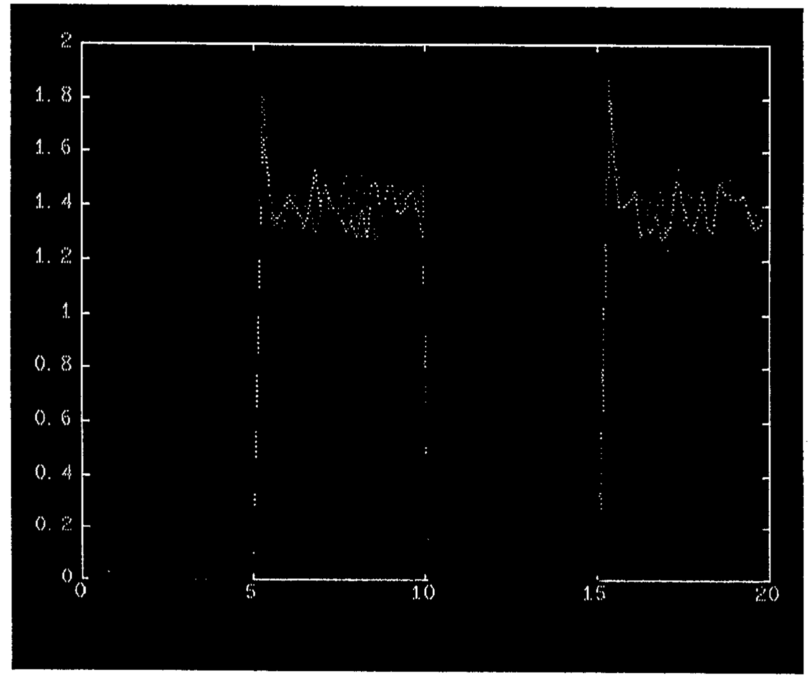
- generalized coupling allows any type of coupling feedback between two extremities: $y^*=0$ (*I*-coupling, negative local feedback) and $y^*=\infty$ (*V*-coupling, positive local feedback).
- y^* may be not constant but to dynamically follow the input conductance of the neighboring part.
- y^* can be determined by analyzing time functions $I(t)$, $V(t)$ in a circuit simulator.

Virtual Test Bed

Modular approach: Simulation of tightly-coupled electro-mechanical system by concurrent relaxation: software model of the Controlling Circuit (Spice) and the hardware model of the Motor



Basic coupling (system is unstable)



Generalized coupling (system is stable)

Virtual Test Bed

- In the above experiment we used PC with an additional processor card and a CAN-bus. The two processors could exchange data via a special section of RAM.
- The general PC clock was used to provide synchronism.
- The main processor (PC) run the Spice-like circuit simulator with software model of the controlling circuit and dynamically adjusted coupling element y^* in it.
- The card processor operated concurrently: it received codes of the input voltage via RAM and controlled the actuator.
- It was found experimentally that the system is quite stable if $1/y^*=20$ Ohm.
- However, we didn‘t use any software model of the motor&load.

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Virtual Test Bed

Conclusion:

- We proposed two easily realized methods (***modified coupling*** and ***generalized coupling***) capable to improve the performance of modular approach when applied to tightly coupled systems.
- In the case of iterative analysis (Waveform Relaxation method) these approaches ensure the ***convergence of iterations***;
- In the case of concurrent one sweep simulation they ensure the ***overall stability*** of the simulation system.
- These methods are effective in the case of strong local couplings.
- The next steps: development of ***multicycle methods*** and implementation of ***damped relaxation*** to fight against the strong ***global feedback*** as well.

Thermodynamical models

- The detailed analysis of a complicated electrical circuit requires considerable consumption of software and hardware resources. The problem grows worse if the numerical simulation has to be done in a real time scale. However, such a detailed analysis often is not needed. It is sufficient to find some coarse, general (macroscopic) parameters and characteristics of a circuit.
- The generalized approach to analysis of complicated systems requires the generalized approach to setting of system's models.
- The idea of such models might be taken from Statistical Mechanics or Thermodynamic. The mathematical description of an electrical circuit is similar to that of motive force of mechanical system, consisting of interacting particles.

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Electro-mechanicaly analogies energy - power

• Mechanical polysystem

- Generalized coordinates - q
  Mechanical impulses - p
- Hamilton Function (Energy)
  $$H(p,q) = \sum_i \frac{p_i^2}{2m_i} = \sum_i \frac{p_i}{2}\frac{dq_i}{dt_i}$$
- Hamilton equation (Movements equation)
  Main equations
  $$\frac{dq_i}{dt} = \frac{\partial H}{\partial p_i} = f_i(q,p);$$
  Conjugate equations
  $$\frac{dp_i}{dt} = -\frac{\partial H}{\partial q_i} = \varphi_i(q,p);$$
- The system state probability dencity is function of energy $w(q,p) = w(H(q,p))$
- Temperature (Energy) T

• Electrical circuits

- Inductances currents i and voltages on capacitances u
  Magnetic flux F and elelectrical charge Q
- Hamilton Function, (Reactive Power)
  $$H(\Phi_L, Q_C; i_L, u_C) = \sum_k \Phi_{Lk}\frac{di_{Lk}}{dt} + \sum_l Q_{Cl}\frac{du_{Cl}}{dt}$$
- Hamilton equation (circuit state variables)
  Main equations
  $$\frac{du_{Cm}}{dt} = \frac{\partial H}{\partial Q_{Cm}} = f_{Cm}(u_C, i_L; Q_C, \Phi_L);$$
  $$\frac{di_{Ln}}{dt} = \frac{\partial H}{\partial \Phi_{Ln}} = f_{Ln}(u_C, i_L; Q_C, \Phi_L);$$
  Conjugate equations
  $$\frac{dQ_{Cm}}{dt} = -\frac{\partial H}{\partial u_{Cm}} = \varphi_{Cm}(u_C, i_L; Q_C, \Phi_L);$$
  $$\frac{d\Phi_{Ln}}{dt} = -\frac{\partial H}{\partial i_{Ln}} = \varphi_{Ln}(u_C, i_L; Q_C, \Phi_L)$$
- The circuit state probability dencity is function of power
  $$w(u_C, i_l; Q_C, \Phi_L) = w(H(u_C, i_l; Q_C, \Phi_L))$$
- Analogue Temperature (Power) θ

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- Circuit Equations

$$\frac{du_{Cm}}{dt} = f_{Cm}(u_C, i_L; z); \qquad \frac{di_{Ln}}{dt} = f_{Ln}(u_C, i_L; z);$$

$$y_k = f_k(u_C, i_L; z); \; z_k - \text{influences}, \; y_k - \text{respondes}$$

- Hamilton Function

$$H(Q_C, \Phi_L, u_C, i_L; z) = \sum_m (Q_{Cm} f_{Cm}) + \sum_n (\Phi_{Ln} f_{Ln});$$

- Hamilton Equation

$$\frac{du_{Cm}}{dt} = \frac{\partial H}{\partial Q_{Cm}}; \quad \frac{di_{Ln}}{dt} = \frac{\partial H}{\partial \Phi_{Ln}}; \quad \frac{dQ_{Cm}}{dt} = -\frac{\partial H}{\partial u_{Cm}}; \quad \frac{d\Phi_{Ln}}{dt} = -\frac{\partial H}{\partial i_{Ln}};$$

- Distribution Function

$$w(H(Q_C, \Phi_L, u_C, i_L; z)) = \frac{1}{\Lambda} \exp\left(-\frac{\sum_m (Q_{Cm} f_{Cm}) + \sum_n (\Phi_{Ln} f_{Ln}) - \sum_k y_k z_k}{\theta}\right);$$

- Normalizing

$$\int_\Gamma w \cdot d\Gamma = 1; \qquad \Lambda = \int_\Gamma \exp\left(-\frac{\sum_m (Q_{Cm} f_{Cm}) + \sum_n (\Phi_{Ln} f_{Ln}) - \sum_k y_k z_k}{\theta}\right) d\Gamma;$$

$$d\Gamma = \frac{dQ_{Cm} du_{Cm} d\Phi_{Ln} di_{Ln}}{(kT)^{M_C} (kT)^{N_L}};$$

- Analog of Liuvill equation for w

$$\frac{dw}{dt} = \frac{\partial w}{\partial t} - \{H, w\} = \frac{\partial w}{\partial t} - \sum_{k,l} \left(\frac{\partial H}{\partial \Phi_{Lk}} \cdot \frac{\partial w}{\partial i_{lk}} + \frac{\partial H}{\partial Q_{Cl}} \cdot \frac{\partial w}{\partial u_{Cl}} - \frac{\partial H}{\partial i_{Lk}} \cdot \frac{\partial w}{\partial \Phi_{Lk}} - \frac{\partial H}{\partial u_{Cl}} \cdot \frac{\partial w}{\partial Q_{Cl}} \right)$$

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- Circuits entropy

$$S = \int_\Gamma w(\Phi_L, i_L, Q_C, u_C; z, t) \ln(w(\Phi_L, i_L, Q_C, u_C; z, t)) d\Gamma =$$
$$= \ln \Lambda - ((\sum_k \overline{y_k} \cdot z_k) / \theta) + \overline{H} / \theta$$

- Circuits information quantity

$$I = S_m - S = -\int_\Gamma (w(\ln \prod_k w_{Lk} \prod_l w_{Cl}) - \ln w) d\Gamma,$$

where $S_m = -\int_\Gamma w(\ln \prod_k w_{Lk} \prod_l w_{Cl}) d\Gamma$ - M - entropy (multiplicity entropy);

w_{Lk}, w_{Cl} – 1 - partial distribution function:

$$w_{Lk} = \int_\Gamma w \cdot \frac{kTd\Gamma}{d\Phi_{Lk} di_{Lk}}; \qquad w_{Cl} = \int_\Gamma w \cdot \frac{kTd\Gamma}{dQ_{Cl} du_{Cl}}$$

- Average values of responses

$$\overline{y_k} = \int_\Gamma z_k w d\Gamma = \frac{\partial}{\partial} \frac{(\ln \Lambda)}{(z_k / \theta)};$$

- Responses deviation

$$\overline{y_k^2} = \frac{\partial}{\partial} \frac{\overline{y_k}}{(z_k / \theta)}$$

- Intercorrelation

$$\overline{y_k y_l} - \overline{y_k}\,\overline{y_l} = \frac{\partial}{\partial} \frac{\overline{y_k}}{(z_l / \theta)} = \frac{\partial}{\partial} \frac{\overline{y_l}}{(z_k / \theta)}$$

- Reactive and consumed power

$$\overline{H} = -\frac{\partial}{\partial} \frac{(\ln \Lambda)}{(1/\theta)}; \quad \overline{H^2} - \overline{H}^2 = \frac{\partial}{\partial} \frac{(H)}{(1/\theta)}; \quad P_0 = \overline{H} + \sum_k \overline{y_k} \cdot z_k$$

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- <u>Linear circuit.</u>

a) Matrixes circuits equations $\frac{d|x|}{dt} = [s]\cdot|x| + [R]\cdot|z|; \quad |y| = [F]\cdot|x| + [Q]\cdot|z|$

b) Statistical weight

$$\ln\Lambda = \ln\left(\frac{4\theta}{kT}\sqrt{\det[g_{S'}]}\right)^{M} + \frac{1}{\theta}\left(\sum_{k=1}^{N_z} Z_{k0}\sum_{l=1}^{N_z}(Q_{kl} - F''_{kl})Z_{l0}\right) - \sigma(T - T_c) +$$

$$+\sum_{i=1}^{M}\ln\left(\frac{\delta_{H_i}\,\mathrm{sh}\left(\frac{1}{\theta}\left(\rho_{i0} - \sum_{k=1}^{N_z} Z_{k0}F'_{ki}\right)\delta_{dx_i/dt}\right)}{\left(\rho_{i0} - \sum_{k=1}^{N_z} Z_{k0}F'_{ki}\right)\delta_{dx_i/dt}}\right),$$ where F'_{ki}, F''_{kl} - elements of matrixes $[F']$, $[F'']$

$[F'] = [F]\cdot[S]^{-1}$, $[F''] = [F']\cdot[R]$; $[g_{S'}]$ – matrix, having $g_{S'kl} = \sum_r M'_{kr}\cdot M'_{rl}$, $[M'] = [M]^{-1}$

c) Information quantity

$$I = S_m - S = \ln\frac{\left(\sqrt{\det[g_{S'}]}\right)^{M-1}}{\prod_{i=1}^{M}\sqrt{[g_{iS'}]}},$$ where $[g_{iS'}]$ – diagonal minor of matrix $[g_{S'}]$

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- Nonlinear circuit: semiconductor chip with p-n-junctions

  a) Circuit equations:

Entropy quantity

$|I| = [E] \cdot |I_{p-n}| + [\alpha] \cdot |I_{p-n}| + ([Y] + [sC]) \cdot |U|; \qquad |I_{p-n}| = [I_s] \cdot (\exp([\varphi_T]^{-1} \cdot (|U| - [R] \cdot |I|)) - |1|),$

where $|\ |$ - means vector of variables images, $[\ ]$ - means matrix of parameters

$$\ln \Lambda = \ln\left(\frac{2\theta}{kT}\sqrt{[g_{s'}]}\right) + \frac{1}{\theta}\left(\sum_k I_k \sum_l (R_{kl} I_l + E^T_{kl} U_{pnl}(I) + \sigma(T - T_c)\right) + \sum_k \frac{C_k \cdot \delta_{uk}\delta_{ik}}{\Delta_k} \cdot \mathrm{sh}\,\frac{\Delta_k}{\theta},$$

where $\Delta_k = \frac{\delta_{ik}}{\theta}\left(U_{pnk} - \sum_l I_l \frac{F'_{lk}}{C_k}\right)$

$$S = \ln \Lambda - \sum_k I_k U_k + \sigma(T - T_c) = \sum_{l=1}^{M} \ln\left(\frac{2\tau_s \delta_{ul}\delta_{il}}{kT_c} \cdot \frac{\mathrm{sh}\Delta_l}{\Delta_l}\right), \text{ where } \tau_s^{\ M} = \sqrt{[g_{s'}]}$$

$$I = S_m - S = \ln \frac{\left(\sqrt{\det[g_{s'}]}\right)^{M-1}}{\prod_{i=1}^{M} \sqrt{[g_{is'}]}}, \text{ where } [g_{is'}] - \text{diagonal minor of matrix } [g_{s'}]$$

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- <u>Analogs of thermodynamical equalities</u>
- Entropy $S = \ln \Lambda - \frac{P_{el}}{\theta} - \frac{P_{ot}}{\theta}$, where $P_{el} = \sum_{k=1}^{N} I_k \overline{U}_k$ – electrical pouer; P_{ot} – enviroment pouer
- a) $P_{ot} = 0$, $\Delta P_{el} = \frac{P_{el}}{\theta} \cdot \Delta\theta - \theta \cdot \Delta S$; $\Delta P_{el} = P_{el2} - P_{el1}$, $\Delta\theta = \theta_2 - \theta_1$, $\Delta S = S_2 - S_1$
- b)

$$\frac{\Delta\theta}{\theta} = \frac{\Delta P_{el}}{\theta}, \quad \text{a. f.} \quad \frac{\theta_2}{\theta_1} = \frac{P_{el2}}{P_{el1}};$$

$$\theta = \text{const:} \quad \Delta S = -\frac{\Delta P_{el}}{\theta}, \quad \text{a. f.} \quad S_2 - S_1 = \frac{P_{el1} - P_{el2}}{\theta};$$

$$P_{el} = \text{const:} \quad \Delta S = \frac{P_{el}}{\theta^2} \cdot \Delta\theta, \quad \text{a. f.} \quad S_2 - S_1 = P_{el}\left(\frac{1}{\theta_1} - \frac{1}{\theta_2}\right);$$

Conclusion

- Proposed EHM method allows to find any "external" (macroscopic, thermodynamical, operating) parameters characterizing the circuit's mode of operation.
- The field of application of EHM is express-analysis of electronic control systems.
- Using of EHM doesn't require solution of circuits differential equations .
- By means of such models we can determinate electrical state of power system, i.e. power fluctuations, entropy, information efficiency, average values and deviation of responses on electrical signals and nonelectrical influences and intercorrelation of responses.
- It is possible to take into account not only electrical but also other types of excitations from environment during operation (destabilizing factors) that allows to estimate their influence on the circuit operation.

The movements separation method in modeling of power systems

Jordan canonical models

A processes in power and electrical systems can be described in form of matrix differential equation in Couchy form:

State equations in the Coushy form:

$$\dot{\vec{x}} = A\vec{x} + B\vec{v}; \quad \vec{y} = C\vec{x},$$

By similarity transform: $AQ=Q\Lambda$, where Λ – Jordan form of matrix A let's turn into Jordan basis

Transfer matrix of modeling system:

$$T(p) = CQ(Ep - \Lambda)^{-1} Q^{-1} B = \sum_{i=1}^{s} \vec{C}'_i \cdot \Theta_i^{-1} \cdot \vec{B}'_i$$

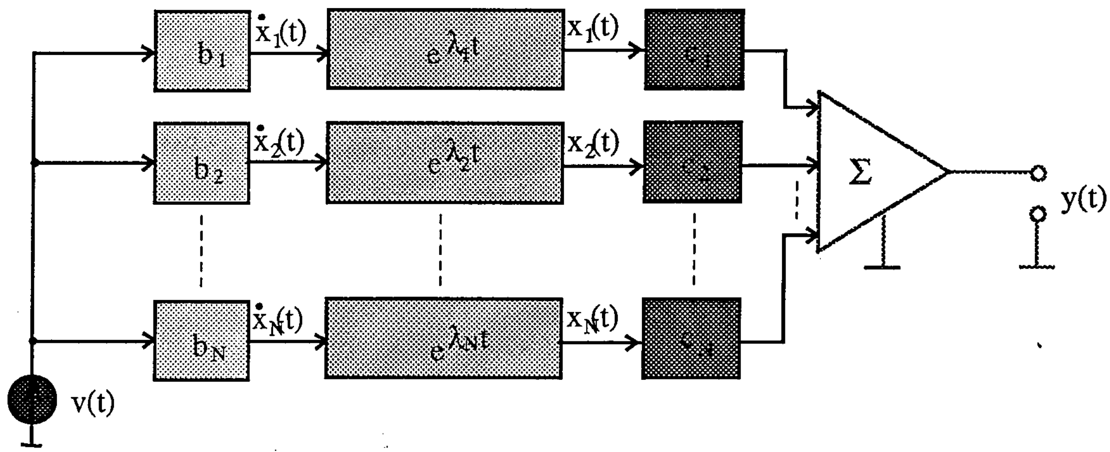
Given transfer matrix may be interpreted as model of parallel-cascade structure, which consists from separated independent submodels, having its own time constant $\tau_i = -\frac{1}{Re(\lambda_i)}$, where λ_i - i-s eigenvalue of matrix A.

By means of such model, electrical processes having the different speeds should be located in different part of the considering system.

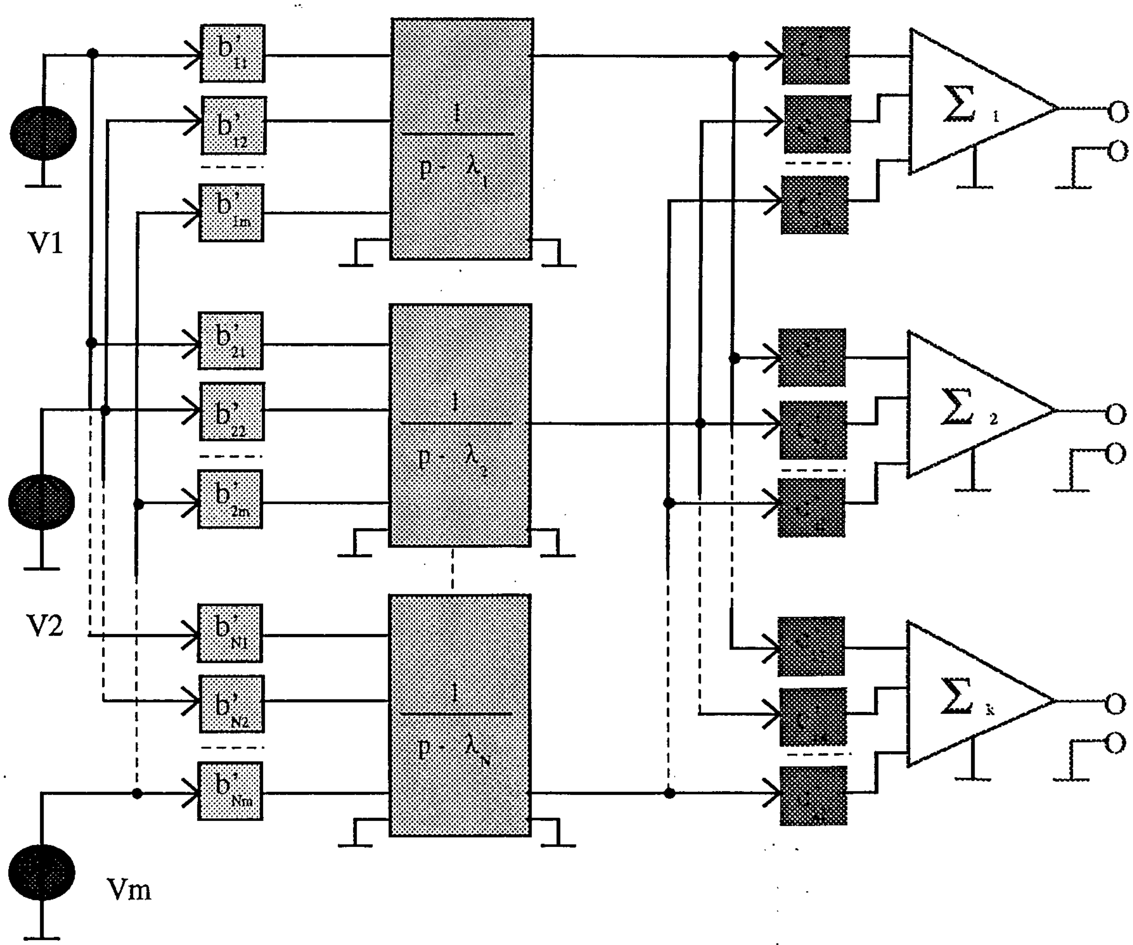
That why method, based on transformation of initial mathematical model to Jordan canonical form we call as **<u>movements separation method</u>** or method of decomposition in the time domain.

The structure of circuits with separated movements

1. The case of single-input - single-output circuit:

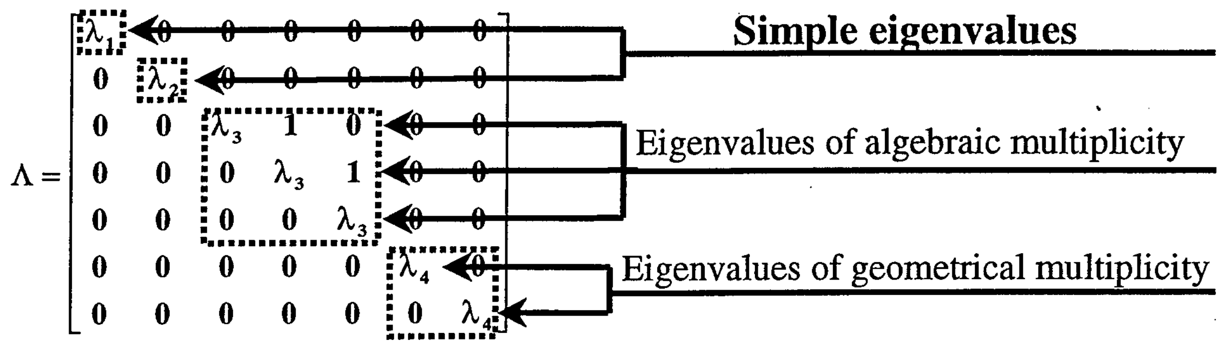


2. The case of multipoles circuit:



Partial transfer functions which corresponds to all possible types of Jordan cells

From structure of system matrix in the Jordan basis followed, that type of any partial transfer function is determine by type and multiplicity of correspondent eigenvalue of the Jordan cell. Hence, for obtaining the such set of primitive circuits is necessary to investigate all cases of types and eigenvalues multiplicity of system matrix Λ.



1. Simple eigenvalue:

$$K_i(p) = \vec{C}_i' \cdot \Theta_i^{-1} \cdot \vec{B}_i' = \frac{c_i' \cdot b_i'}{(p - \lambda_i)}$$

2. Complex-conjugate pair eigenvalues:

$$K_i(p) = \frac{a_1 p + a_0}{p^2 + b_1 p + b_0}$$

3. Simple eigenvalue of algebraic multiplicity:

$$K_i(p) = \sum_{m=1}^{r_i} \sum_{k=1}^{r_i - m+1} \frac{b_k' c_{k+m-1}'}{(p - \lambda_i)^m}$$

4. Complex-conjugate pair eigenvalues of algebraic multiplicity:

$$K_i(p) = \sum_{m=1}^{r_i} \sum_{k=1}^{r_i - m+1} \frac{a_{0mk} p + a_{1mk}}{(p^2 + b_1 p + b_0)^m},$$

5. Simple eigenvalue of geometric multiplicity:

$$K_i(p) = \sum_{j=1}^{r_i} k_j(p)$$

$$k_j(p) = C_j' \Theta_j^{-1} B_{r_i}' = \frac{c_j' \cdot b_{r_i}'}{p - \lambda_i}$$

6. Complex-conjugate pair eigenvalues of geometric multiplicity:

$$K_i(p) = \sum_{j=1}^{r_i} k_j(p)$$

$$k_i(p) = \frac{a_1 p + a_0}{p^2 + b_1 p + b_0}$$

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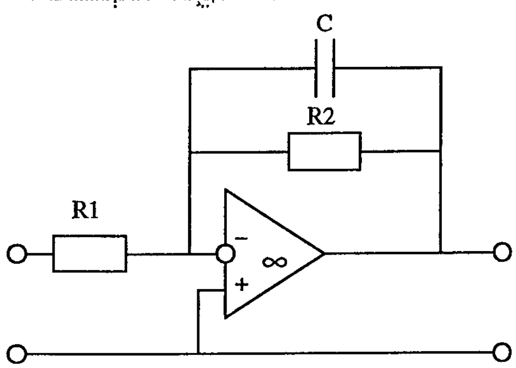
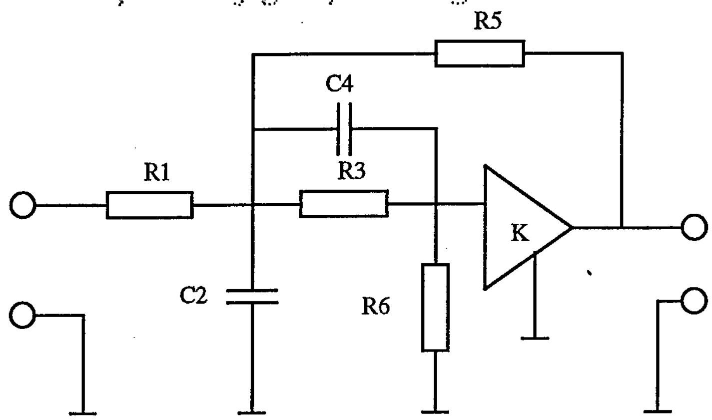
Realizations of all possible types of Jordan cells:

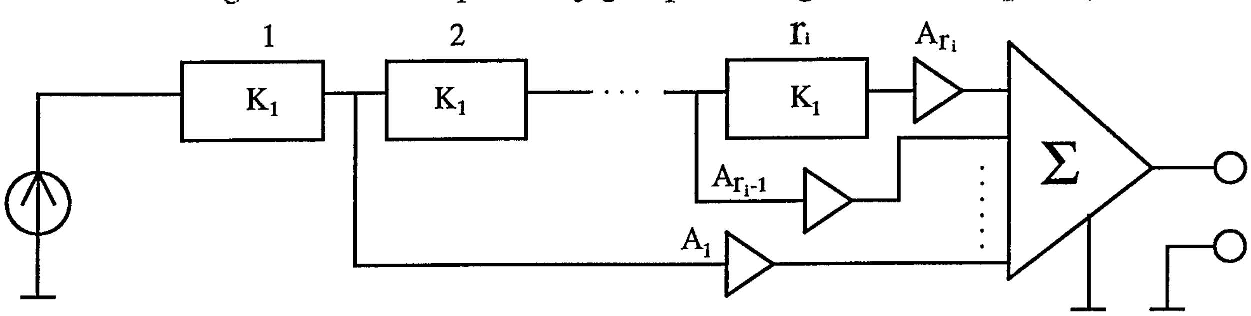
1. Simple eigenvalue.



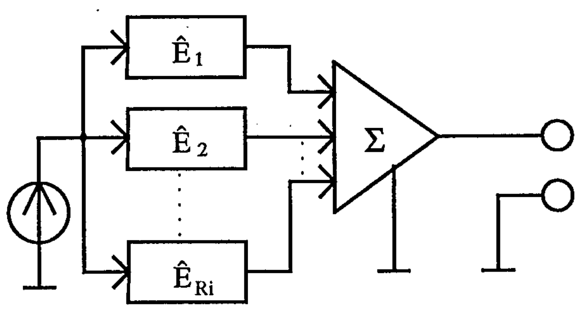
2. Complex-conjugate pair of eigenvalues.



3 - 4. Simle eigenvalue or complex-conjugate pair of algebraic multiplicity r_i .



5 - 6. Simle eigenvalue or complex-conjugate pair of geometric multiplicity r_i .



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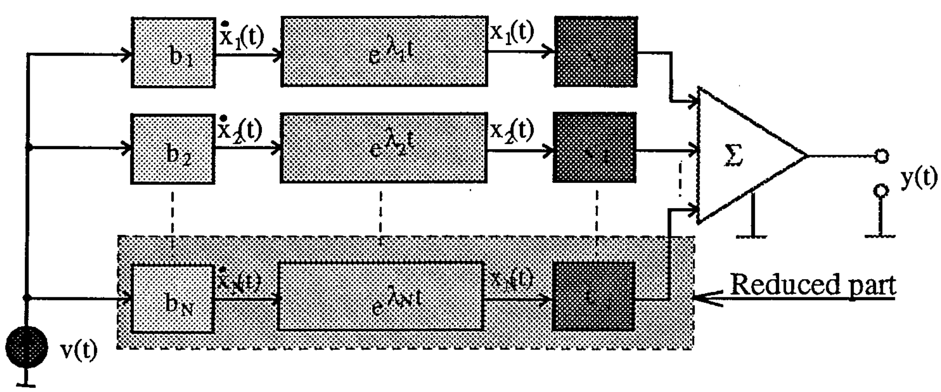
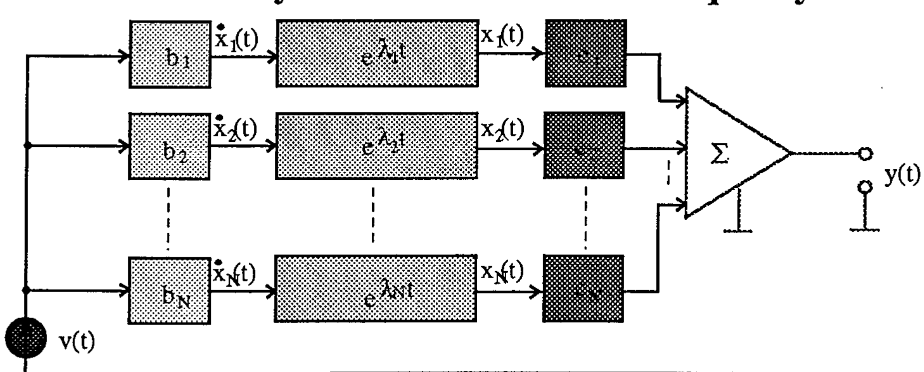
Reduction of circuits with separated movements

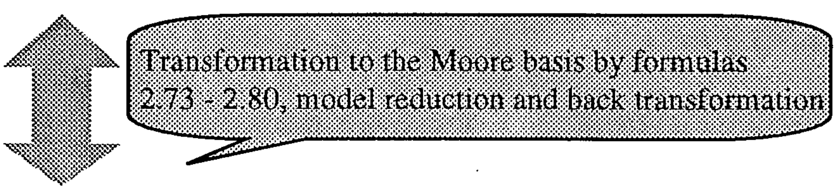
1. Reduction in the time domain:

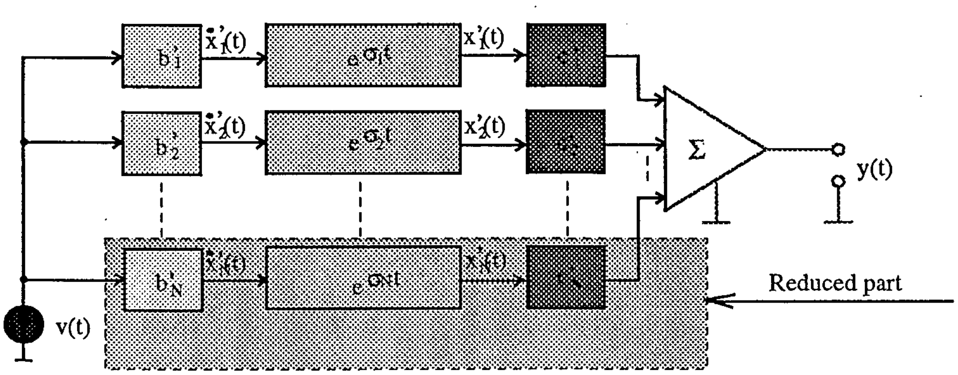


In the Jordan basis system eigenvalues are separated. Due to any eigenvalue determine the speed of partial transient process the movements separation method open the way to system reduction in time domain by removing parts with the smallest eigenvalues.

2. Simultaneously reduction in time and frequency domains:







In the Moore basis system singularvalues are separated. As any singularvalue determine energetic contribution to the system dynamic behavior then we can reduce system simultaneously in time and frequency domains by removing parts with the smallest singularvalues .

By means of (2.73-2.80) relations between Jordan and Moore basises we can accomplish flexible reduction, not only in the time domain, but also in time and frequency domains simultaneously

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Controllability and observability of circuits with separated movements

Controllable if $\vec{B}, A\vec{B}, \ldots, A^{N-1}\vec{B}$ are linear independent.

Observable if $\vec{C}^T, A^T\vec{C}^T, \ldots, [A^T]^{N-1}\vec{C}^T$ are linear independent.

In the Jordan Basis

$$\begin{cases} \mathrm{Det}\left[\vec{B}' \quad A\vec{B}' \quad A^2\vec{B}' \quad \cdots \quad A^{N-1}\vec{B}'\right] \neq 0 \\ \mathrm{Det}\left[\vec{C}' \quad \vec{C}'A^T \quad \vec{C}'\left[A^T\right]^2 \quad \cdots \quad \vec{C}'\left[A^T\right]^{N-1}\right] \neq 0 \end{cases}$$

$$\begin{cases} \left(\prod_{i=1}^{N} b'_i\right) \cdot \mathrm{Det}(V) \neq 0 \\ \left(\prod_{i=1}^{N} c'_i\right) \cdot \mathrm{Det}(V) \neq 0 \end{cases}$$

V - Vandermond matrix

System matrix have a simple spectra.

Controllability and observability are defined by controllability and observability coefficients respectively.

System matrixincludes eigenvalues of algebraic multiplicity

Controllability and observability of circuit depends only from it part which doesn't include eigenvalues of algebraic multiplicity.

System matrix includes eigenvalues of geometric multiplicity

Circuit is uncontrollable and unobservable independently of controllability and observability coefficients.

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Conclusions

•1. Transformation of operator with given input-output map for power systems and its components to Jordan form is equivalent to construction of system with such structure that processes having the different speeds should be located in different parts of that system. In this case we have system with time and space-separated movements. Processes in different parts of the such system are independent one from another.

•2. Mathematician model of any electrical network in Jordan form can be constructed in form of parallel-sequential structure. In the general case this structure can be composed from six base primitive circuits which are determining by type and multiplicity of correspondent eigenvalues of mathematician model. With help of such structure the tasks of modeling and synthesis can be solved by determination number, type and parameters of primitive circuits.

•3. Space and time model decomposition gives possibility of effective using analysis methods, based on movements separation (direct integration methods, adaptive algorithms) as well as algorithms, based on space decomposition of the system (relaxation methods, iterative algorithms of type Gauss-Jacobi and Gauss-Zeidel).

•4. Jordan canonical models are very effective in setting the hierarhial families of circuit and system models. They are effective for making model reduction in the time domain.

•5. For simultaneous reduction in the time and frequency domains great results might be received by transformation the Jordan models into Moore basis.

•6. The general features (controllability and observability) of circuits with such models have been investigated.

•7.The circuit synthesis method based on Jordan canonical models have been developed.

•8. Suggested model is an invariant for a set of power (or electrical) systems having similar input-output characteristics and can be used as abstract class for models derivation in CAD systems.

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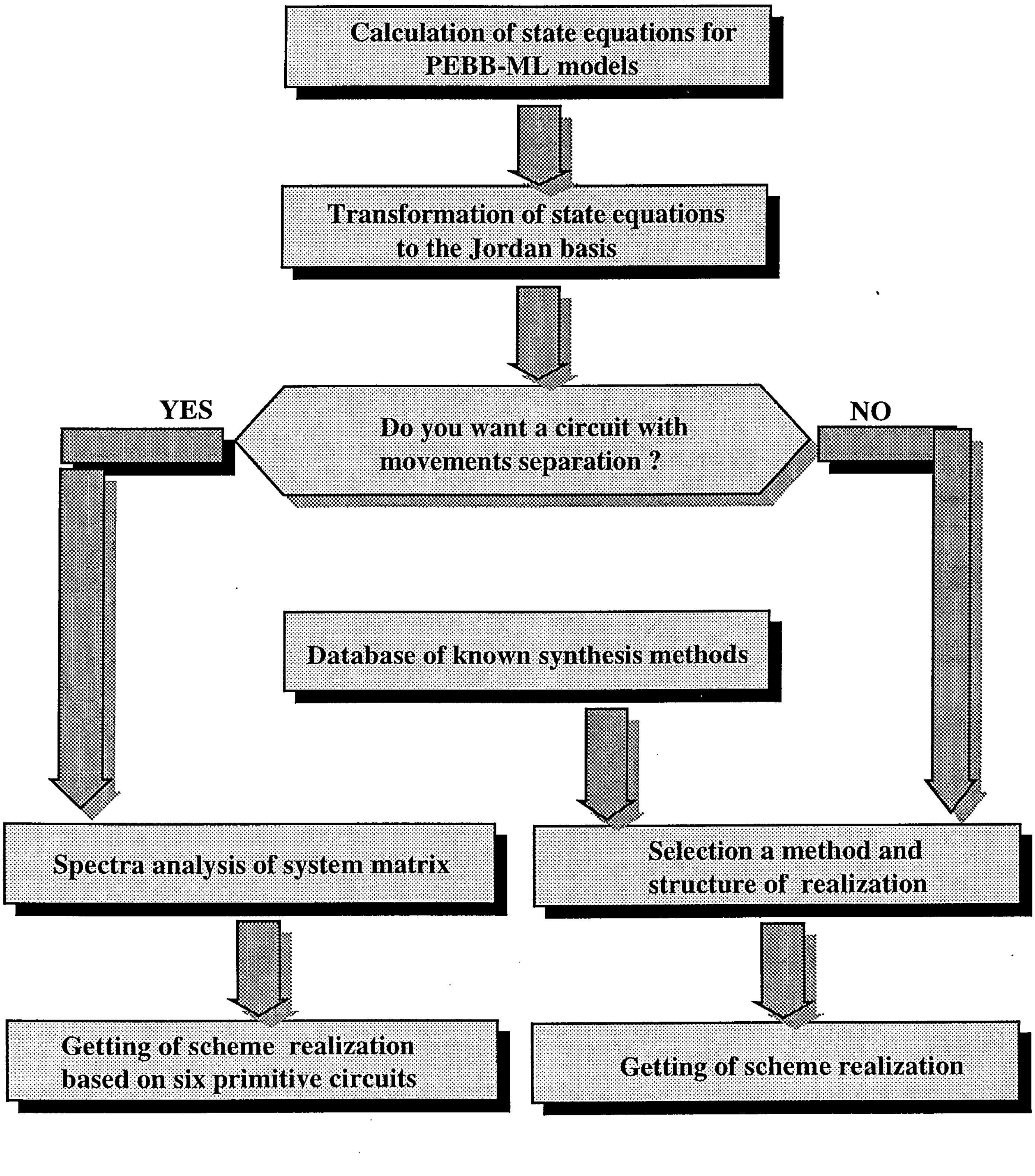
Electrical circuits synthesis algorithm, based on the movements separation



Pseudocode of the algorithm:

```
CStateEquations StateEquations, JordanEq;
StateEquations = CalculateStateEquations(AFCArray /* TransientFunArray */);
JordanEq = TransformToJordan(StateEquations);
if (JordanBasis())
{
  CListOfEigenValues eig = JordanEq.GetEigenValues();
  CListOfControl ControlVector;
  CListOfObserve ObserveVector;
  CJordanBlocksList JordanBlocks = NULL;
  eig.First();
  int n_Multiplicity;
  for (int i = 0; i < eig.GetLength(); i++)
  {
    if (eig.GetType() == TYPE_REAL)
    {
      Multiplicity = eig[i].GetMultiplicity();
      JordanBlocks.Add(GiveRealBlock(eig[i], ControlVector[i],
                                     ObserveVector[i], n_Multiplicity));
     i += n_Multiplicity - 1;
    }
    else // Complex pair of eigenvalues
    {
      Multiplicity = eig[i].GetMultiplicity();
      JordanBlocks.Add(GiveComplexBlock(eig[i], ControlVector[i],
                                     ObserveVector[i], n_Multiplicity));
      i += 2*n_Multiplicity - 1;
    }
  }
  ConnectJordanBlocks(&JordanBlocks);
}
else
{
  switch (BASIS)
  {
    case PARALLEL:
      CalculateParallelRealization(JordanEq);
      break;
    case CASCADE:
      CalculateSequentialRealization(JordanEq);
      break;
    case MOORE:
      CalculateMooreRealization(JordanEq);
      break;
    case FENCES:
      CalculateFencesRealization(JordanEq);
      break;
    default:
      break;
  }
}
```

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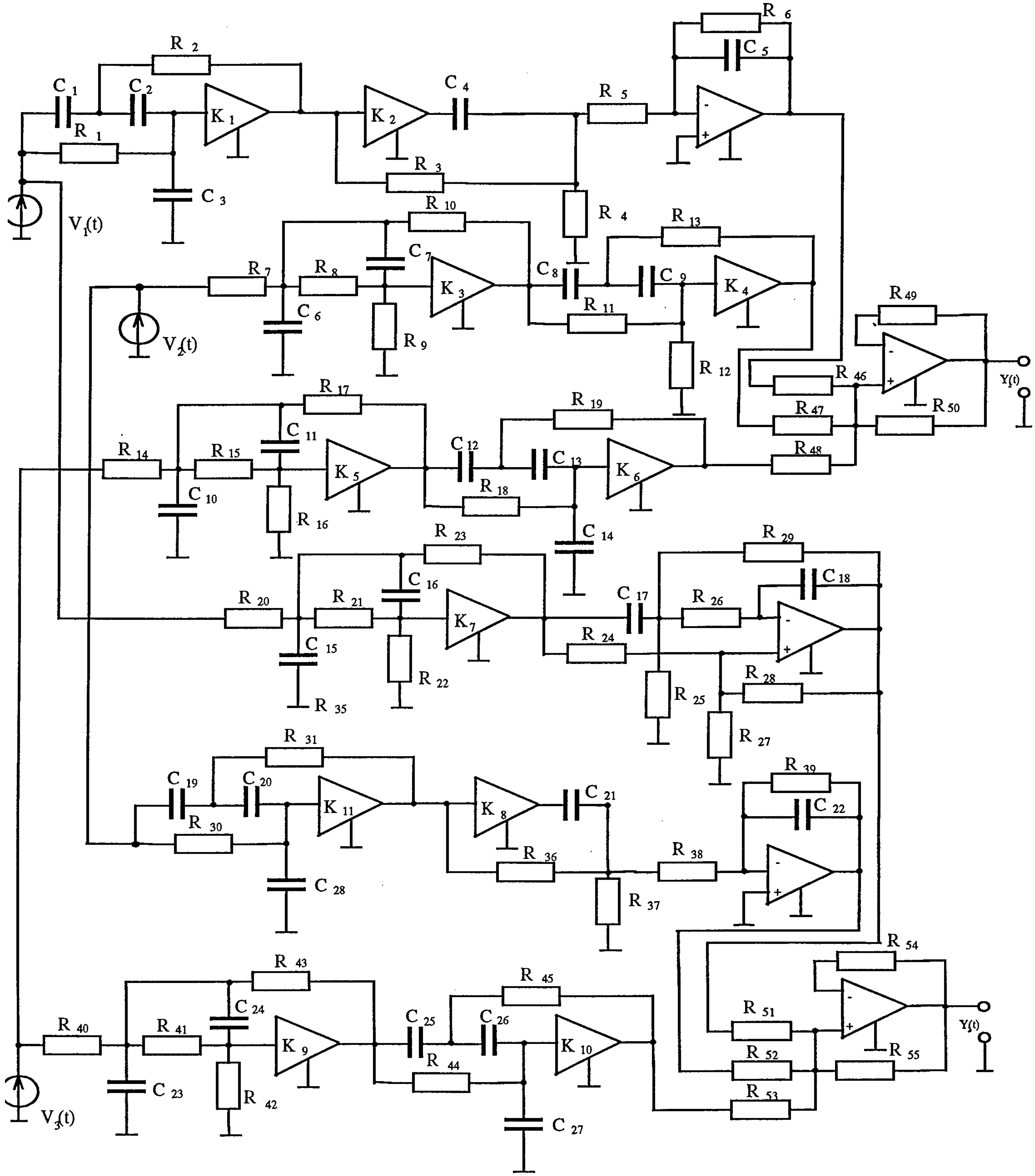
An example of circuit realized by it transfer matrix



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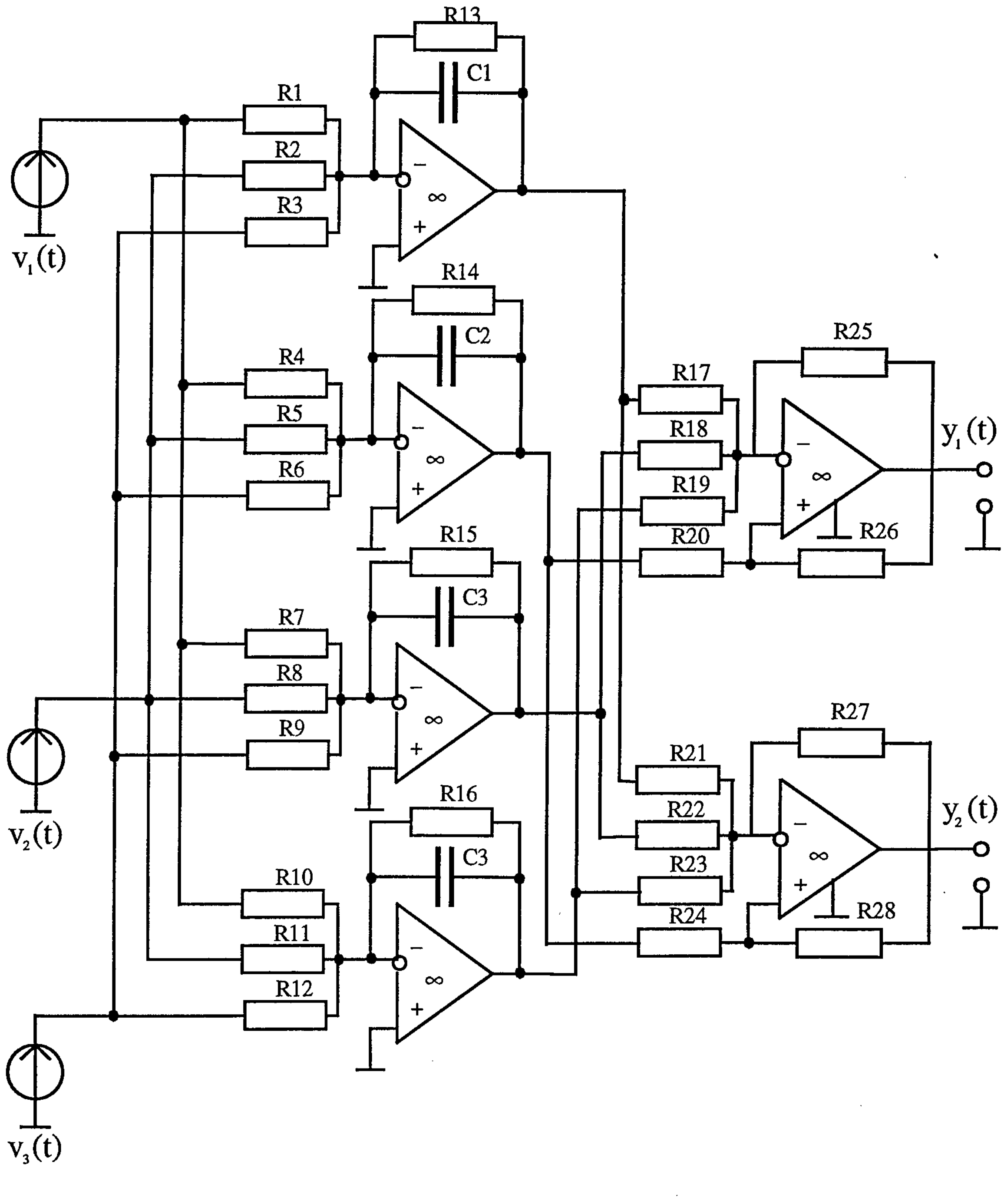
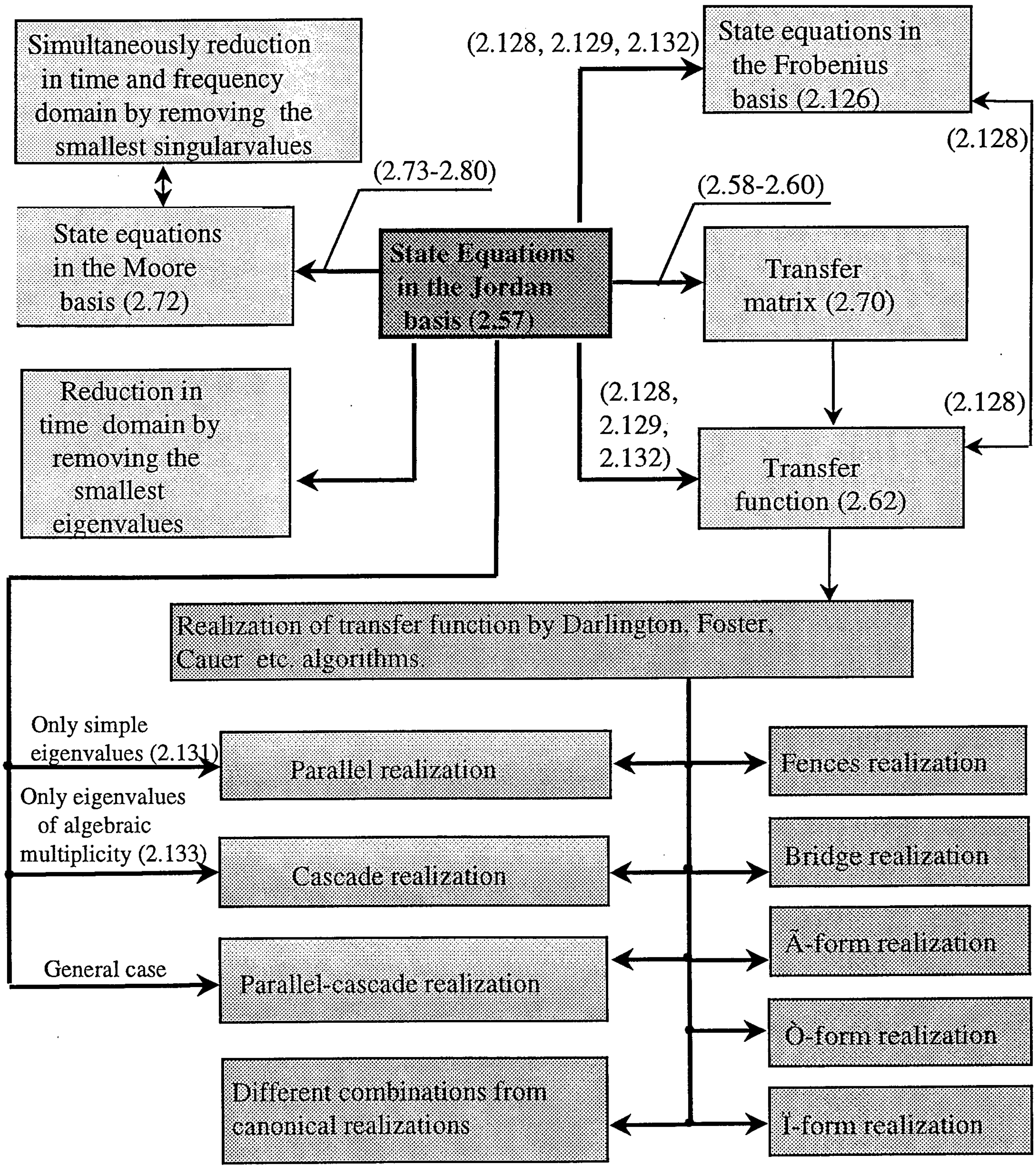
An example of circuit with separated movements which equivalent to shown on previous slide



Relations between the movements separation method and other circuit synthesis methods.



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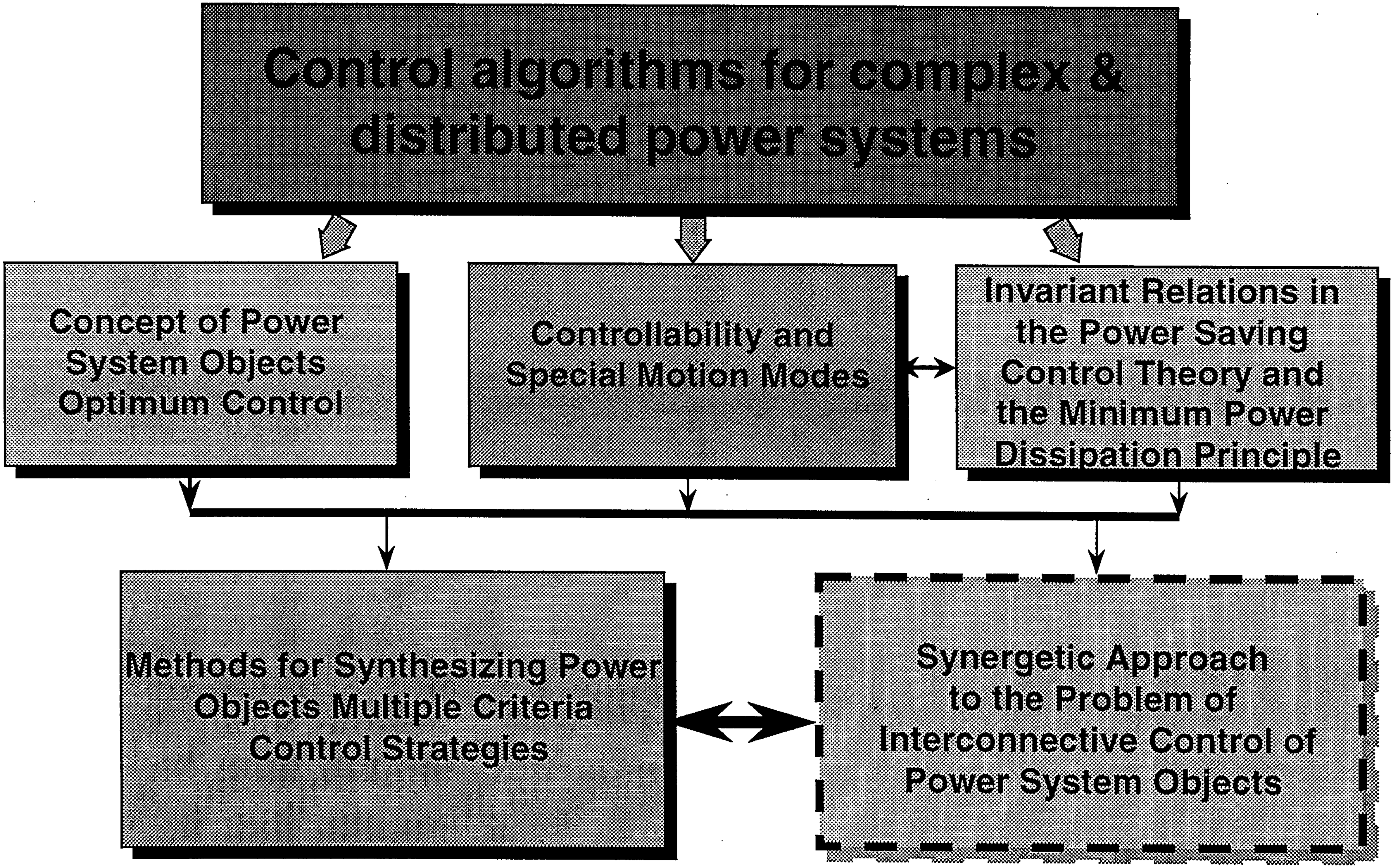

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Theoretical Foundations for Developing New Strategies of Power System Objects Multicriterial Control

Concept of Power System Objects Optimum Control

Power system control should provide the realization of three basic requirements to its regimes:

- **reliability and stability of the consumers power supply ;**
- **guaranteeing normative quality of produced power;**
- **a general economy of power system operation .**

Power Objects Dynamic Peculiarities

- *multi-connectivity*
- *non-linearity*
- *multi-dimensionality*

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The concept of power, substance and information controlled interaction allows to formulate the following basic directions for detecting new multicriterial control strategies of power system object:

- ***development of an applied theory for optimal power saving control based on the synergetic approach and minimum power dissipation principle;***

- ***development of an applied synthesis methods and implementation of multi-criterial control laws opimal by totality of power consumption, performance and accuracy criteria;***

- ***development of applied synergetic methods for synthesizing and implementing power saving control laws providing best accordance of power object natural properties and requirements to its technological processes.***

Theoretical Foundations of Power Systems Objects Optimum Control

The technological process in a power object is described by the system of non-linear differential equations:

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}, \mathbf{u})$$

It is required to find the admissable control u transfering power object from a certain initial state $\mathbf{x}(0)$ to a final one $\mathbf{x}(T)$ and minimizing a quality criterion in the form of the funcional on motion trajectories

$$I = \int_0^T f_0(\mathbf{x}, \mathbf{u})dt$$

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Generalized functional is specified for the following quality criteria

minimizing fuel or substance expenditure

$$I_1 = \int_0^T \sum_{k=1}^m c_k |u_k| dt$$

minimizing power expenditure

$$I_2 = \int_0^T \sum_{k=1}^m c_k^2 u_k^2 dt$$

minimizing power expenditure along with a high accuracy of control

$$I_3 = \int_0^T \left(\sum_{k=1}^m a_k^2 x_k^2 + c_k^2 u_k^2 \right) dt$$

minimizing transient processes time

$$I_4 = \int 1 dt$$

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Hamilton's functions

For I_1 *and* I_2

$$H_1 = f_0(\mathbf{u})\psi_0 + f(\mathbf{x},\mathbf{u})\psi$$

$$\dot{\psi}(t) = -\left(\frac{\partial f(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}}\right)'\psi$$

For I_3

$$H_2 = f_0(\mathbf{x},\mathbf{u})\psi_0 + f(\mathbf{x},\mathbf{u})\psi$$

$$\dot{\psi}(t) = -\left(\frac{\partial f_0(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}} + \frac{\partial f(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}}\right)'\psi$$

Controllability and Special Motion Modes

$$\dot{\mathbf{x}}(t) = A(\mathbf{x}) + B(\mathbf{x})\mathbf{u}$$

The condition of special modes' appearing $(\psi, B(\mathbf{x})) = \mathbf{u}_{max}$

if we differentiate *n* times with respect to the time we get the *n*-equation system

$$\left(B_2(\mathbf{x},\mathbf{u}), \quad B_3(\mathbf{x},\mathbf{u}), \quad \ldots, \quad B_n(\mathbf{x},\mathbf{u}), \quad B_{n+1}(\mathbf{x},\mathbf{u})\right)^T \psi = 0 \qquad (*)$$

where the vectors $B_j(\mathbf{x},\mathbf{u})$, $j = 2, \ 3, \ \ldots, \ n, \ n+1$ **are determined from the recurrent relation**

$$B_j(\mathbf{x},\mathbf{u}) = \frac{\partial B_{j-1}(\mathbf{x},\mathbf{u})}{\partial \mathbf{x}}(A(\mathbf{x}) + B(\mathbf{x}))\mathbf{u} - \left(\frac{\partial A(\mathbf{x})}{\partial \mathbf{x}} + \frac{\partial B(\mathbf{x})\mathbf{u}}{\partial \mathbf{x}}\right)B_{j-1}(\mathbf{x},\mathbf{u})$$

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We will now compose the matrix D_n of the size *n* x *n*, whose columns are the vectors

$B_j(\mathbf{x},\mathbf{u}), \quad j = 2, \ 3, \ \ldots, \ n, \ n+1$ **, that is**

$$D_n = \begin{pmatrix} B_2 & B_3 & \ldots & B_n & B_{n+1} \end{pmatrix}$$

Then the equation system (*) is reduced to the following equation:

$$D_n^T \psi = 0$$

That is for the equality to be true it is necessary that the matrix D_n be degenerate

$$det\, D_n = F(\mathbf{x},\mathbf{u}) = 0$$

Invariant Relations in the Power Saving Control Theory and the Minimum Power Dissipation Principle

It should be emphasized that when developing the PSCT an important problem of researching the power object control processes interconnectivity and interactivity properties from the power and fuel waste minimization's point of view arises.

It turns out that when a vector control of power objects is used, the certain invariant relations providing *the minimum power dissipation principle* realization and, consequently, *the minimum power waste in the system*, must be established among the controlling actions.

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General mathematical power object model

$$\begin{cases} \dot{x}_j(t) = f_j(x_1,\ldots,x_n, \quad u_1,\ldots,u_m), & j = 1,\ldots,r, \\ \dot{x}_k(t) = f_k(x_1,\ldots,x_n), & k = r+1,\ldots,n. \end{cases}$$

The problem of determining a control vector $\mathbf{u}(u_1,\ldots,u_m)$ transferring the power object from a certain initial state $\mathbf{x}(x_{10},\ldots,x_{n0})$ to the given final $\mathbf{x}(x_{1T},\ldots,x_{nT})$ with a minimum value of optimizing functional is stated:

$$I = \Phi(x_1,\ldots,x_n)$$

The object's initial differential equation system should be expanded by adding a coordinate to it

$$x_{n+1} = I_i = \int_0^T f_0(x_1,\ldots,x_n, \quad u_1,\ldots,u_m)dt.$$

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Taking $\Phi = x_{n+1}$, an equivalent Mayer's problem can be formulated: among the admissible controls $u_1,\dots,u_m$ find such ones that provide the minimum to the functional

$$\Phi = x_{n+1}(T),$$

and the variables x_i must meet the following boundary conditions:

when $t=0$: $x_{10}, \quad \dots, \quad x_{n0}, \quad x_{n+1,0} = 0,$

when $t=T$: $x_{1T}, \quad \dots, \quad x_{nT}, \quad x_{n+1,T}$ **- arbitrary values.**

Hamiltonian looks as follows:

$$H_3 = \sum_{j=1}^{r} \psi_j f_j(x_1,\dots,x_n, \quad u_1,\dots,u_m) + \sum_{k=r+1}^{n} \psi_k f_k(x_1,\dots,x_n).$$

Then the optimum controls are determined from the conditions of the function H_3 maximum, that is

$$\sum_{j=1}^{r} \psi_j \frac{\partial f_j(x_1,\dots,x_n, \quad u_1,\dots,u_m)}{\partial u_\mu} = 0, \qquad \mu = 1,2,\dots,m.$$

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The following conditions are true for motion trajectories when $m \geq r$

$$D\left(\frac{f_1,\dots,f_r}{u_1,\dots,u_{r-1},u_r}\right)=0,\quad D\left(\frac{f_1,\dots,f_r}{u_1,\dots,u_{r-1},u_{r+1}}\right)=0,\quad D\left(\frac{f_1,\dots,f_r}{u_1,\dots,u_{r-1},u_m}\right)=0,$$

For $m = r$

$$D=\begin{vmatrix} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_2}{\partial u_1} & \cdots & \frac{\partial f_r}{\partial u_1} \\ \frac{\partial f_1}{\partial u_2} & \frac{\partial f_2}{\partial u_2} & \cdots & \frac{\partial f_r}{\partial u_2} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial f_1}{\partial u_r} & \frac{\partial f_2}{\partial u_r} & \cdots & \frac{\partial f_r}{\partial u_r} \end{vmatrix}=0.$$

For the simplest marginal case $m=r=2$ **we have:**

$$\frac{\partial f_1}{\partial u_1}\cdot\frac{\partial f_2}{\partial u_2}=\frac{\partial f_1}{\partial u_2}\cdot\frac{\partial f_2}{\partial u_1}$$

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The controls can be limited or belong to the certain given boundary surfaces

$$\varphi_S(x_1,\ldots x_n,\quad u_1,\ldots,u_m)=0,\qquad S=1,\ldots,q.$$

Then the necessary conditions for the maximum of hamiltonian look as follows

$$D\left(\frac{f_1,\ldots,f_r,\quad \phi_1,\ldots,\phi_q}{u_1,\ldots,u_{r+q}}\right)=0,\quad D\left(\frac{f_1,\ldots,f_r,\quad \phi_1,\ldots,\phi_q}{u_1,\ldots,u_{r+q-1},u_{r+q+1}}\right)=0,\quad \ldots,\quad D\left(\frac{f_1,\ldots,f_r,\quad \phi_1,\ldots,\phi_q}{u_1,\ldots,u_{r+q-1},u_m}\right)=0,$$

Those relations are certain additional connections' equations whose attachment to the object equations decreases the control vector's dimensionality by the value *(m-r-q+1)*. From which it follows that the number of freely selected equations in the object is equal to *r-1*. The other equations are tied by the exceeded invariant relations. If the relations are not true than it means that the control is not optimal in the sense of power waste.

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Basic Porblems of Power Systems Objects Control

Considered basic conditions and fundamental problems allow to come to a number of important conclusions and single out the following key scientific directions for solving the power system object multicriterial power saving control problem.

- ***Developing the Garanteed Quality Princilpe and Forming Power Saving Control Criteria.***
- ***Developing Methods for Synthesis of Control Laws Optimum by Minimum Power Expenditure Criterion.***
- ***Developing Methods for Synthesis of Power Saving Control Laws Suboptimum by the Combination of Minimum Power Expenditure and Speed Performance Criteria.***
- ***Developing Methods for Synthesizing Power Saving Control Laws Suboptimum by the Combination of Minimum Power Expenditure, Speed Performance and Accuracy Criteria.***
- ***Developing Synergetic Methods for Synthesizing Power Saving Laws of Multi-connected Control of Power Systems' Non-linear Objects.***

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Researching Power System Mathematical Models

Dynamic Properties of Power Systems and Basic Requirements to Electro-mechanical Processes

Optimal strategies of todays EPS control must solve two fundamental problems:

providing the biggest domain of EPS synchronous dynamic stability

providing the required quality of damping EPS's electro-mechanical transients

Fundamental requirements for the autonomous EPS

Providing reliable operation in normal and emergency regimes for a smooth supply of electrical power to electrified mechanisms

Providing an electrical power of good quality means a constant voltage and frequency

Providing an economical operation of generators and electrical power receivers

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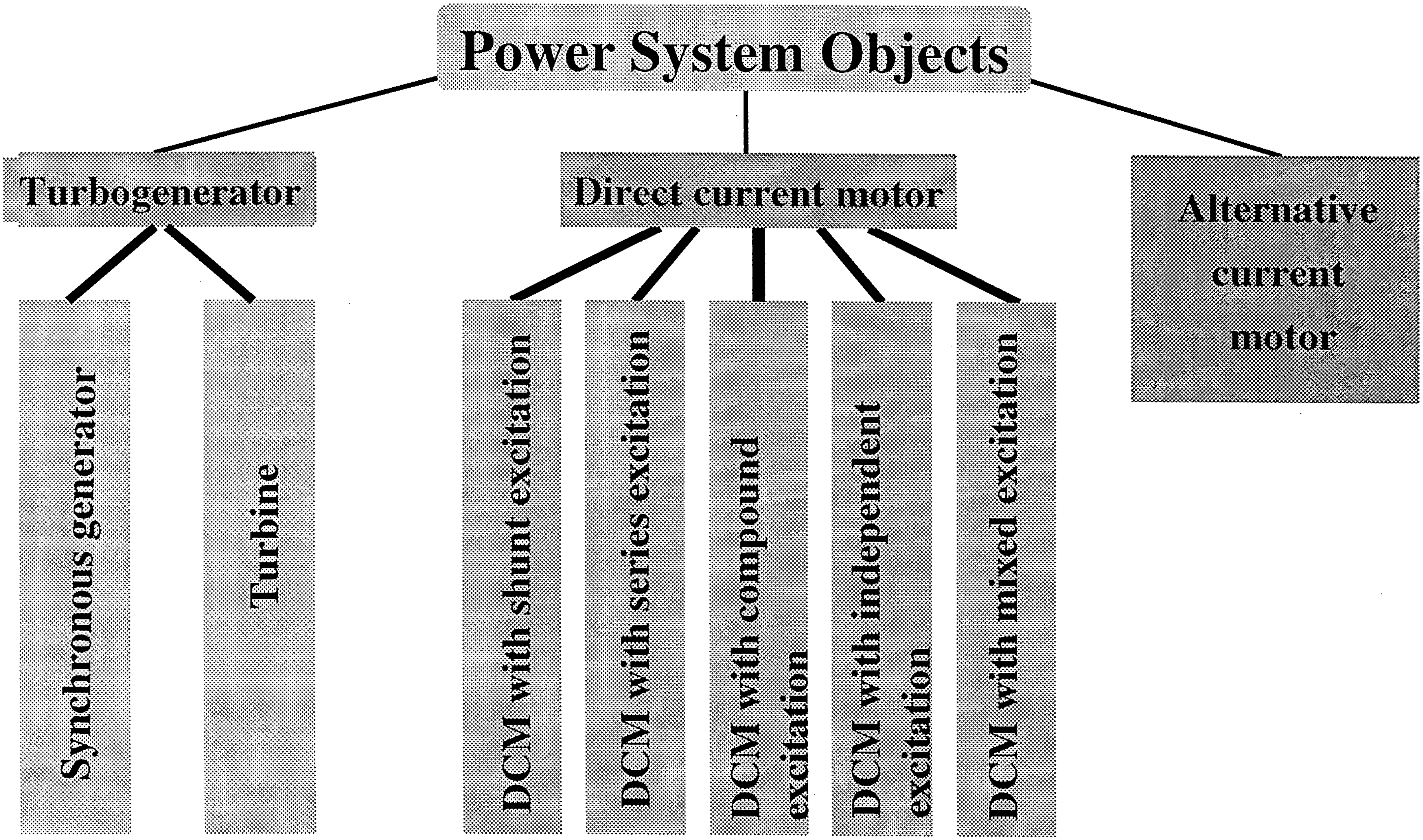

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Turbogenerator

Synchronous generator

$$\dot{x}_1(t) = x_2,$$
$$\dot{x}_2(t) = a_0 - a_1 \sin x_1 - (a_2 + a_3 \sin x_1) x_3 - c x_3^2 - m_l(x_2, t),$$
$$\dot{x}_3(t) = -k x_3 + a_4 x_2 \sin x_1 + k u_1$$

x_1 - *an SG rotor rotation angle relatively to synchronic rotation axis;*

x_2 - *sliding;* x_3 - *an SG EMP deviation;*

u_1 - *an SG excitement voltage deviation;*

a_0 - *an effect proportional to turbine mechanical power;*

$m_l(x_2, t)$ - *external disturbance at SG, reflecting the asynchronic and synchronic engines and other loads impact;*

a_i, k - *positive constants.*

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Control optimum by speed performance will be piecewise constant for the whole phase space

$$u_{1opt}(t) = u_{1max} sign\psi_3(t) \qquad \begin{array}{l} u_{opt} = u_{max},\ if\ \ \psi_3(t) > 0; \\ u_{opt} = u_{min},\ if\ \ \psi_3(t) < 0. \end{array}$$

For special manifold $S = a_2 + a_3 sinx_1 + 2a_4 x_4 = 0$

special control looks as follows

$$ku_{1sn} = 0{,}5k\frac{a_2}{a_4} + 0{,}5\frac{a_3}{a_4}k\,sin\,x_1 - \left(a_3\,sin\,x_1 + 0{,}5\frac{a_3}{a_4}cos\,x_1\right)x_2$$

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Quantitative methods for searching of switching line are based on a jointly integrating equations of the system and conjugated system in a reverse time

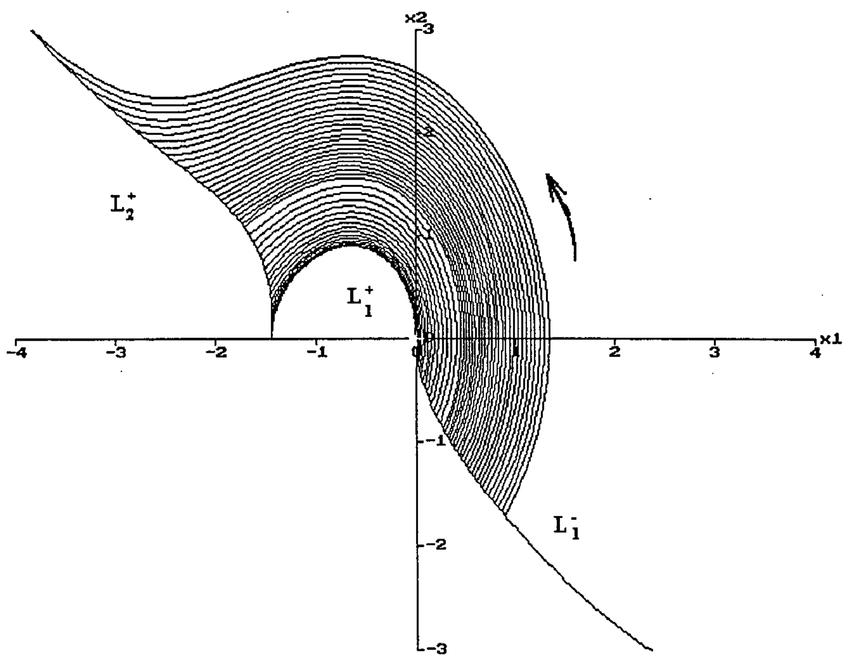

Fig. 1.31

Phase portrait of the system when U_m is equal to 0,8

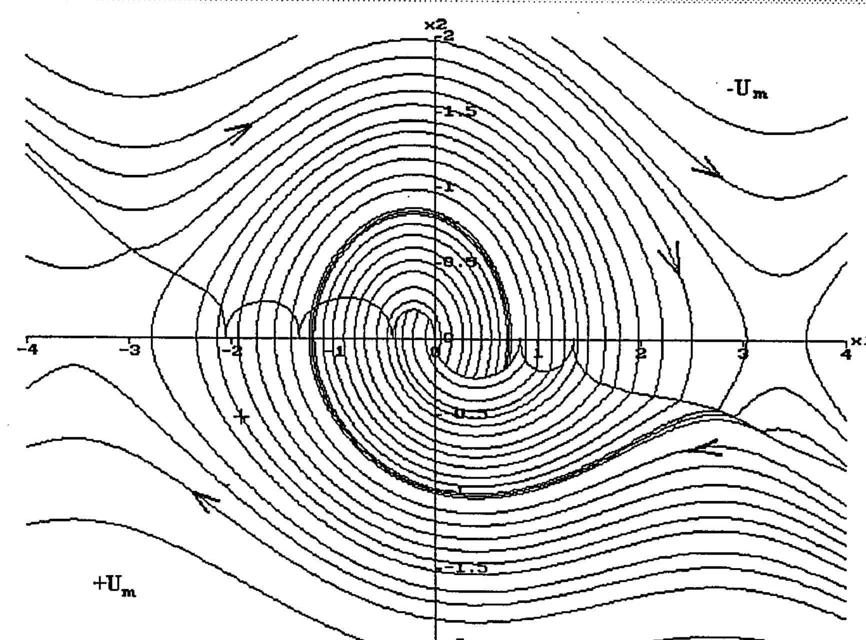

Fig. 1.34

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Turbine

$$\dot{x}_1(t) = x_2$$

$$\dot{x}_2(t) = a_0 x_4 - a_1 sin x_1 - m(x_2)$$

$$\dot{x}_4(t) = -a_6 x_4 - a_7 x_2 + u_2$$

x_1 - *an electrical angle of SG rotation relativly to rotation synchronous axle;*

x_2 - *sliding;*

x_4 - *turbine rotation (power) frequency (speed);*

$m(x_2)$ - *an external load;*

u_2 - *a controlling influence at the input of speed regulator* $u_{2min} \le u_2 \le u_{2max}$.

Control optimum by speed performance

$$u_2 = u_{2max}, \quad \psi_4 > 0; \qquad u_2 = u_{2min}, \quad if \quad \psi_4 < 0.$$

Virtual Test Bed

Turbogenerator

$$\dot{x}_1(t) = x_2,$$

$$\dot{x}_2(t) = a_0 x_4 - a_1 sin x_1 - (a_2 + a_3 \sin x_1) x_3 - a_4 x_3^2 - m_l(x_2),$$

$$\dot{x}_3(t) = -k_1 x_3 + a_5 x_2 \sin x_1 + k_1 u_1,$$

$$\dot{x}_4(t) = -a_6 x_4 - a_7 x_2 + u_2,$$

x_1 - *an SG rotor rotation angle relatively to synchronous rotation axis;*

x_2 - *sliding;*

x_3 - *an SG EPS deviation;*

x_4 - *rotation frequency proportional to turbine mechanical power;*

u_1 - *SG excitement voltage deviation;*

u_2 - *frequency regulator input control effect ;*

$a_5 = 1/T_{fr}, a_6 = 1/\sigma; T_{fr}, \sigma$ - *time constants and frequency regulator statics coefficient.*

Control optimum by speed performance

$$u_1 = u_{max},\ if\ \psi_3(t) > 0;\ u_1 = u_{1min},\ if\ \psi_3(t) < 0;$$

$$u_2 = u_{max},\ if\ \psi_4(t) > 0;\ u_2 = u_{2min},\ if\ \psi_4(t) < 0$$

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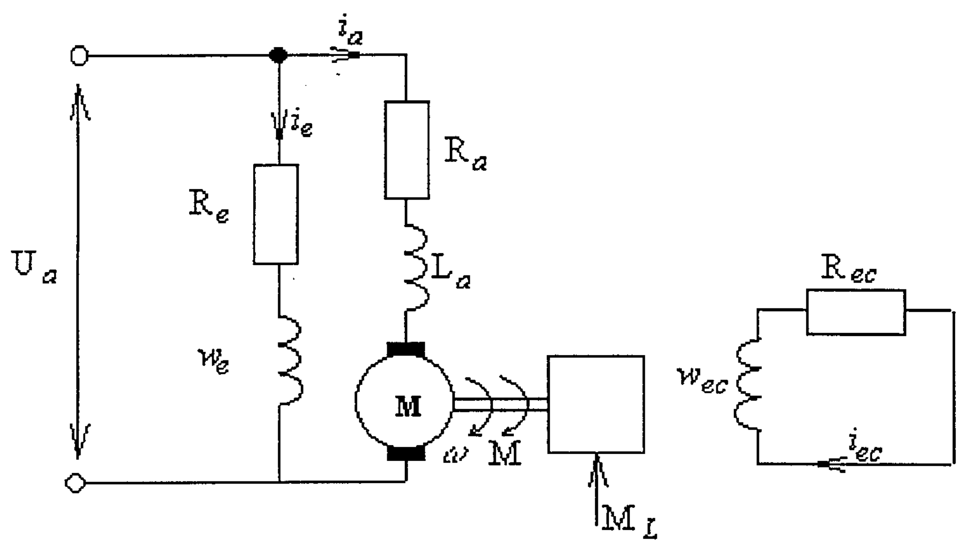
Direct current motors

DCM with shunt excitation



$\dot{x}_1(t) = x_2;$

$\dot{x}_2(t) = (x_4 x_3 - \mu(x_1, x_2, t))a_{21};$

$\dot{x}_3(t) = (u_1 - x_4 x_2 - a_{31} x_3)a_{32};$

$\dot{x}_4(t) = (u_1 - f_1(x_4))a_{41};$

x_1 - *shaft rotation angle;*

x_2 - *rotation frequency;*

x_3 - *current of rotor circuit;*

x_4 - *flux;*

$\mu(x_1, x_2, t)$ - *torque of load.*

Virtual Test Bed

Control optimum by speed performance will be piecewise constant

$$u_1(t) = u_{1max}\, sign(a_{32}\Psi_3(t) + a_{41}\Psi_4(t)) \, .$$

For special manifold

$$\frac{a_{21}}{a_{31}a_{41}} x_4^3 - 2x_4 + 2x_2x_4 = 0$$

special control

$$u_1^* = \frac{3\frac{a_{21}}{a_{31}} x_4^3 - 2x_4a_{41} + 2a_{41}x_2x_4 + 2\frac{a_{21}}{a_{31}} x_4^3 x_2}{5\frac{a_{21}}{a_{31}} x_4^2 + 2a_{41}x_2 - 2a_{41}}$$

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The phase portrait of optimal by speed performance process under relay control

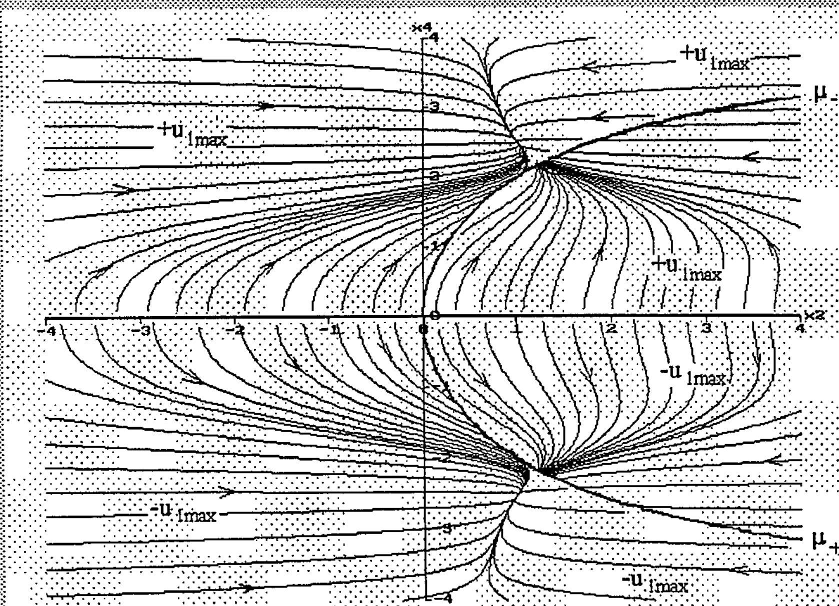

Fig. 1.37

The phase portrait of optimal by speed performance process under relay and special controls

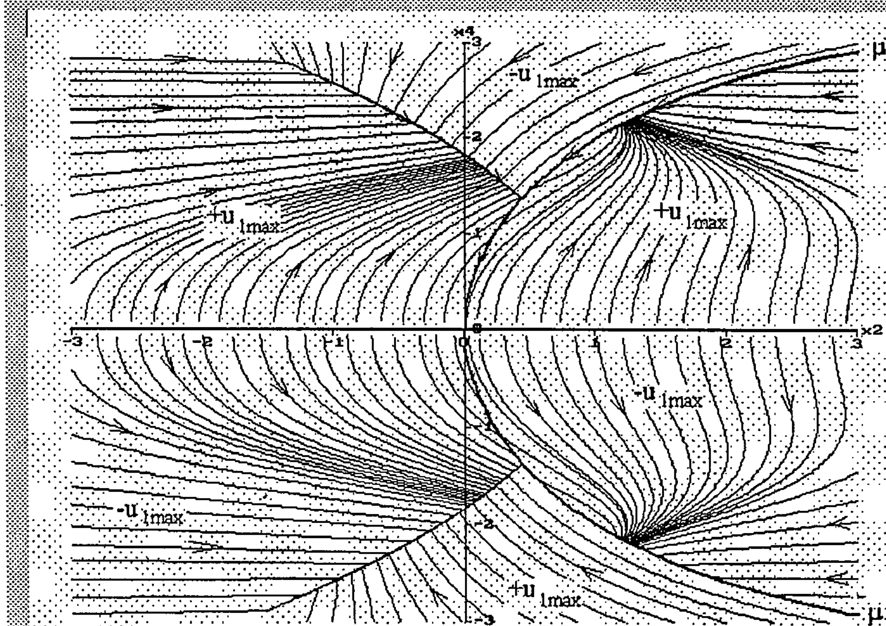

Fig. 1.38

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DCM with series excitation

$$\dot{x}_1(t) = x_2 \;;$$

$$\dot{x}_2(t) = (x_3 x_4 - \mu(x_1, x_2, t))a_{21} \;;$$

$$\dot{x}_3(t) = (u_1 - a_{31}x_3 + a_{33}f_1(x_4) - x_4 x_2)a_{32} \;;$$

$$\dot{x}_4(t) = (x_3 - f_1(x_4))a_{41} \;;$$

Control optimum by speed performance will be piecewise constant

$$u_1(t) = u_{1max}\, sign(\psi_3(t)) \,.$$

For special manifold $x_4 = 0$

special control $u_1 = 0$

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The phase portrait of optimal by speed performance process in the regime of a dumb motion

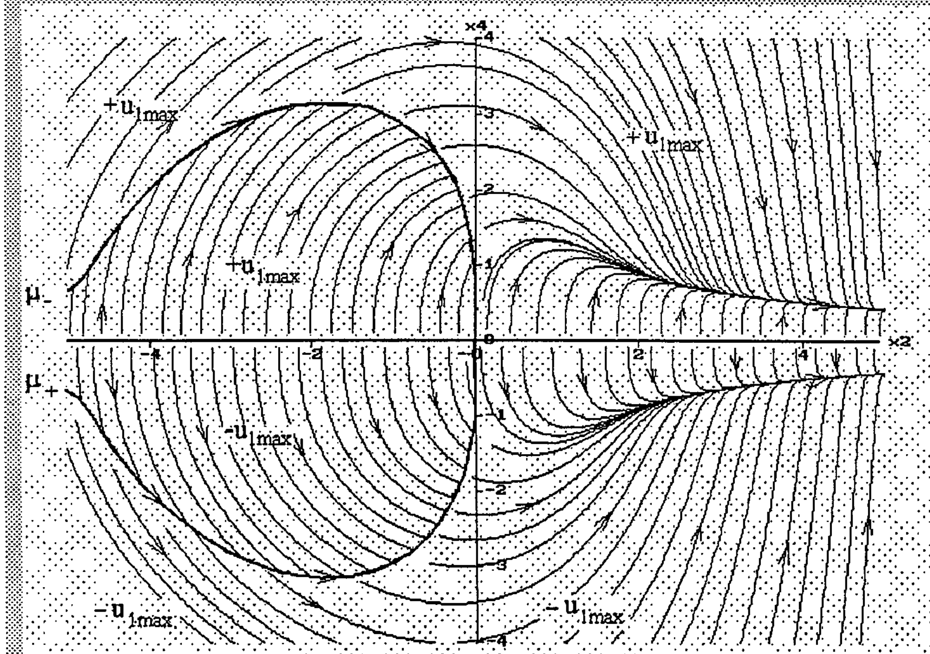

Fig.1.40

The phase portrait of optimal by speed performance process under a load

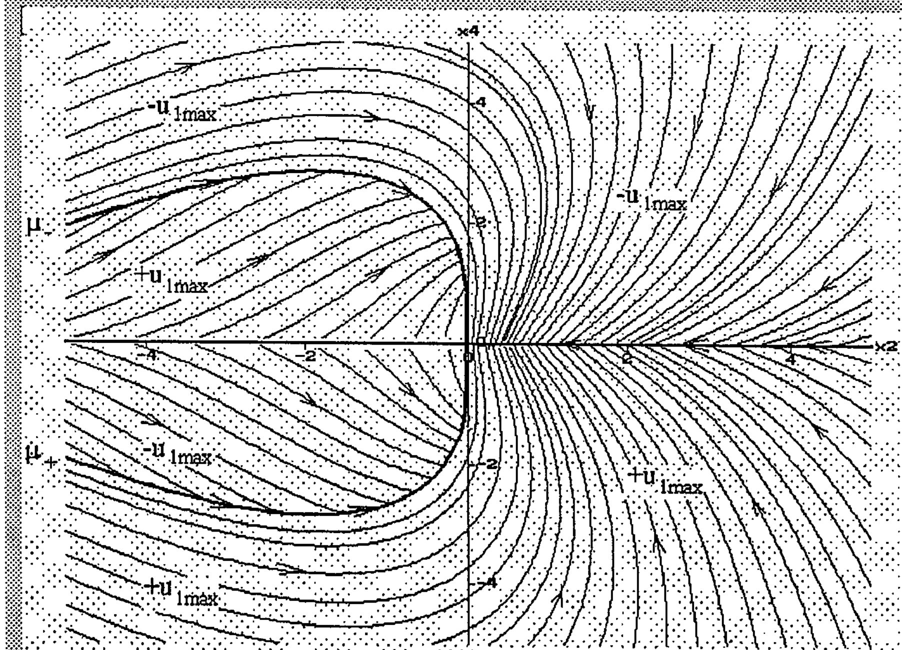

Fig. 1.41

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DCM with independent excitation

$\dot{x}_1(t) = x_2;$

$\dot{x}_2(t) = (x_4 x_3 - \mu(x_1, x_2, t))a_{21};$

$\dot{x}_3(t) = (u_1 - x_4 x_2 - a_{31} x_3)a_{32};$

$\dot{x}_4(t) = (u_2 - f_1(x_4))a_{41};$

Control optimum by speed performance will be piecewise constant

$u_1(t) = u_{1max}\, sign(\psi_3(t));$

$u_2(t) = u_{1max}\, sign(\psi_4(t)).$

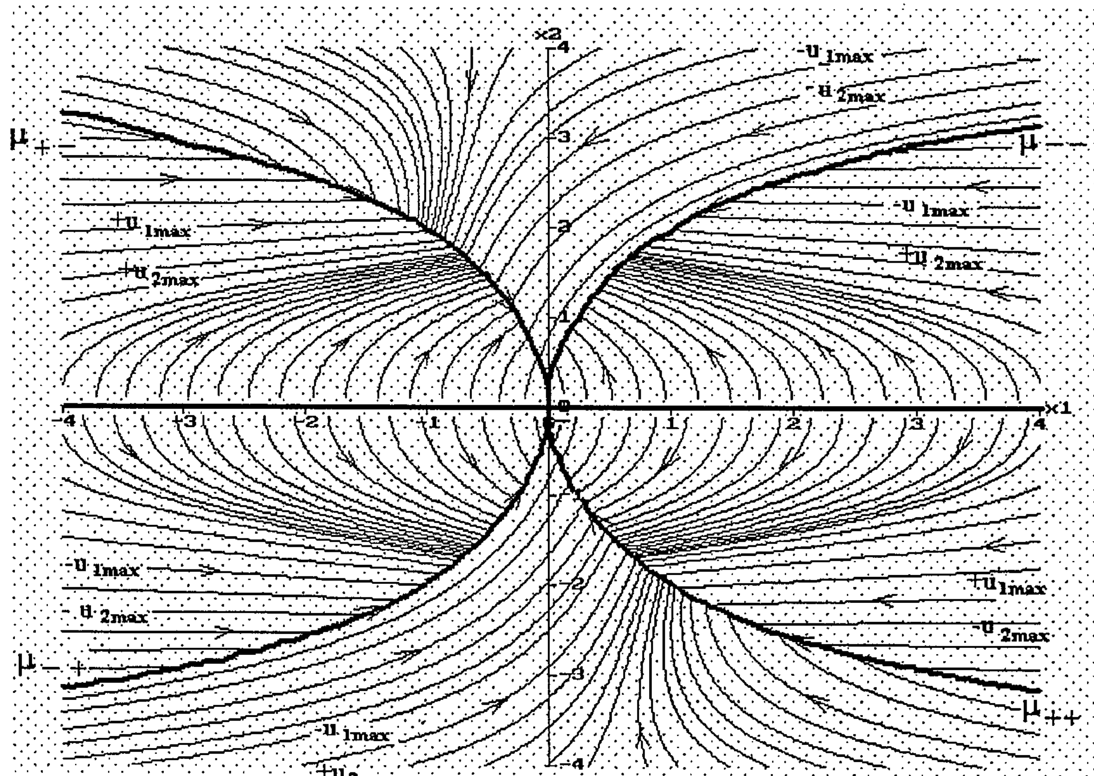

Fig. 1.43

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Asynchronous Electrical Motor

$$\dot{x}_1(t) = x_2;$$

$$\dot{x}_2(t) = a_1 x_4 x_5 - a_2 m_l;$$

$$\dot{x}_3(t) = -a_3 \frac{x_5}{x_4};$$

$$\dot{x}_4(t) = -a_4 x_4 + a_3 x_6;$$

$$\dot{x}_5(t) = -a_5 x_5 - a_6 x_6 - a_7 x_4 x_2 + b u_1;$$

$$\dot{x}_6(t) = -a_5 x_6 + a_6 x_5 + a_8 x_4 + b u_2,$$

x_1 - *shaft rotation angle;*

x_2 - *rotation frequency;*

x_3 - *variable characterizing an AM shaft turning angle with respect to the coordinate system;*

x_4 - *rotor flux linkage;*

x_5 - *stator curent projection to the axis x;*

x_6 - *stator current projection to the axis y ;*

u_1 - *stator voltage projection to the axis x ;*

u_2 - *stator voltage projection to the axis y.*

Control optimum by speed performance will be piecewise constant

$$u_{1opt}(t) = U_{1max} sign \psi_5;$$

$$u_{2opt}(t) = U_{2max} sign \psi_6.$$

Controllability by Separate Control Channels

Controllability by the channel u_1

$$\dot{x}_2(t) = a_1 x_4 x_5 - a_2 m_l;$$
$$\dot{x}_4(t) = -a_4 x_4 + a_3 x_6;$$
$$\dot{x}_5(t) = -a_5 x_5 - a_6 x_6 - a_7 x_4 x_2 + b u_1;$$
$$\dot{x}_6(t) = -a_5 x_6 + a_6 x_5 + a_8 x_4;$$

Special manifold $F_1(x_4, x_5, x_6) = (a_3 + a_4)(a_3 x_6 - a_4 x_4) - a_3 a_6 x_5 = 0.$

Special control

$$u_1 = \frac{\left((a_3 + a_4)(a_3 a_8 + a_4^2) + a_3 a_4 a_6 a_7 x_2\right) x_4 - a_3\left(\left(a_3^2 + 2a_3 a_4 + a_4^2 + a_6^2\right) x_6 - (a_3 + a_4 + a_5) a_6 x_5\right)}{a_3 a_6 b}.$$

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Controllability by the channel u_2

$$\dot{x}_2(t) = a_1 x_4 x_5 - a_2 m_l;$$
$$\dot{x}_4(t) = -a_4 x_4 + a_3 x_6;$$
$$\dot{x}_5(t) = -a_5 x_5 - a_6 x_6 - a_7 x_4 x_2;$$
$$\dot{x}_6(t) = -a_5 x_6 + a_6 x_5 + a_8 x_4 + b u_2;$$

Special manifold

$$F_2(x_2, x_4, x_5, x_6) = a_1 a_3 a_6 a_7 x_4^2 x_5 - a_1 a_6^2 a_7 x_4^3 - a_2 a_3^2 a_7 m_l x_5 + a_2 a_3 a_6 a_7 m_l x_4 +$$
$$+ 2a_3^2 a_5 a_7 x_2 x_5 + 2a_3^2 a_6 a_7 x_2 x_6 + 2a_3 a_4 a_5 a_6 x_5 + 2a_3 a_4 a_6^2 x_4 - 2a_3 a_4 a_6 a_7 x_2 x_4 - 2a_3 a_5^2 a_6 x_5 -$$
$$- 2a_3 a_5 a_6^2 x_6 - 2a_4^2 a_6^2 x_4 + 2a_4 a_5 a_6^2 x_4 = 0;$$

Carried out research of an AM's controllability separately by the channels u_1 and u_2 allow us to come to an important conclusion: when AM one-chanel control is used particular manifolds limiting its controllability appear in its phase space.

Considering the Limitations in an Alternating Current Motor Drive Optimal by Speed Performance

The equations system describing AM is complemented by an equation describing thermal processes in the motor

$$\dot{x}(t) = -a_9 x_7 + b_9 (x_5^2 + x_6^2)$$

For the phase space domain in which the coordinate x_7 has not attained its boundary value that is $x_7 < x_{7m}$, the control is determined from the Hamilton's maximum principle

$$u_1 = u_{1m} sign(\psi_5),$$

$$u_2 = u_{2m} sign(\psi_6).$$

For special manifold $$K(t) = x_7 - x_{7m} = 0,$$

special control

$$u_1 = \frac{1}{b}(a_5 x_5 + a_6 x_6 + a_7 x_2 x_4),$$

$$u_2 = \frac{1}{b}(a_5 x_6 + a_6 x_5 + a_8 x_4).$$

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Conclusions and Recommendations Suggested after Researching Models of Power Systems Objects

The application of the maximum principle to a problem of the search for new optimal control strategies of power system's objects allows not only to reveal the character and form of optimal controls in the function of time but also to receive the corresponding equations for their quantitative calculation.

In the case of the limitation which is popular in practice, an optimal control is piecewise constant with the pieces of relay and continuous (singular) control.

For a quantitative calculation of optimal control strategies it is necessary, according to the maximum principle, to solve the corresponding boundary problem of object's differential equations and equations conjugated to them.

The development of applied problem-oriented methods for solving boundary problems of modelling strategies of vessel power systems' objects optimal control is required in order to consider the peculiarities of power systems' non-linear objects.

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The application of position generality conditions (PGC) of the maximum principle allows to reveal the domains of controllability (attainability) of power systems' non-linear objects, to find degenerate regimes of their motion and also to determine the singular controls.

The basic conlusion on directed current motor drives: one should use an interconnected dual-channel control - by anchore circuit and excitement circuit which will allow to design a new class of highly efficient optimal motor drives.

For alternating current motor: the most effective is the use of interconnected dual-channel control whose application will allow to create a new class of highly dynamic optimal directed current motor drives. The development of a theory and methods for optimal dual-channel control of alternating current motor drives will be some kind of thrust and know-how in the field of motor drives

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The developed methods application of qualitative research of power systems' non-linear objects control allows to reveal new most important regularites connected with the nature of flowing physical processes and structure of those objects.

Having found, as the result of applying the methods of qualitative research, the particular manifolds-invariants we can then point out the ways of improving dynamic characteristics, the methods for expanding properties of controllability and for elevating other most important indicators of power systems' controllable objects.

The developed in the first section qualitative methods and received by using them results of investigating optimal dynamic processes and their fundamental regularities allow to reveal marginal, theoretically achievable indicators of vessel power systems' controllable objects.

Theory and Methods for Synthesizing Power Objects Multiple Criteria Control Strategies

We consider controlled power objects whose behavior is described by non-linear differential equations in the form of

$$\dot{x}_i(t) = f_i(x_1, x_2, \ldots, x_n) + \sum_{p=1}^{r} b_{ip} u_p(t) + c_i M_i(t),$$

$$i = 1,n; \qquad p = 1\ldots r.$$

Let a vector quality criterion in N-dimensional Euclid's space have the form

$$\overline{J} = (J_1, J_2, \ldots, J_n),$$

where

$$J_l = \int_{t_0}^{t_k} F_l(x_1, \ldots, x_n, u_1, \ldots, u_r, t)\,dt$$ – l-th scalar quality criterion $(l = \overline{1,N})$.

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In the space E^N vector coordinates of maximally admissible concessions by scalar criteria are given

$$\overline{\delta} = (\delta_1, \delta_2, \ldots, \delta_N)$$

The system's G^n conditions space will be presented by unifying not intersected domains $G_l, l = \overline{1, N}$

$$G = G_1 U G_2 U \ldots U G_N$$

For the power object described by the mathematical model it is necessary to synthesize a control law

$$u_p^0 = u_{pl}(x_1, \ldots, x_n, M_1, \ldots, M_m); \quad p = \overline{1, r}\,; \quad l = \overline{1, N} \;,$$

Virtual Test Bed

For a wide class of power systems one can practically restrict himself to two domains of the conditions space: an internal one containing coordinates origin, G_1, and external, G_2, which can be related to the regimes of small (G_1) and big (G_2) deviations of power system's motion from the defined one.

Power object's behavior in the domain G_1 can be described by the linearized system of differential equations

$$\dot{x}_i \geq (t) = \sum_{j=1}^{n} a_{ij} x_j(t) + \sum_{p=1}^{r} b_{ip} u_p(t) + c_i M_i(t),$$

where

$$a_{ij} = \frac{\partial f_i(x_1, \ldots, x_n)}{\partial x_j}; \quad i = \overline{1,n} \; ; \quad j = \overline{1,n} \, .$$

Mapping the Quality of Functioning Dynamic Systems in a Criteria Space

We will associate each variant of the control strategy $\mathbf{u}(\mathbf{x}) \in \mathbf{U}^r$ with the N-dimensional vector-function $\mathbf{J}(\mathbf{u})$ of quality criteria of a technical system operation:

$$\mathbf{J}(\mathbf{u}) = \{J_1(\mathbf{u}), \quad J_2(\mathbf{u}), \quad \ldots, \quad J_N(\mathbf{u})\}$$

$$J_l(\mathbf{u}) = \int_{t_0}^{t_k} F_l(\mathbf{x}, \mathbf{u}, t)\,dt, \qquad l = \overline{1, N}$$

Virtual Test Bed

We will call the control strategy $\mathbf{u}^{(1)}(\mathbf{x}) \in \mathbf{U}^r$ strictly more preferable to the control strategy $\mathbf{u}^{(2)}(\mathbf{x}) \in \mathbf{U}^r$ [designating this fact in the form of $\mathbf{u}^{(1)}(\mathbf{x}) > \mathbf{u}^{(2)}(\mathbf{x})$] if

$$\mathbf{J}(\mathbf{x},\mathbf{u}^{(1)},t) \leq \mathbf{J}(\mathbf{x},\mathbf{u}^{(2)},t)$$

that is among the systems of equalities and inequalities

$$J_l(\mathbf{x},\mathbf{u}^{(1)},t) \leq J_l(\mathbf{x},\mathbf{u}^{(2)},t), \qquad l = \overline{1,N}$$

at least one strict inequality can always be found. If

$$\mathbf{J}(\mathbf{x},\mathbf{u}^{(1)},t) = \mathbf{J}(\mathbf{x},\mathbf{u}^{(2)},t)$$

than considered control strategies are identical to $\left[\mathbf{u}^{(1)}(\mathbf{x}) \sim \mathbf{u}^{(2)}(\mathbf{x})\right]$.

Virtual Test Bed

For the introduced relations a property of transitivity holds true:

if $\mathbf{u}^{(1)}(\mathbf{x}) > \mathbf{u}^{(2)}(\mathbf{x})$ **and** $\mathbf{u}^{(2)}(\mathbf{x}) > \mathbf{u}^{(3)}(\mathbf{x})$ **then** $\mathbf{u}^{(1)}(\mathbf{x}) > \mathbf{u}^{(3)}(\mathbf{x})$

if $\mathbf{u}^{(1)}(\mathbf{x}) \sim \mathbf{u}^{(2)}(\mathbf{x})$ **and** $\mathbf{u}^{(2)}(\mathbf{x}) \sim \mathbf{u}^{(3)}(\mathbf{x})$ **then** $\mathbf{u}^{(1)}(\mathbf{x}) \sim \mathbf{u}^{(3)}(\mathbf{x})$

For dynamic systems when considering the class of piece-wise continuous control strategies the subset P (called an unimprovable surface) is a continuous hyper-surface of the dimension N - 1:

$$\Phi(J_1, J_2, \ldots J_N) \doteq 0$$

Virtual Test Bed

Let us assume that the optimal control strategy has been synthesized by known methods for each $l = 1, \ldots, N$.

$$\mathbf{u}^{(l)} = \mathbf{u}^{(l)}(x_1, \ldots, x_n, \quad M_1, \ldots, M_m), \qquad l = \overline{1, N}$$

The scalar functional $J_l(\mathbf{u}^{(l)})$ is equal to a minimal value on the system's trajectory passing given boundary points in the domain $\mathbf{G}_l$:

$$\{\mathbf{x}(t_{l-1}), \quad \mathbf{x}(t_l)\} \in \mathbf{G}_l$$

Then the set of admissible control strategies $\{\mathbf{u}\}$ is fully determined by solving the problems of synthesizing the strategies in conditions space domains which represents a separate and difficult problem especially for non-linear power objects of a higher order and can be written in the following form:

$$\{\mathbf{u}\} = \begin{cases} \mathbf{u}^{(1)}(\mathbf{x}) & \text{for} \quad t \in [t_0, t_1], \quad \mathbf{x} \in \mathbf{G}_1; \\ \mathbf{u}^{(2)}(\mathbf{x}) & \text{for} \quad t \in [t_1, t_2], \quad \mathbf{x} \in \mathbf{G}_2; \\ \cdots\cdots & \cdots\cdots \quad \cdots\cdots\cdots\cdots \quad \cdots\cdots\cdots \\ \mathbf{u}^{(N)}(\mathbf{x}) & \text{for} \quad t \in [t_{N-1}, t_k], \quad \mathbf{x} \in \mathbf{G}_N. \end{cases}$$

Virtual Test Bed

Methods for Synthesizing Control Systems Optimal by Speed Performance and Quadratic Quality Criterion

Methods for structural combining control laws

Linear synthesizing function

$$\mu_1(x_1,\dots,x_n) = \sum_{i=1}^{n} \gamma_i x_i = 0;$$

$$u^{(1)}(\mathbf{x}) = u_{max}\, sign\, \mu_1(x_1,\dots,x_n).$$

Non-linear synthesizing function

$$\mu_2(x_1,\dots,x_n) = \varphi(x_1,\dots,x_n) = 0;$$

$$u^{(2)}(\mathbf{x}) = u_{max}\, sign\, \mu_2(x_1,\dots,x_n),$$

Virtual Test Bed

We introduce to consideration the function:

$$\Phi(x_1,\ldots,x_n)=\begin{cases}0, & \text{if } \mathbf{x}\in\mathbf{G}_1;\\ \varphi(x_1,\ldots,x_n)-\sum_{i=1}^{n}\gamma_i x_i, & \text{if } \mathbf{x}\in\mathbf{G}_2.\end{cases}$$

Using methods for approximating equations of switching hyper-surface by super-positioning a function of one variable, we present the function $\Phi(x_1,\ldots,x_n)$ for the domain $\mathbf{G}$ in the following form:

$$\Phi(x_1,\ldots,x_n)=\sum_{i=1}^{n}\left[g_i(x_i)-\gamma_i x_i\right]+\Theta\left[g_{ij}(x_i)\right],$$

The generalized law of optimal by quality criterion control will be written in the form of:

$$u^0=u_{max}sign\left\{\sum_{i=1}^{n}\gamma_i x_i+\sum_{i=1}^{n}\Phi_i(x_i)+\Theta\left[g_{ij}(x_i)\right]\right\},$$

Analyzing Systems' Motion Processes When Optimizing by Speed Performance and Quadratic Criteria

The generalized synthesizing function takes the form:

$$\mu(x_1, x_2) = x_1 - \gamma_2 x_2 - \Phi_2(x_2)$$

The generalized control law can be written in the form

$$u^0 = u_{max} sign \mu(x_1, x_2);$$

$$\mu(x_1, x_2) = (x_1 + S) - \gamma_2 x_2 - \Phi_2(x_2) =$$

$$= x_1 - \gamma_2 x_2 - [\Phi_2(x_2) - S].$$

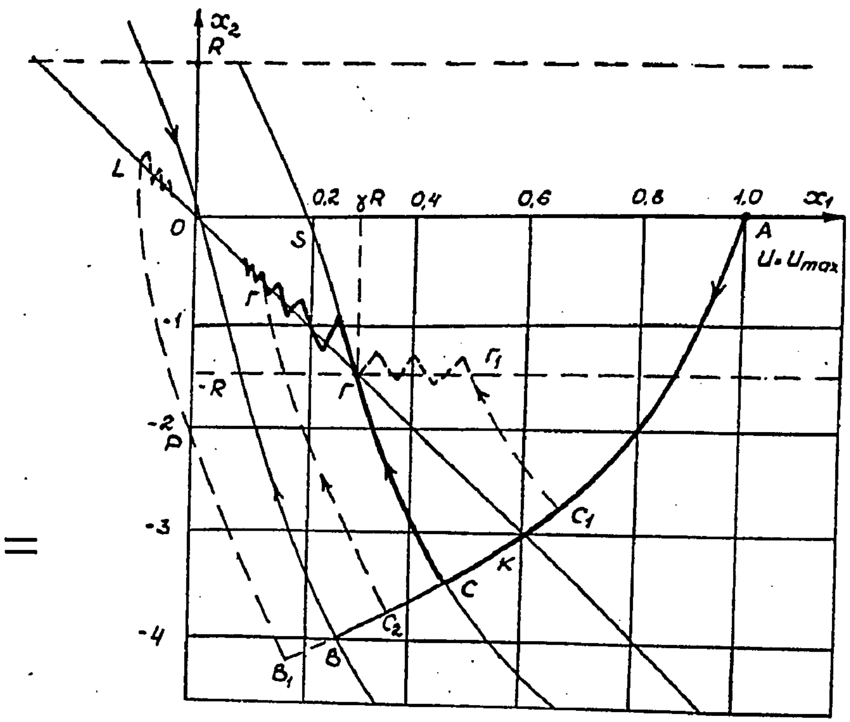


Fig. 1.13

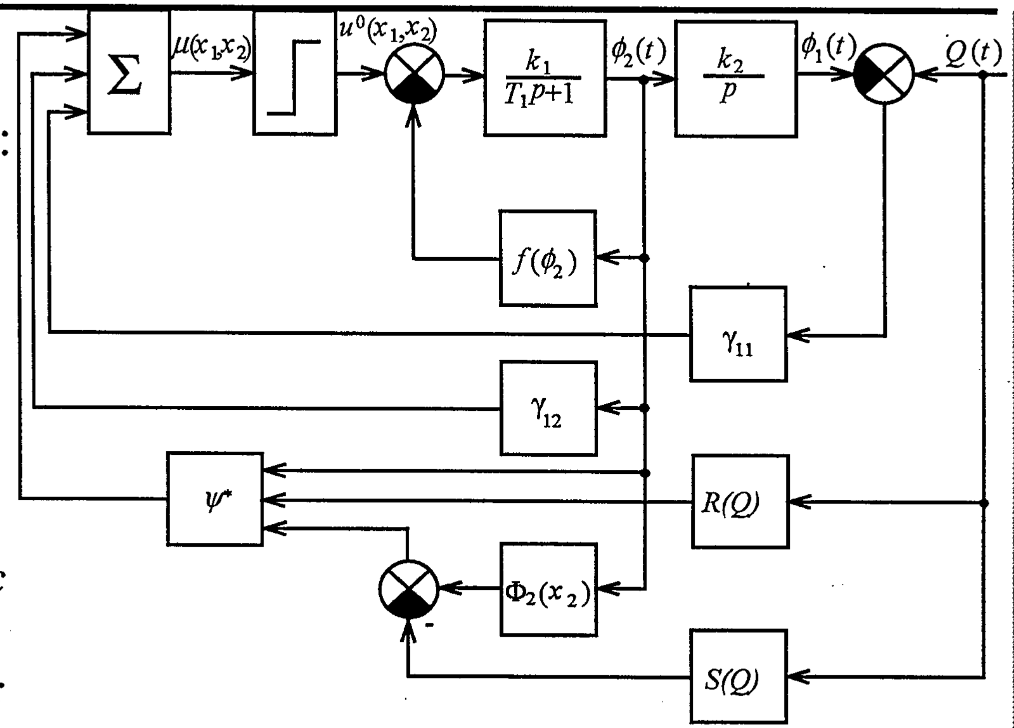
Then the domain $\mathbf{G_1}$ will be determined by the following set:

$$\mathbf{G}_1 = \{(x_1, x_2): x_1 \in [-\gamma_2 R, \gamma_2 R] \cup x_2 \in [-R, R]\}.$$

Virtual Test Bed

The non-linear link φ^* is a comparing device with the following characteristic:

$$\varphi^* = \begin{cases} \varphi, & \text{if } |x_2| > R; \\ 0, & \text{if } |x_2| \le R. \end{cases}$$



Example of synthesis.

We will consider an example of synthesizing optimal by speed performance and quadratic criteria control system of the object whose equations of motion have the following form:

$$\dot{x}_1(t) = x_2(t),$$

$$\dot{x}_2(t) = -\frac{1}{T_1}\left[k_1 k_2 u(t) + x_2(t) + \frac{A}{k_2^2} x_2^3(t)\right];$$

$$|u(t)| \le u_{max}.$$

where $x_1(t) = Q(t) - \varphi_1(t)$

In the domain G_1 *a control law should be realized:*

$$u^{(1)}(x_1, x_2) \doteq u_{max} sign(x_1 - \gamma_{12} x_2).$$

Methods for Synthesizing Multiple Criteria Control Systems with Limitations on Fuel-Power Resources

Necessary conditions of optimality in the problem of minimizing fuel consumption

The quantitative estimation of fuel in the system during the time of a transient process $T=t_k - t_0$ is reflected by the criterion

$$J_3 = \int_0^T \sum_{k=0}^{N} |u_k(t)| dt$$

According to the guaranteed quality principle, the time of transition process in the system is limited by the given vector of admissible concessions with respect to the particular criteria. Then

$$T_f - t \leq \delta_2 J_2^0(x_1, \dots, x_n)$$

Virtual Test Bed

We will consider as an example a non-linear power object of the second order with one controlling action

$$\dot{x}_1(t) = x_2;$$

$$\dot{x}_2(t) = f(x_1, x_2) + u(t).$$

Hamiltonian for the system has the following form:

$$H = \psi_1(t)x_2(t) + \psi_2(t)f(x_1, x_2) + \psi_2(t)u(t) + |u(t)|$$

The control minimizing the hamiltonian H under the limitations to $|u(t)| \le u_{max}$ is equal to

$$u(t) = 0, \quad \text{if} \quad |\psi_2(t)| < u_{max}$$

$$u(t) = -u_{max} sign\, \psi_2(t), \quad \text{if} \quad |\psi_2(t)| > u_{max}$$

$$0 \le u(t) \le u_{max}, \quad \text{if} \quad \psi_2(t) = -u_{max}$$

$$-u_{max} \le u(t) \le 0, \quad \text{if} \quad \psi_2(t) \le u_{max}$$

Additional variables $\psi_1(t)$ and $\psi_2(t)$ meet the equations system

$$\left.\begin{aligned} \dot{\psi}_1(t) &= -\psi_2 \frac{\partial f(x_1, x_2)}{\partial x_1}; \\ \dot{\psi}_2(t) &= -\psi_1 - \psi_2 \frac{\partial f(x_1, x_2)}{\partial x_2}. \end{aligned}\right\}$$

Virtual Test Bed

For different initial conditions and limited time of the transient process only six control sequences can be optimal:

$$\{-u_{max}\},\{+u_{max}\},\{+u_{max}\},\{-u_{max}\},$$
$$\{+u_{max},0,-u_{max}\},\{-u_{max},0,+u_{max}\}$$

Optimal control law for given T_f is uniquely defined by equations of the curves $F_1(x_2)$ and $F_2(x_2)$ which divide the phase surface into four domains:

$$\mathbf{H}_1=\{(x_1,x_2):x_1 \geq F_2(x_2) \cup x_1 > F_1(x_2)\};$$
$$\mathbf{H}_2=\{(x_1,x_2):x_1 < F_2(x_2) \cup x_1 \geq F_1(x_2)\};$$
$$\mathbf{H}_3=\{(x_1,x_2):x_1 \leq F_2(x_2) \cup x_1 < F_1(x_2)\};$$
$$\mathbf{H}_4=\{(x_1,x_2):x_1 > F_2(x_2) \cup x_1 \leq F_1(x_2)\}.$$

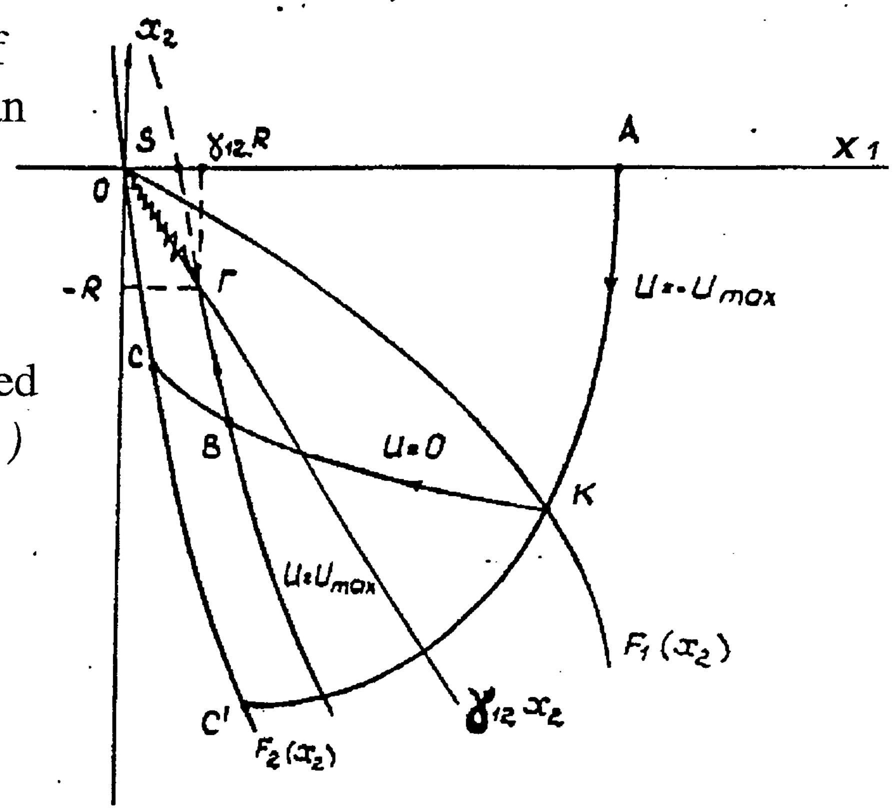


Fig. 1.19

The optimal control as a function of the condition (x_1, x_2) is determined by the equations

$$\left.\begin{aligned} u_0 &= -u_{max} && \text{for} \quad (x_1,x_2) \in \mathbf{H}_1; \\ u_0 &= u_{max} && \text{for} \quad (x_1,x_2) \in \mathbf{H}_3; \\ u_0 &= 0 && \text{for} \quad (x_1,x_2) \in \mathbf{H}_2 \cup \mathbf{H}_4. \end{aligned}\right\}$$

Synergetic Approach to the Problem of Interconnective Control of Power System Objects

Concept of Cybernetic Self-organization by N.Viner (“A Phenomenon of Shrinking Frequencies”):

“Let us consider a number of alternating current generators whose frequencies are regulated by the regulators assigned to primary motors. Those regulators hold frequencies in comparatively narrow strips. Let us assume that generators’ outputs are parallely connected to collecting buses and current from them goes to an external load which, in the general case, is subject to more or less random fluctuations.

... In such a system the generator aspiring to revolve too quickly, and consequently, to have an excessively high frequency takes a larger part of the load than it is supposed to and the generator revolving too slowly takes lesser than its normal load. *As the result, the generators’ frequencies are coming closer. Generating system, on the whole, acts as if under the control of a hidden generator that is more accurate than the regulators of separate generators and represents a combination of those regulators along with an electrical interaction among them...*

So, we see that a non-linear interaction creating an attraction of the frequencies can give birth to a self-organizing system.”

TAGANROG STATE UNIVERSITY OF RADIO ENGINEERING 1952

Virtual Test Bed

The Problem of Synthesizing Interconnected Systems of an Accordant Control of Groups of Power Systems' Turbo-generators

$$\dot{\delta}_i(t) = S_i,$$
$$H_i \dot{S}_i(t) = P_{Ti} - E_i U Y_{ij} \sin\delta_i - \sum_{\substack{j=1 \\ j\neq i}}^{n} E_i E_j Y_{ij} \sin\delta_{ij} + M_i(t)$$
$$T_{di} \dot{E}'_i(t) = u_{1i} - E_i$$
$$T_{pi} \dot{P}_T(t) = \mu_i - P_{Ti}$$
$$T_{\mu i} \dot{\mu}_i(t) = \mu_i - k_i S_i + u_{2i}, \qquad \delta_{ij} = \delta_i - \delta_j$$
$$E'_i = F_i(E_i, \delta_i, \alpha_i), \qquad E_i = \varphi_i(\delta_i, \alpha_i)$$
$$i, j = 1,2,\ldots,n$$

where δ - the i-th SG rotor turning angle relatively to the synchronous rotation angle;

S_i - sliding;

P_{Ti} - a mechanical power of the i-th turbine (motor);

E_i - electrical moving power of the i-th SG following a synchronous reactance;

E'_i - electrical moving power of the i-th SG following a transiting reactance; U - voltage at the EPS buses;

Y_{ij} - a mutual conductivity of the i-th and j-th system' branches;

μ_i - a position of the executing device regulating supply of a power bearer to the i-th turbine;

u_{1i} - a voltage at the excitation winding of the i-th SG;

u_{2i} - control at the input of the i-th turbine speed regulator;

$M_i(t)$ - a disturbance influencing the i-th turbo-generator.

Virtual Test Bed

The Statement of a Problem of EPS Vector Accordant Control

It is necessary to synthesize a central coordinating regulator with the control channels $u_{1i}(\delta_i, \delta_{ij}, P_{Ti}, E_i, \mu_i)$ of excitation of the corresponding SGs and control channels $u_{2i}(\delta_i, \delta_{ij}, P_{Ti}, E_i, \mu_i)$ of speed (power) of the corresponding turbines guaranteeing a maximum domain asymptotic stability of the EPS and a marginal speed performance in the regimes of big deviations of the EPS (peak and emergency regimes) from equilibrium and also providing the desired damping properties of the EPS in the regime of small deviations.

Besides that, the regulator must provide an "absorption" (selective invariantness) of the disturbances $M_i(t)$ and also provide limitations to the turbo-generator. The synergetic approach allows not only to meet the presented above requirements to the regulator but also to satisfy to 2n (according to the number of controls) desired relations (accordance conditions) among the variables of the EPS:

$$\psi_{1k}(\delta_i, S_i, P_{Ti}, E_i, \mu_i) = 0$$

$$\psi_{2k}(\delta_i, S_i, P_{Ti}, E_i, \mu_i) = 0$$

$$k = 1,2,\dots,n$$

Particular Problems of Power Systems Turbo-generators Control

Synthesizing coordinating regulators of turbines' speed (power):

$$\dot{\delta}_i(t) = S_i,$$

$$H_i \dot{S}_i(t) = P_{Ti} - P_i \sin\delta_i - \sum_{\substack{j=1 \\ j\neq i}}^{n} P_{ij} \sin\delta_{ij} + M_i(t)$$

$$T_{di} \dot{P}_T(t) = \mu_i - P_{Ti}$$

$$T_\mu \dot{\mu}_i(t) = \mu_i - k_i S_i + u_{2i}, \quad i = 1,2,\dots,n$$

Synthesizing coordinating regulators of the SG group excitation:

$$\dot{\delta}_i(t) = S_i,$$

$$H_i \dot{S}_i(t) = P_{Ti0} - E_i U Y_{ij} \sin\delta_i - \sum_{\substack{j=1 \\ j\neq i}}^{n} E_i E_j Y_{ij} \sin\delta_{ij} + M_i(t)$$

$$T_{di} \dot{E}_i'(t) = u_{1i} - E_i$$

$$i = 1,2,\dots,n$$

Examples of Synergetic Synthesis of Multiconnected Control Systems of Electro-mechanical Objects

Turbo-generator Control

$$\dot{x}_1(t) = x_2 \ ,$$
$$\dot{x}_2(t) = a_0 \cdot x_4 - a_1 \cdot sin(x_1) - (a_2 + a_3 \cdot sin(x_1)) \cdot x_3 - a_4 \cdot x_3^2 + w_1 \ ,$$
$$\dot{x}_3(t) = -k \cdot x_3 + a_5 \cdot x_2 \cdot sin(x_1) + k \cdot x_5 \ ,$$
$$\dot{x}_4(t) = -a_6 \cdot x_4 + a_8 \cdot x_6 \ ,$$
$$\dot{x}_5(t) = -a_{10} \cdot x_5 + a_{10} \cdot U_1 \ ,$$
$$\dot{x}_6(t) = -a_{11} \cdot x_6 + a_{12} \cdot x_2 + a_{11} \cdot U_2 \ ,$$
$$\dot{w}_1(t) = w_2 \ ,$$
$$\dot{w}_2(t) = -\omega_0 \cdot w_1 \ ,$$

x_1- a deviation of SG rotor turning angle with respect to the synchronous axis,
x_2- sliding,
x_3- a deviation of the generator's synchronous EMP,
x_4- a deviation of the turbine mechanical power,
x_5 - a deviation of exciting device voltage,
x_6 - an alternation of server-motor's position,
w_1,w_2 - variables of disturbance model condition,
ω_0 - disturbance frequency,
U_1 - excitation regulator controlling influence,
U_2- power regulator controlling influence

The expressions for the controls are ommitted here due to their cumbersomeness.

Virtual Test Bed

Results of Modelling

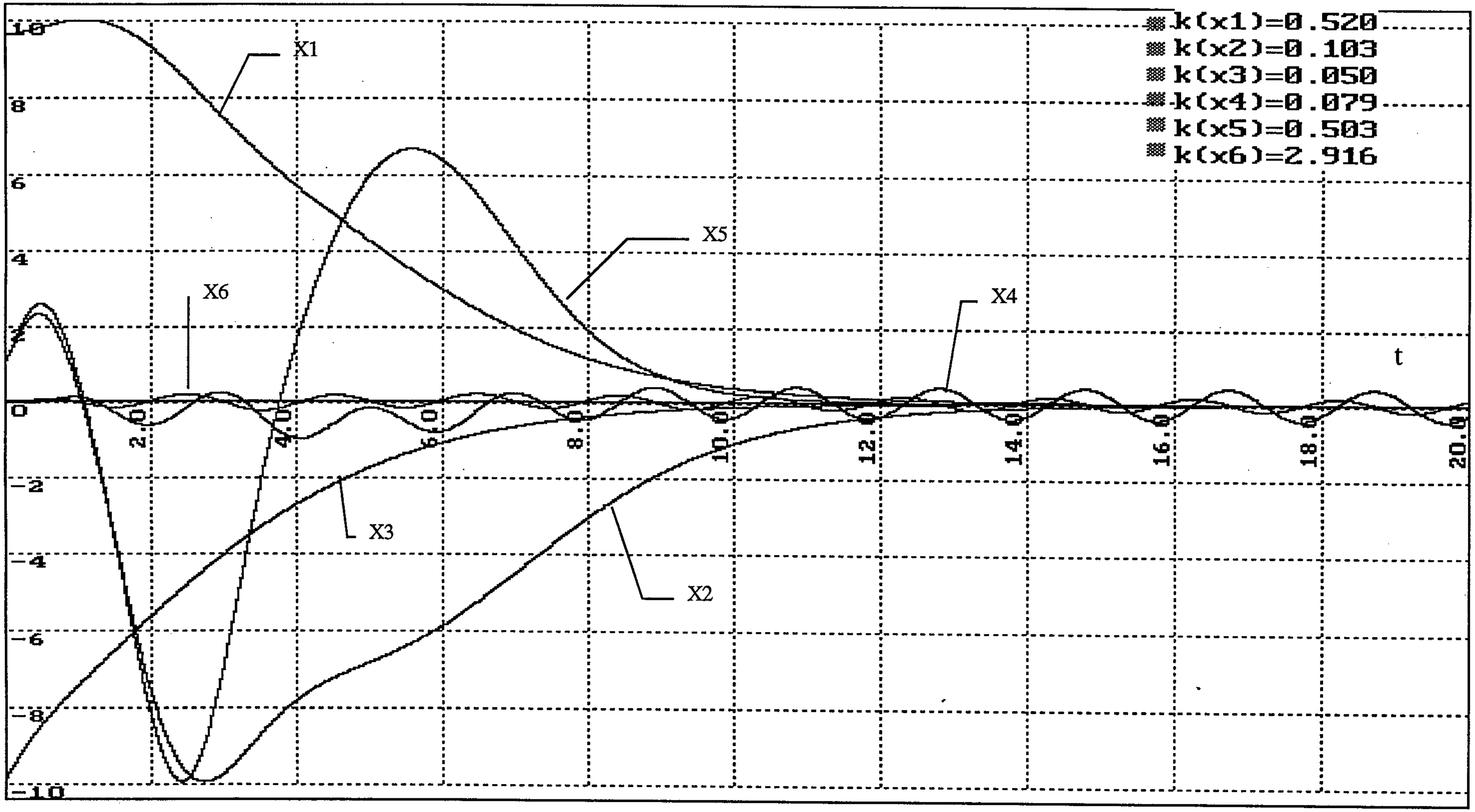


Chart of Transients of the Conditions Variables

Virtual Test Bed

Asynchronous Motor's Turning Angle Control

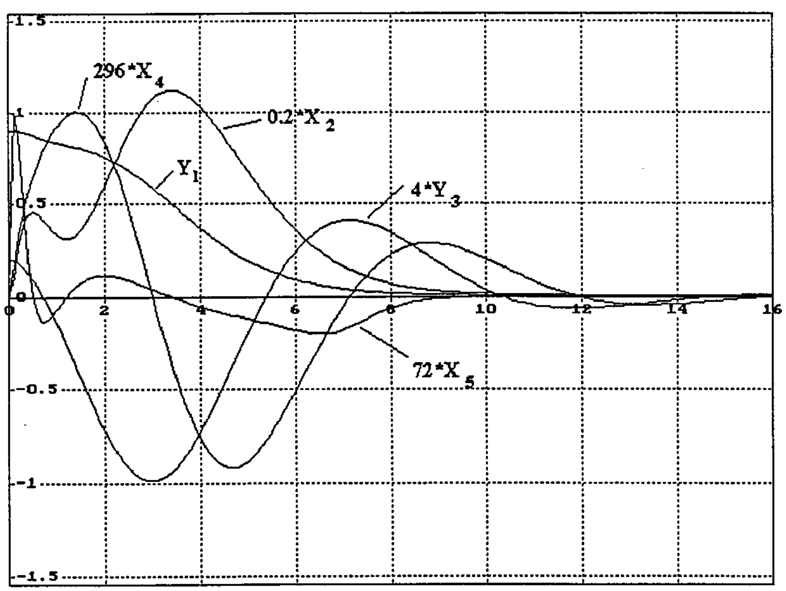
$$\dot{y}_1(t) = -x_2$$

$$\dot{x}_2(t) = -a_1 y_3 x_5 + a_1 g_3 x_5 - a_2 m_l$$

$$\dot{y}_3(t) = a_4 y_3 - a_3 x_4 - a_4 g_3$$

$$\dot{x}_4(t) = b_1 u_1 - a_6 x_3 + a_6 g_3 + x_5 x_2 + a_5 x_4 + \frac{a_3 x_5^2}{g_3 - y_3}$$

$$\dot{x}_5(t) = a_5 x_5 - \frac{a_3 x_4 x_5}{g_3 - y_3} - x_2 x_4 + \frac{a_6 x_2 (g_3 - y_3)}{a_4} + b_1 u_2$$



y_1 - a deviation with respect to the rotation angle,

x_2 - rotation frequency,

y_3 - deviation with respect to rotor fluz-linkage,

x_4,x_5 - projection of the stator's current to the axis X and Yof rotating coordiantes system,

u_1,u_2 - projections of the stator's voltage to the axis X and Yof rotating coordiantes system,

Real Time System Modeling

Presented

at

VTB Annual Meeting

University of South Carolina

by

P. C. Krause, S. D. Pekarek, and O. Wasynczuk

Purdue University

June 3, 1997

OUTLINE

1) Synchronous Machine Models
   a) Coupled-Circuit Physical-Variable Model
   b) Park's Model
   c) Voltage-Behind-Reactance Physical-Variable Model

2) Comparison of Simulation Efficiency
   a) Computational Requirements
   b) Eigenstructure

3) Magnetic Saturation

4) Multi-rate Simulation

5) Future Research

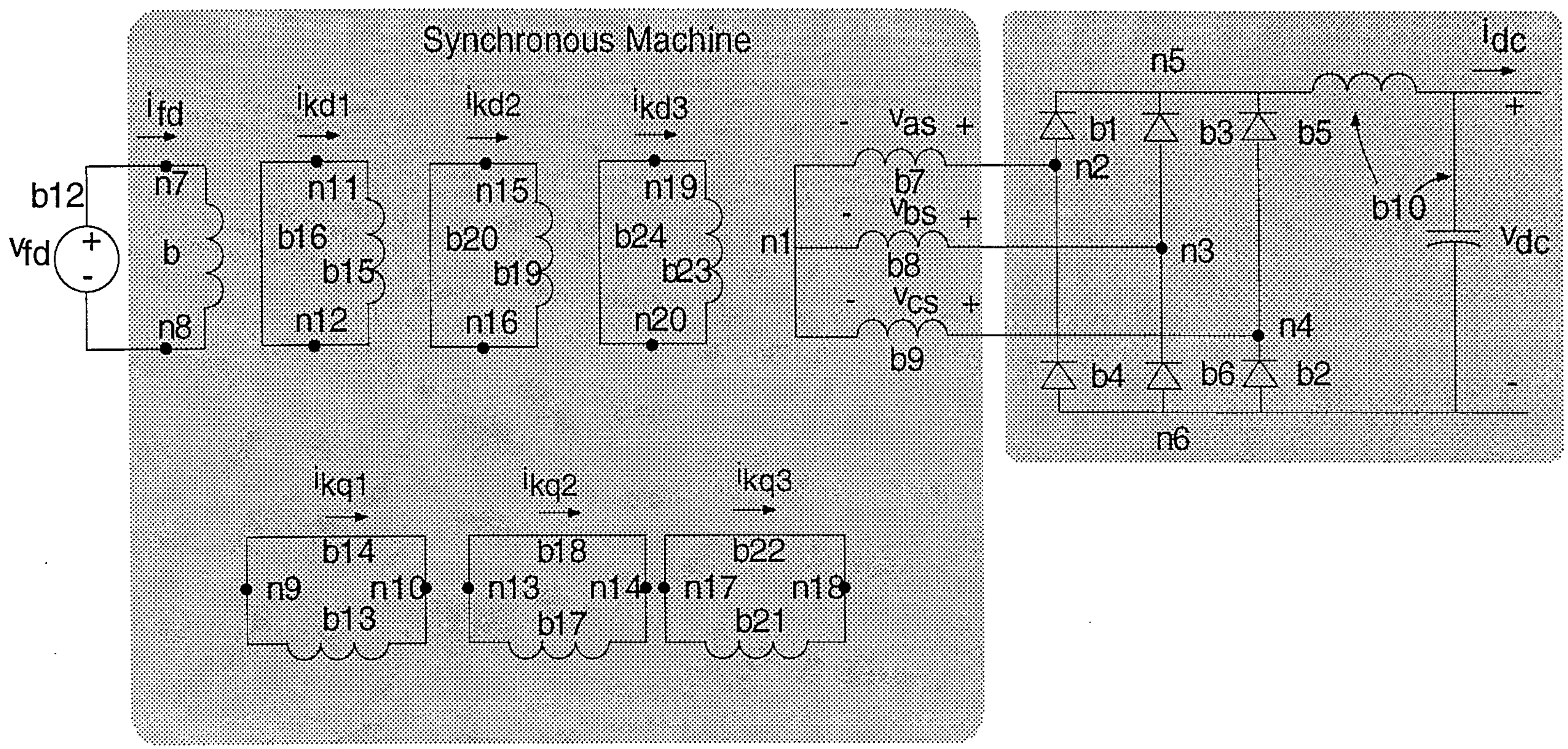
COUPLED-CIRCUIT MODEL

$$\mathbf{v}_{abcs} = r_s\mathbf{i}_{abcs} + p[\mathbf{L}_{abcs}(\theta_r)\mathbf{i}_{abcs}] + p[\mathbf{L}_{sr}(\theta_r)\mathbf{i}_{qdr}]$$

$$\mathbf{v}_{qdr} = \mathbf{r}_r\mathbf{i}_{qdr} + p[\mathbf{L}_r i_{qdr}] + p[\mathbf{L}_{rs}(\theta_r)\mathbf{i}_{abcs}]$$

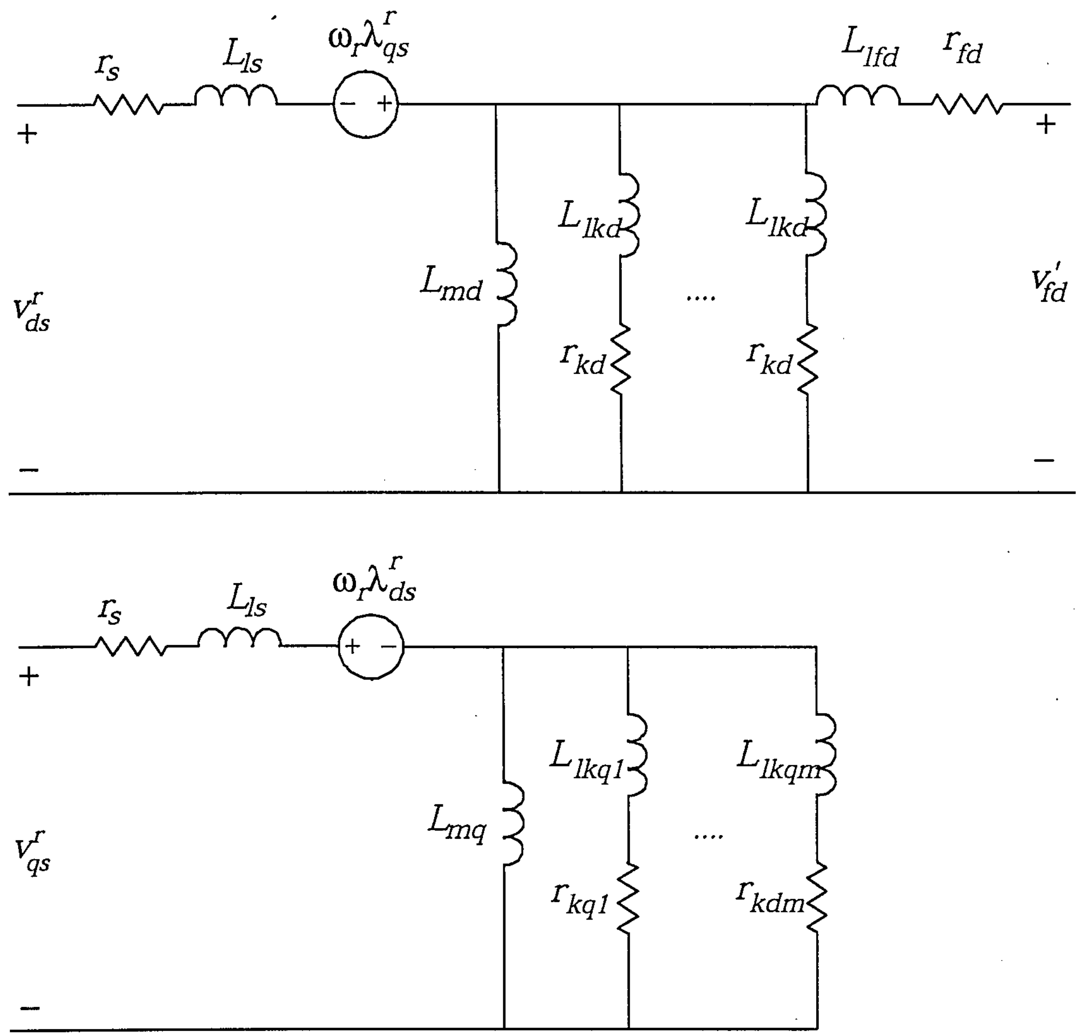
$$\mathbf{L}_{abcs}(\theta_r) = \begin{bmatrix} L_S(2\theta_r) & L_M\left(2\theta_r - \frac{2\pi}{3}\right) & L_M\left(2\theta_r + \frac{2\pi}{3}\right) \\ L_M\left(2\theta_r - \frac{2\pi}{3}\right) & L_S\left(2\theta_r - \frac{4\pi}{3}\right) & L_M(2\theta_r) \\ L_M\left(2\theta_r + \frac{2\pi}{3}\right) & L_M(2\theta_r) & L_S\left(2\theta_r + \frac{4\pi}{3}\right) \end{bmatrix}$$

COUPLED-CIRCUIT MODEL



Number of nodes - 20
Number of branches - 24

PARK'S CIRCUIT



VOLTAGE-BEHIND-REACTANCE MODEL

$$v_{qs}^{r} = r_q'' i_{qs}^{r} + \omega_r L_d'' i_{ds}^{r} + p L_q'' i_{qs}^{r} + v_q''$$

$$v_{ds}^{r} = r_d'' i_{ds}^{r} - \omega_r L_q'' i_{qs}^{r} + p L_d'' i_{ds}^{r} + v_d''$$

Transforming to Physical Variables

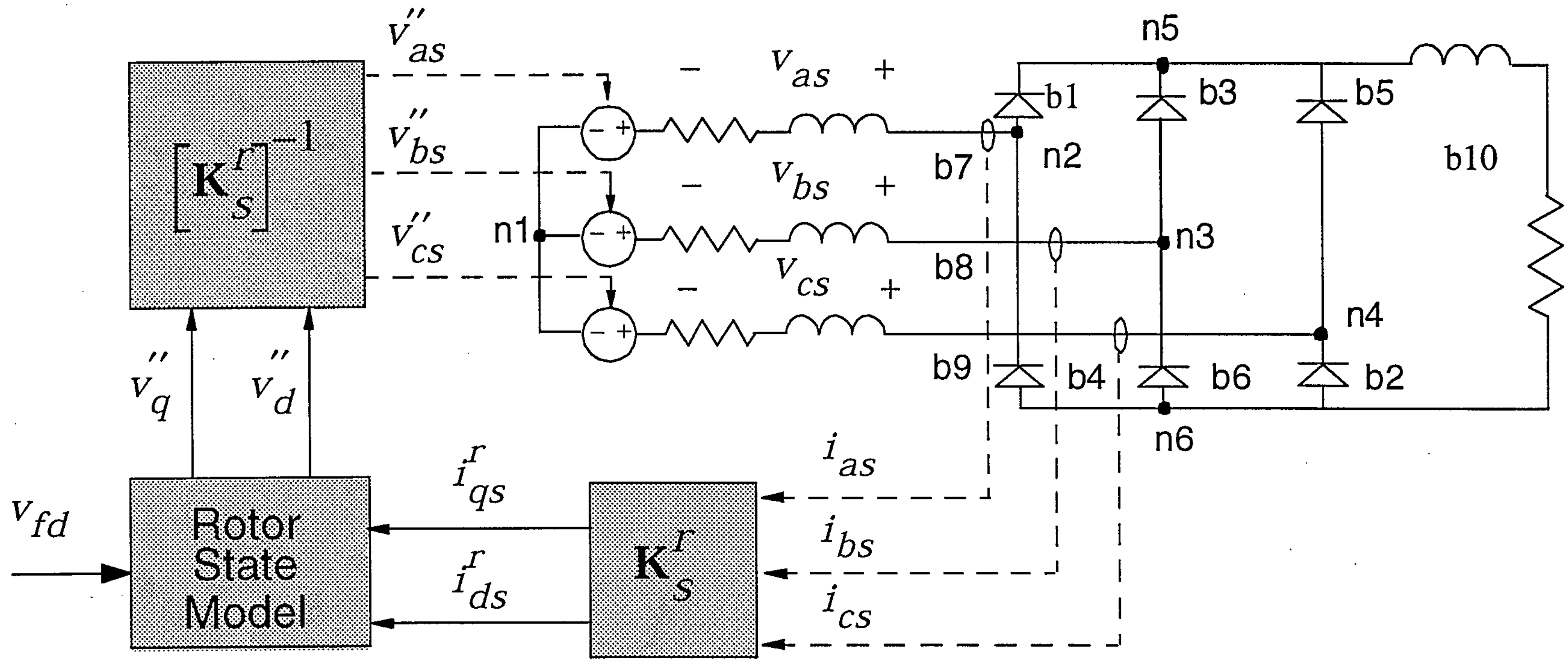
$$\mathbf{v}_{abcs} = \mathbf{r}_s''(\theta_r)\mathbf{i}_{abcs} + p[\mathbf{L}_{abcs}''(\theta_r)\mathbf{i}_{abcs}] + \mathbf{v}_{abcs}''$$

$$p\lambda_{kq\mu} = \frac{r_{kqu}}{L_{kqu}}(\lambda_q'' + L_{mq}'' i_{qs}^{r} - \lambda_{kq\mu});\ \mu = 1, \ldots, m$$

Coupling between stator and rotor represented as back emf

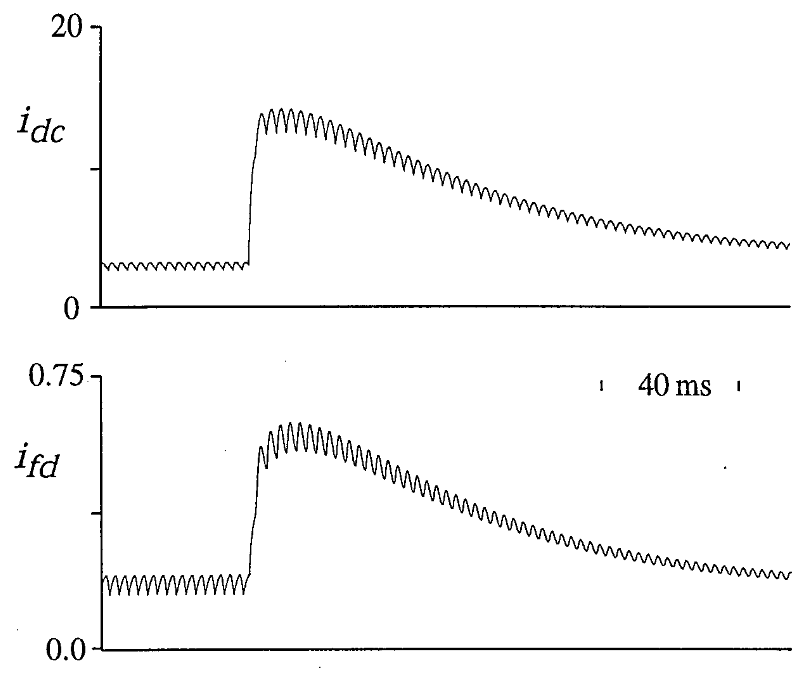
Stator and rotor equations in partitioned form

VOLTAGE-BEHIND-REACTANCE MODEL

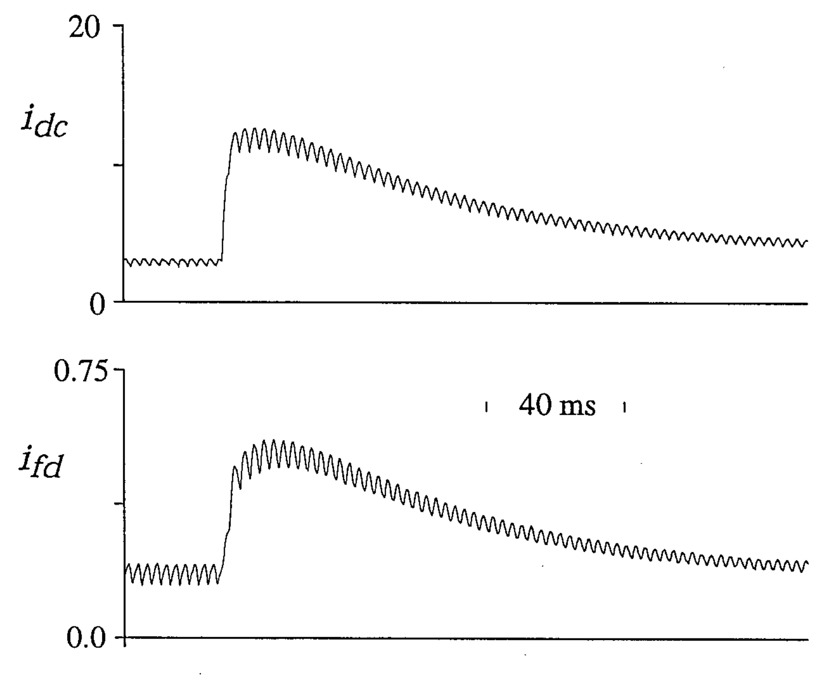


Number of nodes - 6
Number of branches - 10

RESPONSE TO STEP-CHANGE IN LOAD



Simulated



Measured

CPU Time (133-Mhz Pentium PC)
Coupled-Circuit Model - 212 s
Voltage-Behind-Reactance Model - 12 s

COMPARISON OF EIGENVALUES

System Eigenvalues using CC and VBR Models

CC	VBR
1,056	-33+9j
326	-33-9j
-46	-52
-279	-205
-802	-370
-1,377	-798
-4,718	-1,176
-13,442	-13,315
-218,060	-214,489

Average integration interval 300% larger using VBR model

EIGENSTRUCTURE

Currents as state variables

$$p\mathbf{i}_x = \mathbf{A}_i(\theta_r)\,\mathbf{i}_x + \mathbf{B}_i(\theta_r)\,\mathbf{e}_{br}$$

where

$$\mathbf{A}_i(\theta_r) = -\mathbf{L}_x^{-1}(\theta_r)[\mathbf{r}_x + p\mathbf{L}_x(\theta_r)]$$

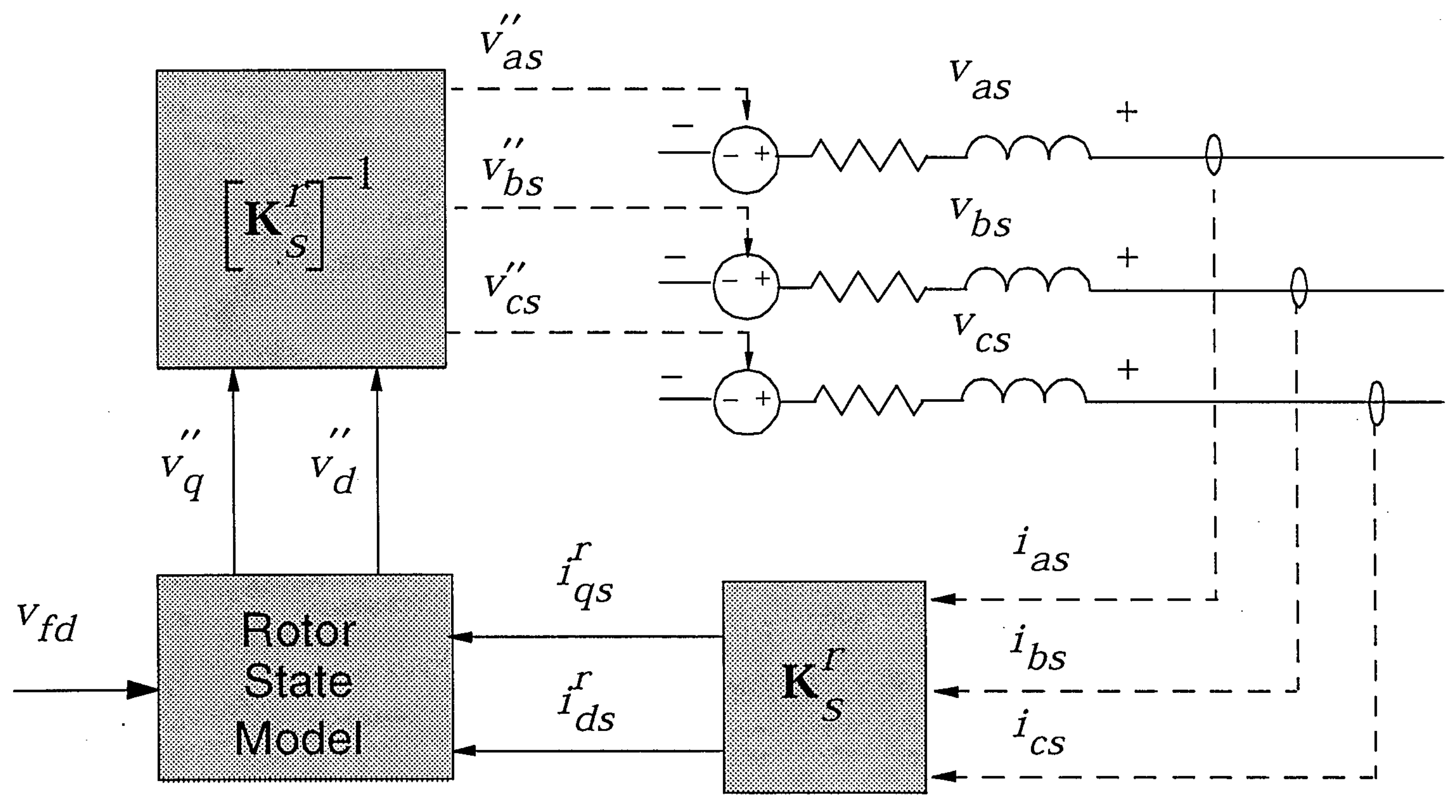
$$\mathbf{B}_i(\theta_r) = -\mathbf{L}_x^{-1}(\theta_r)\mathbf{B}_b\mathbf{e}_{br}$$

Flux linkages as state variables

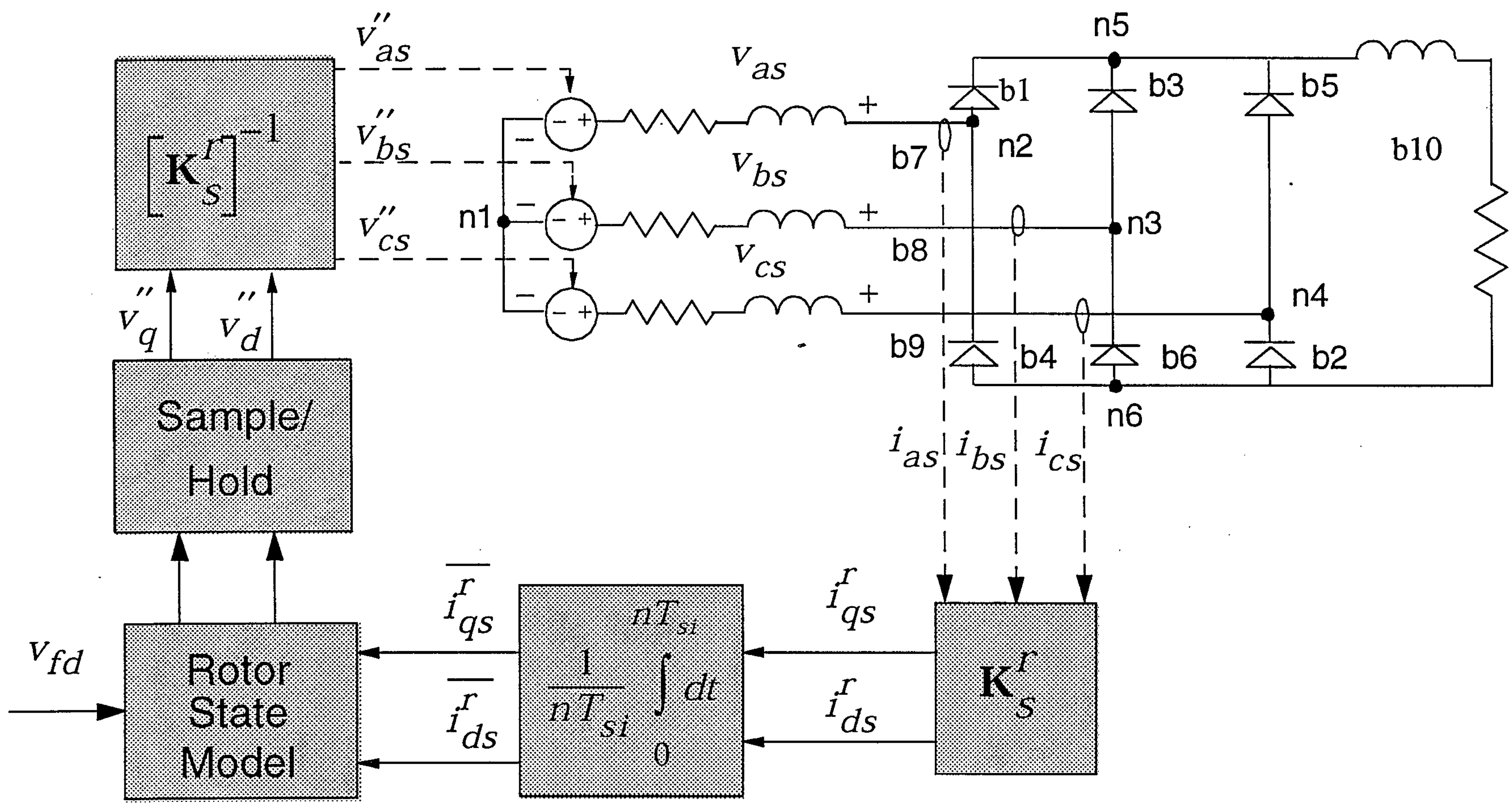
$$p\lambda_x = \mathbf{A}_\lambda(\theta_r)\,\lambda_x + \mathbf{B}_\lambda\mathbf{e}_{br}$$

where $\mathbf{A}_\lambda(\theta_r) = -\mathbf{r}_x\mathbf{L}_x^{-1}(\theta_r)$ $\quad \mathbf{B}_\lambda = -\mathbf{B}_b$

SYNCHRONOUS MACHINE TEMPLATE

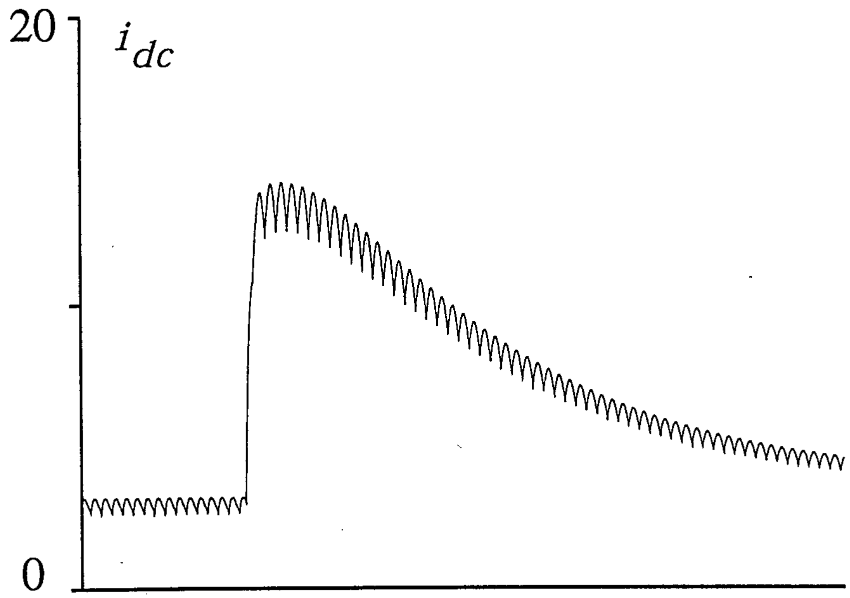


MULTI-RATE SIMULATION

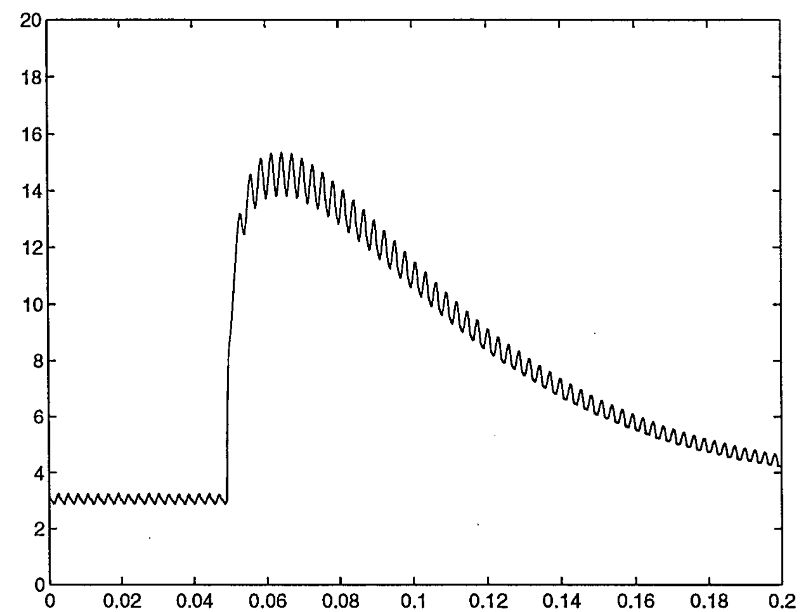


RESPONSE TO STEP-CHANGE IN LOAD

Single-Rate

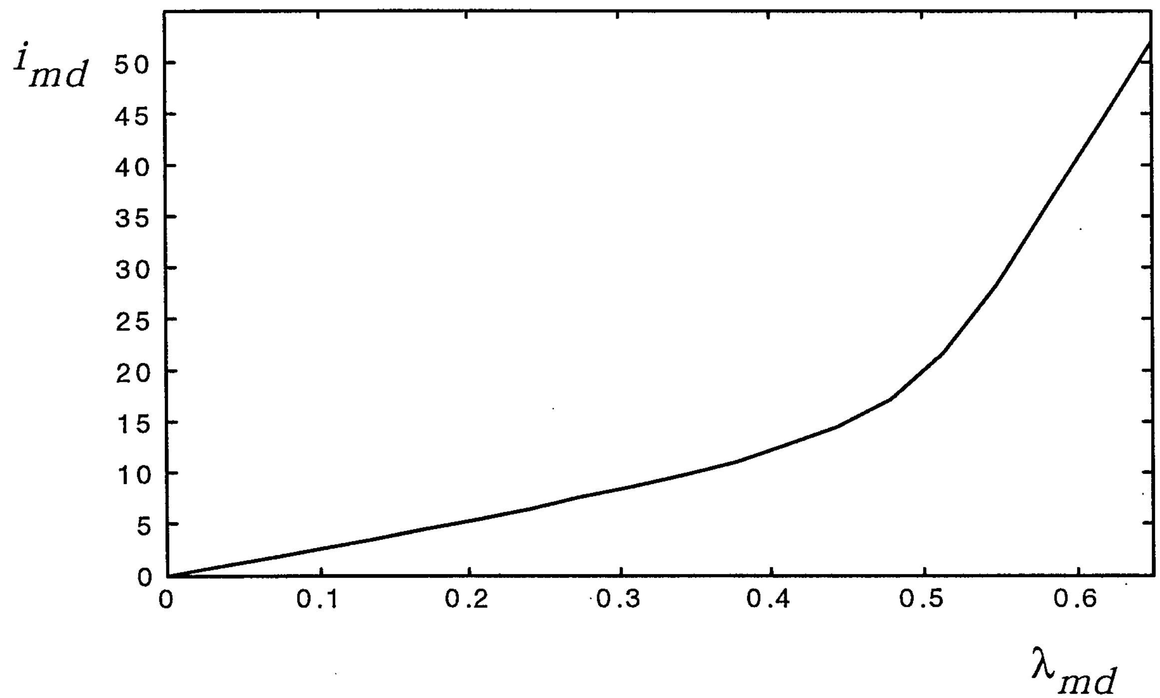


Multi-Rate



CPU Time (133-Mhz Pentium PC)
Single-Rate - 12 s
Multi-Rate - 4 s

VOLTAGE-BEHIND-REACTANCE MODEL (SATURATION INCLUDED)



$$i_{md}(\lambda_{md}) = F(\lambda_{md})$$

$$\frac{\partial}{\partial \lambda_{md}} F(\lambda_{md}) = \frac{2}{\pi} \operatorname{atan}(\tau_T(\lambda_{md} - \lambda_T)) + M_a$$

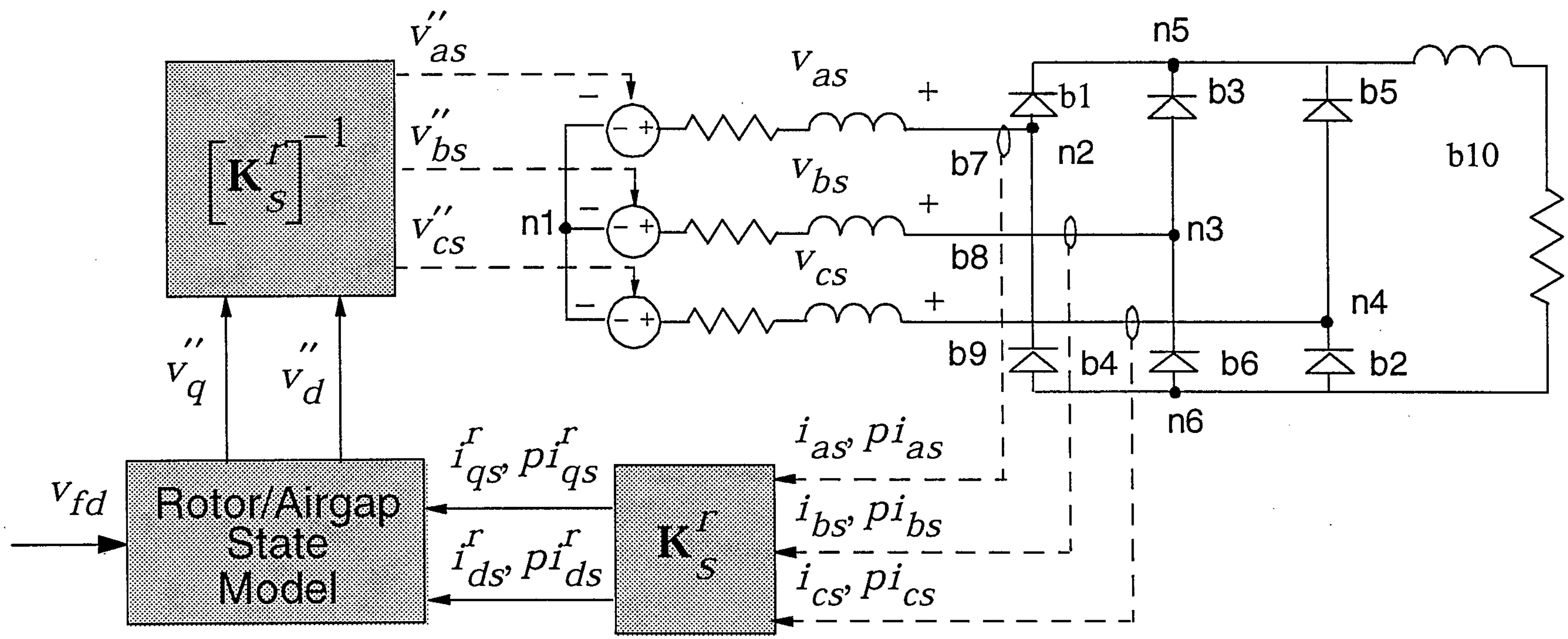
VOLTAGE-BEHIND-REACTANCE MODEL (SATURATION INCLUDED)

$$\mathbf{v}_{abcs} = r_s\mathbf{i}_{abcs} + \mathbf{L}''_{abcs}(\theta_r, \lambda_{md})p\mathbf{i}_{abcs} + \omega_r\frac{\partial}{\partial\theta_r}\mathbf{L}''_{abcs}(\theta_r, \lambda_{md})\mathbf{i}_{abcs} + \mathbf{v}''_{abcs}$$

$$p\lambda_j = v_j - r_j i_j \qquad j = kq1, \ldots, kqm-1, \ldots, fd$$

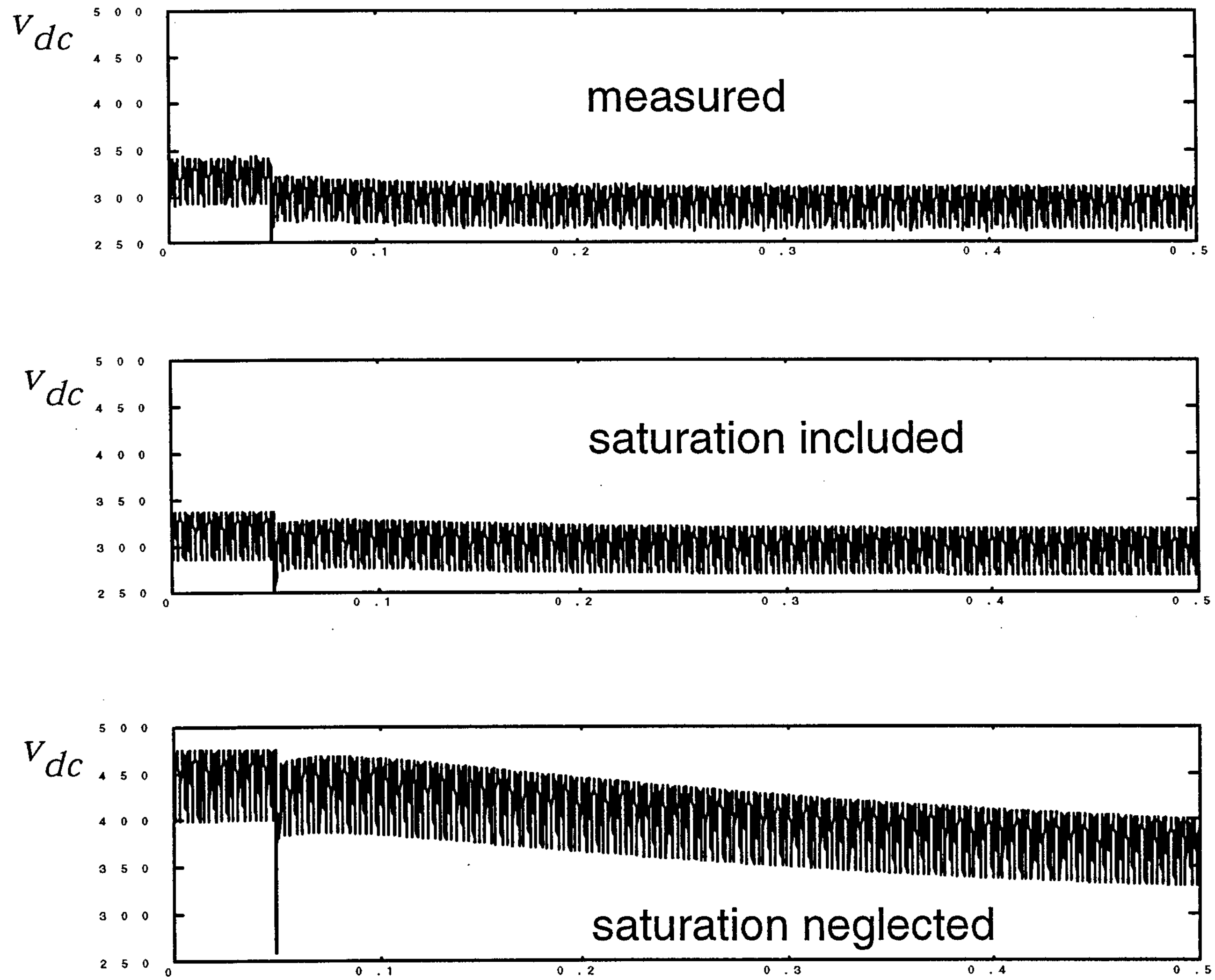
$$p\lambda_{md} = L_{md}(\lambda_{md})\left[p i^r_{ds} + p\frac{\lambda_{fd}}{L_{lfd}} + \sum_{j=1}^{n}\frac{p\lambda_{kdj}}{L_{lkdj}}\right]$$

VOLTAGE-BEHIND-REACTANCE MODEL
(SATURATION INCLUDED)

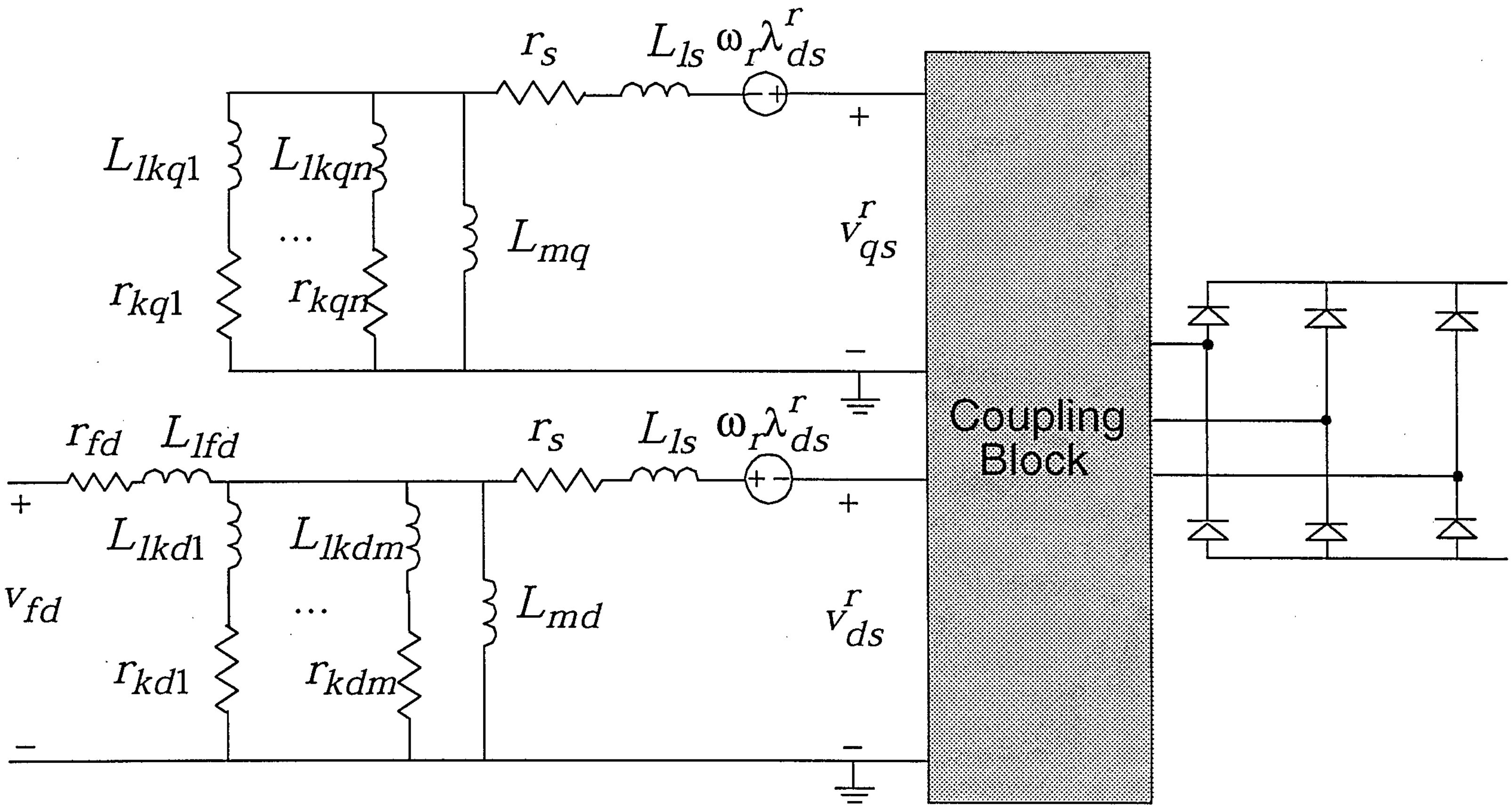


Number of nodes - 6 - Number of branches - 10

RESPONSE TO STEP-CHANGE IN LOAD

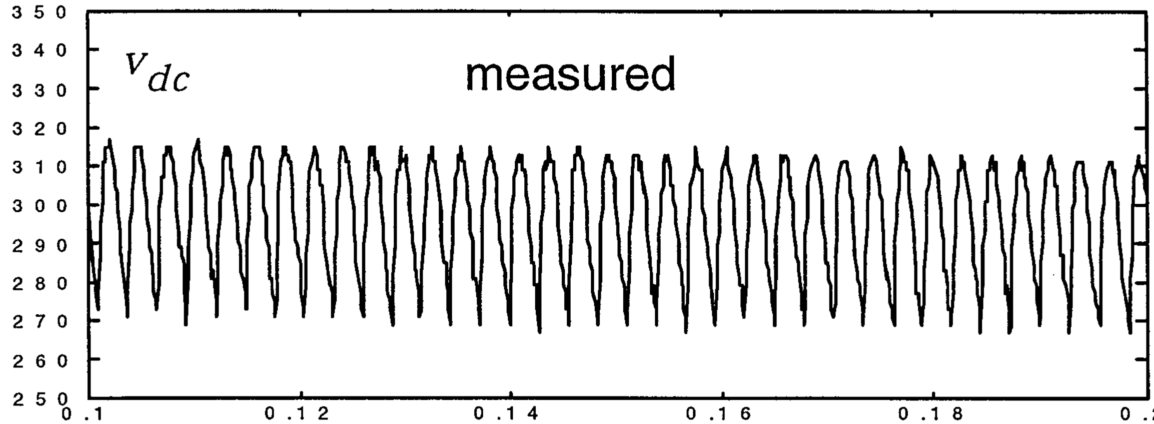


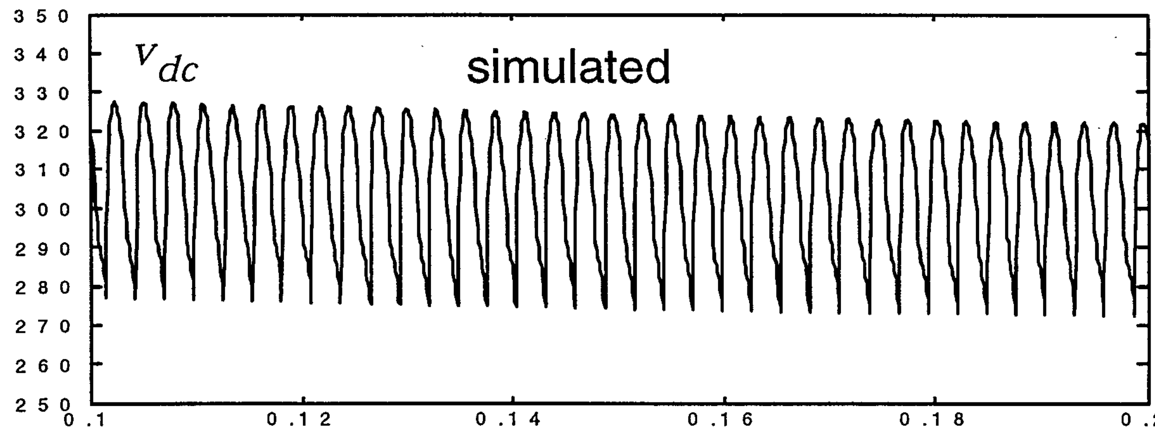
SABER MODEL



r_s
L_{ls}
$\omega_r \lambda_{ds}^r$
L_{lkq1}
L_{lkqn}
r_{kq1}
r_{kqn}
L_{mq}
v_{qs}^r
r_{fd}
L_{lfd}
L_{lkd1}
L_{lkdm}
r_{kd1}
r_{kdm}
L_{md}
v_{fd}
v_{ds}^r
Coupling Block

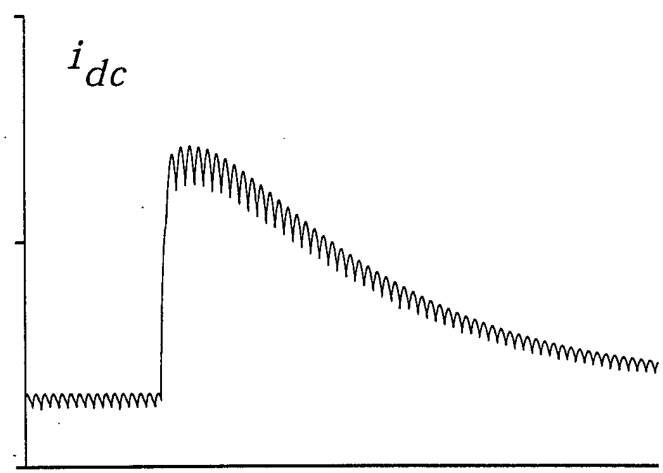
RESPONSE TO STEP-CHANGE IN LOAD (EXPANDED)



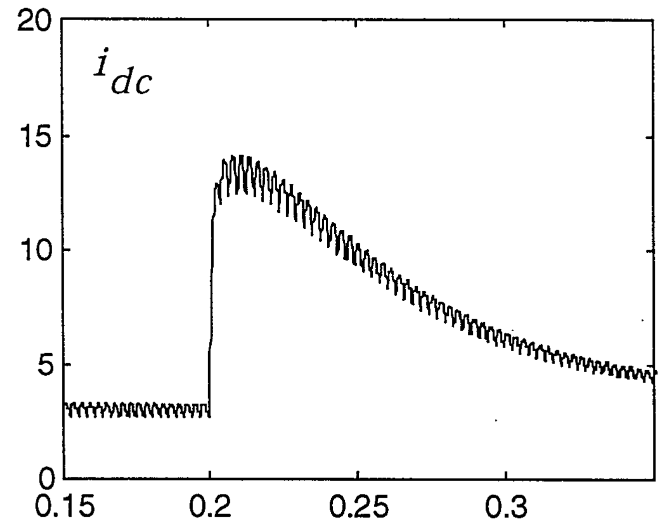


STATE-SPACE VERSUS CIRCUIT-BASED SIMULATION

ACSL (11 s, Sparc 10)



Saber (170 s, Sparc 10)



CPU TIMES OF VARIOUS MODELS

Computer	CC Model	VBR Model (saturation neglected)	VBR Model (saturation included)	Multi-Rate Simulation	Saber Simulation
133-Mhz Pentium	212 sec	12 sec	12 sec	4 sec	
Sun Sparc 10		11.3 sec			41-180 sec

0.2-sec study

FUTURE RESEARCH

1) Speed/accuracy trade-off of neglecting subtransient saliency

2) Semi-analytical (basis function) solution of fast stator/network dynamics

3) Optimized variable-time-step algorithms for the solution of switched-network systems

4) Computational requirements of state-model versus circuit-based approaches

5) Model partitioning in parallel computing platforms

High Frequency Modeling and EMC of Power Electronic Circuits and Motor Drives

S.D. Sudhoff, J.L Drewniak, J.L. Tichenor
University of Missouri - Rolla

Traditional Detailed Simulation

- Uses
  - Approximate Steady State System Waveforms
  - Evaluate System Wide Transient Performance
- Assumptions
  - Idealized Switching Elements (On/Off)
  - Neglect All Circuit Parasitics
  - Neglect All High Order Effects

Need For High Frequency Analysis

- Semiconductor Switching Stress
- Common Mode Currents
- EMI With Control Circuitry
- Electric Insulation Breakdown at Machine Terminals
- Mechanical Failure of Bearings Due to Fluting
- Loss Analysis

H.F. Simulation Approach

- Dual Mode Simulation
  - Standard Detailed Simulation
  - High Frequency Simulation
  - Seamless Integration of Simulation Modes
- H.F. Models
  - Wide Bandwidth Electric Machine Models
  - Behavioral Semiconductor Models
  - Good Parasitic Models

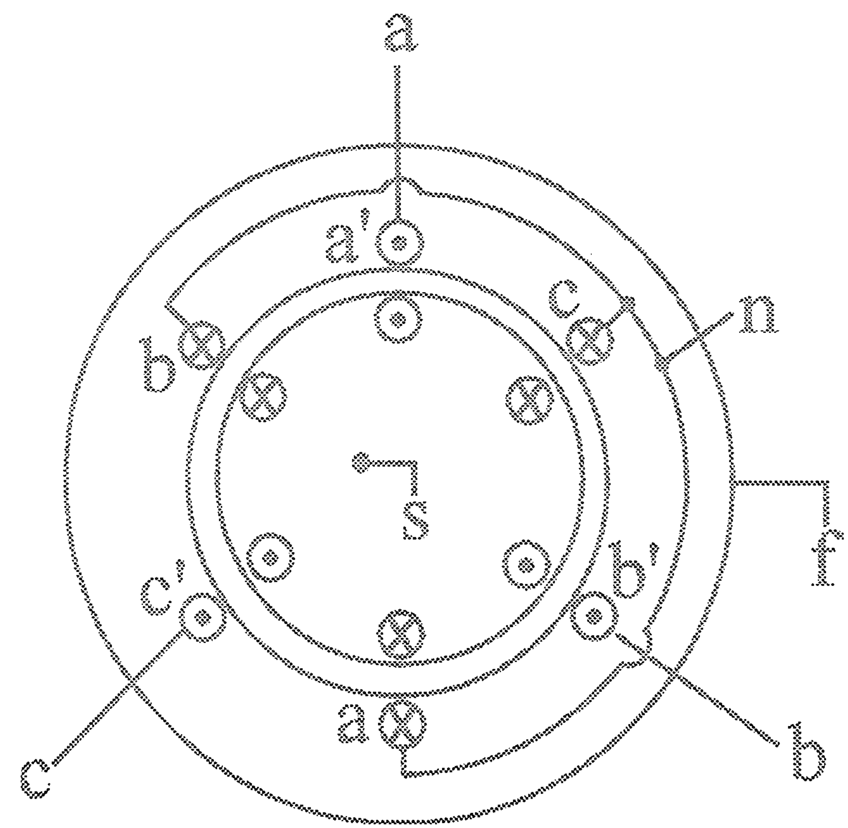
Uses For Proposed Environment

- Loss Evaluation
- Snubber Design
- EMC Design
- Verification of Controller Robustness in Presence of Noise
- Switching Algorithm Evaluation
- Common Mode Current Analysis
- Anticipate Likelihood of Bearing Currents
- Everything Standard Detailed Simulation is Used For

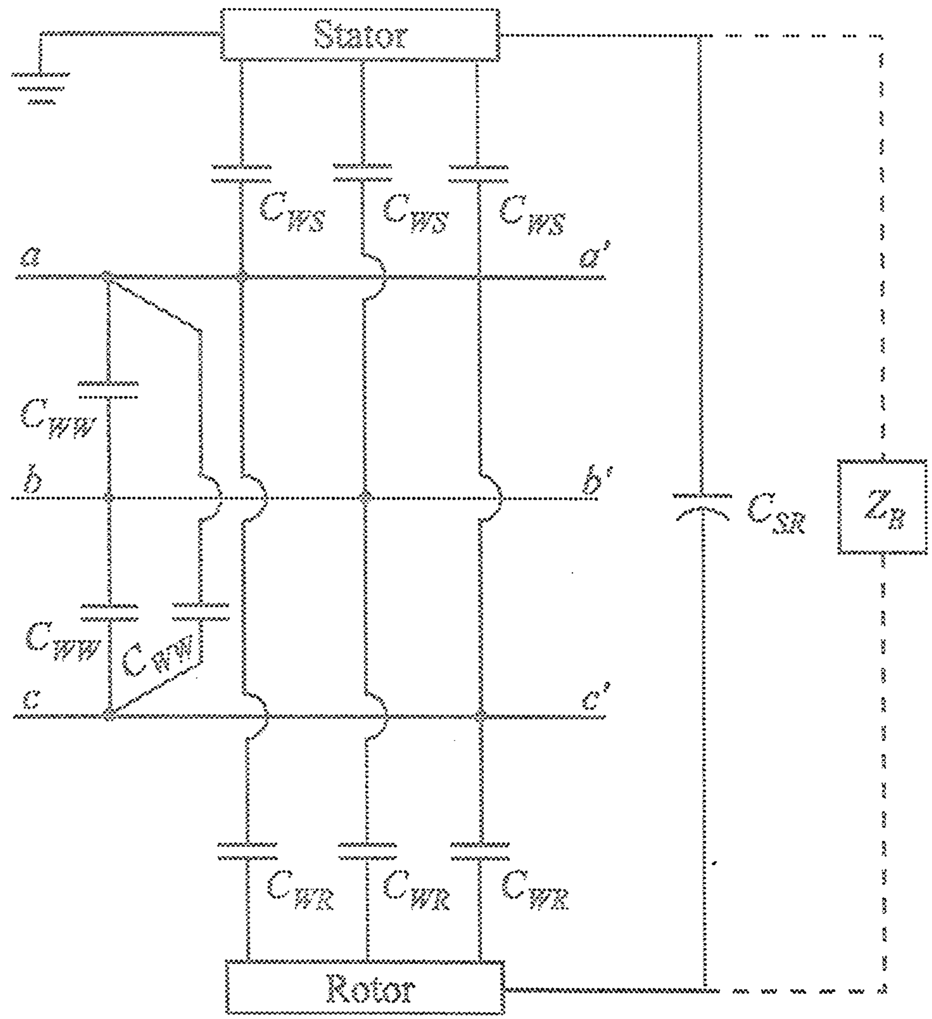
Work To Date

- Machine Models
  - High Frequency Characterization of Standard 3-Phase Induction Motor
  - High Bandwidth Characterization and Mathematical Model of 3-Phase Surface Mounted Permanent Magnet Synchronous Machine (SM-PMSM)
  - Dual Mode Simulation of SM-PMSM
- Semiconductor Device Modeling
  - New Behavioral IGBT Model

Induction Motor Structure



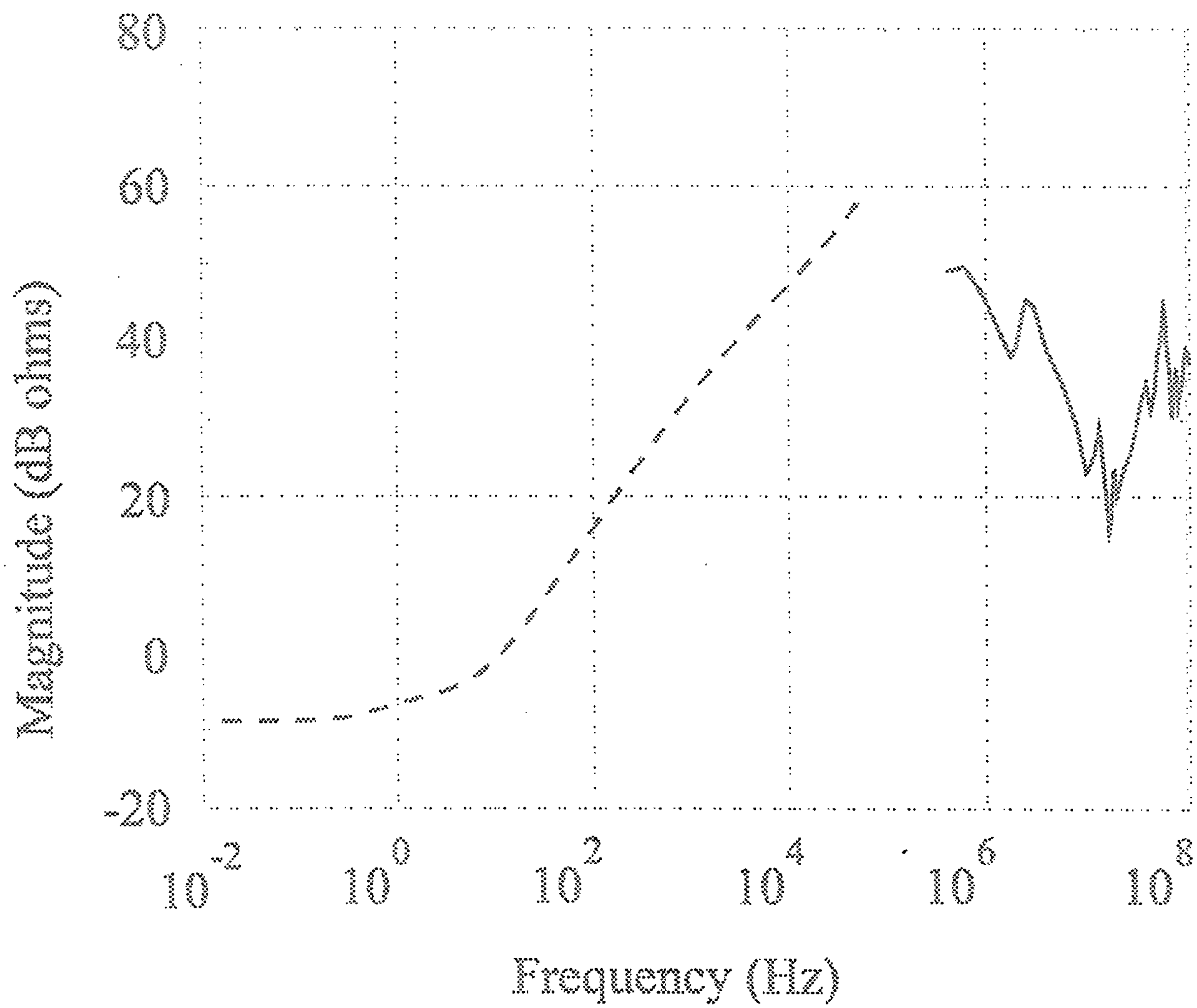
Induction Motor Capacitances



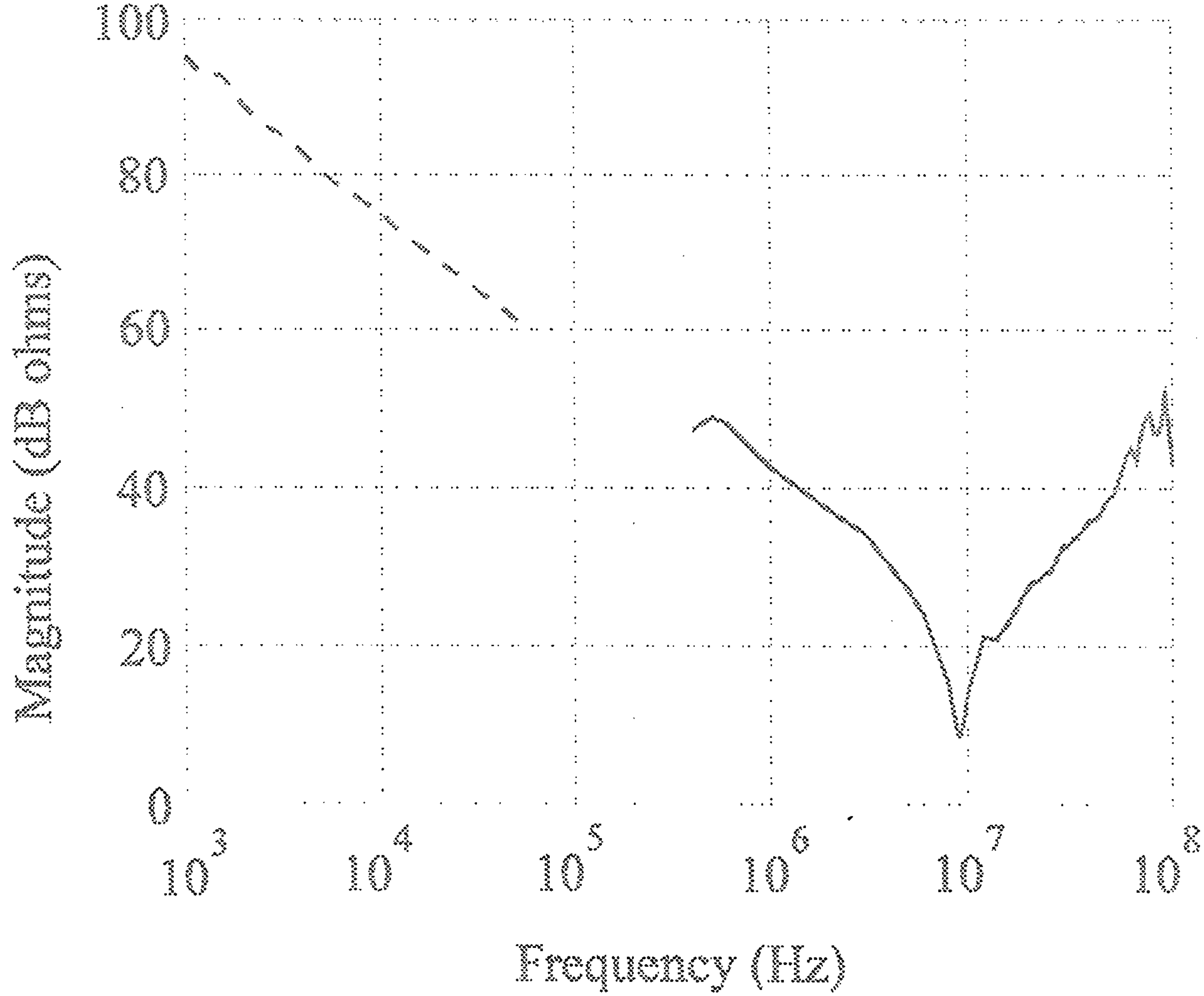
IM Capacitance Values (5 Hp)

- C_{ws} - 1.01 nF
- C_{sr} - 1.1 nF
- C_{ww} - 153 pF
- C_{wr} - 15 pF

IM Q- and D-Axis Impedance



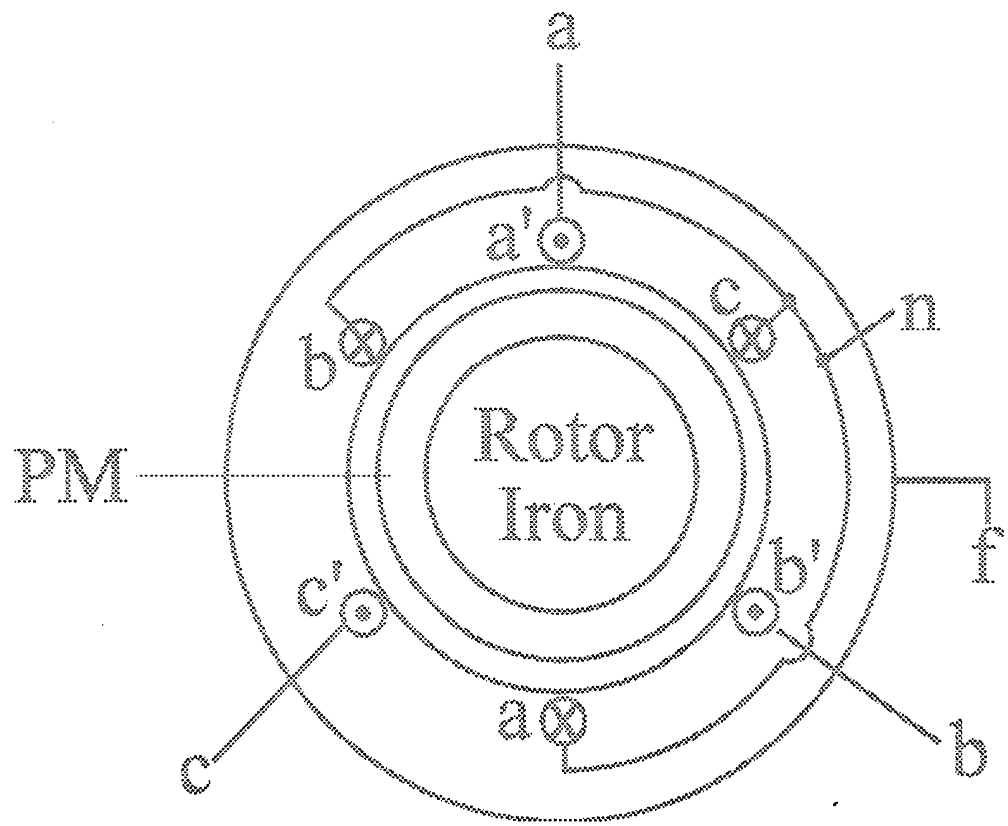
IM Common Mode Impedance



Model Requirements /Approach

- Must Incorporate Capacitive Effects
- Must Be Compatible With Standard Model
- Should Recognize Distributed Nature of HF Machine Model

Surface Mounted Permanent Magnet Synchronous Machine

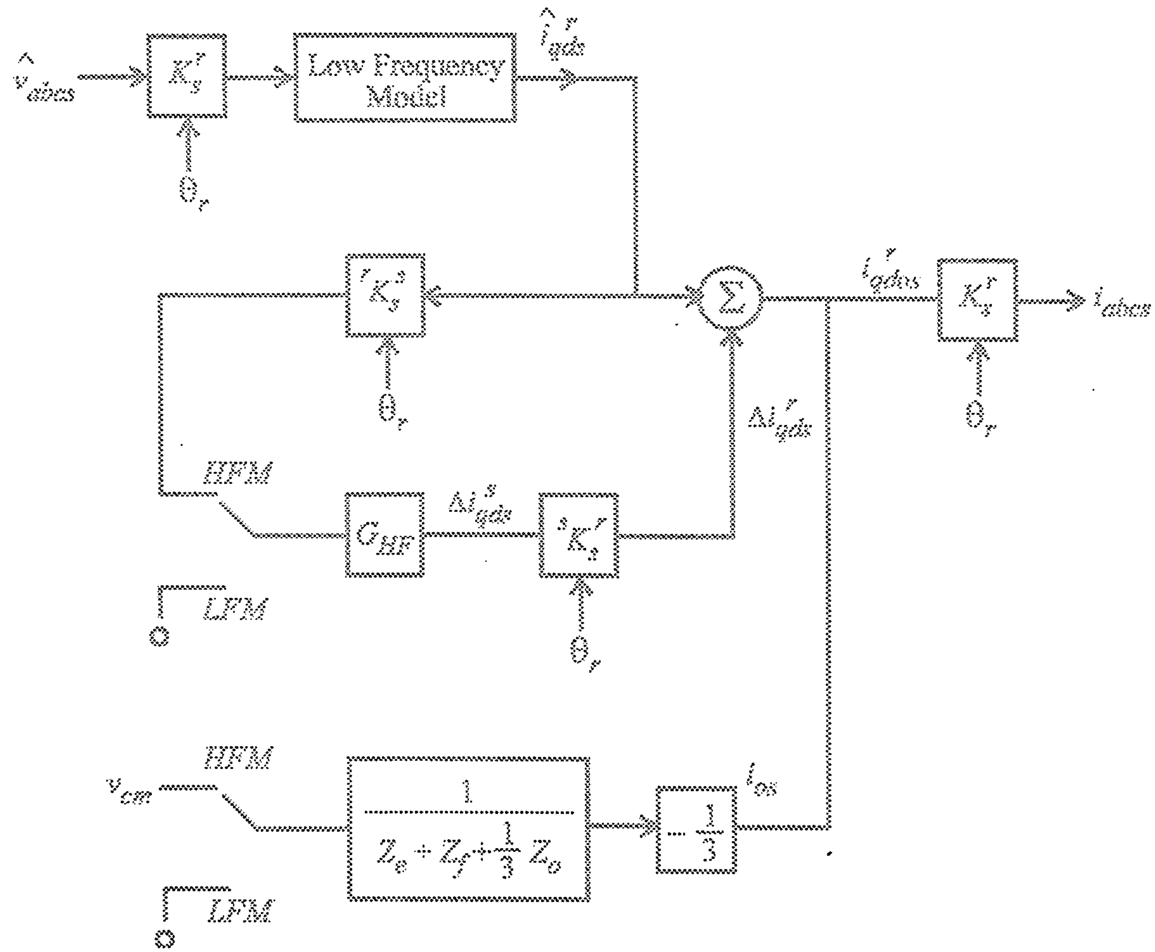


H.F. Machine Variable Model

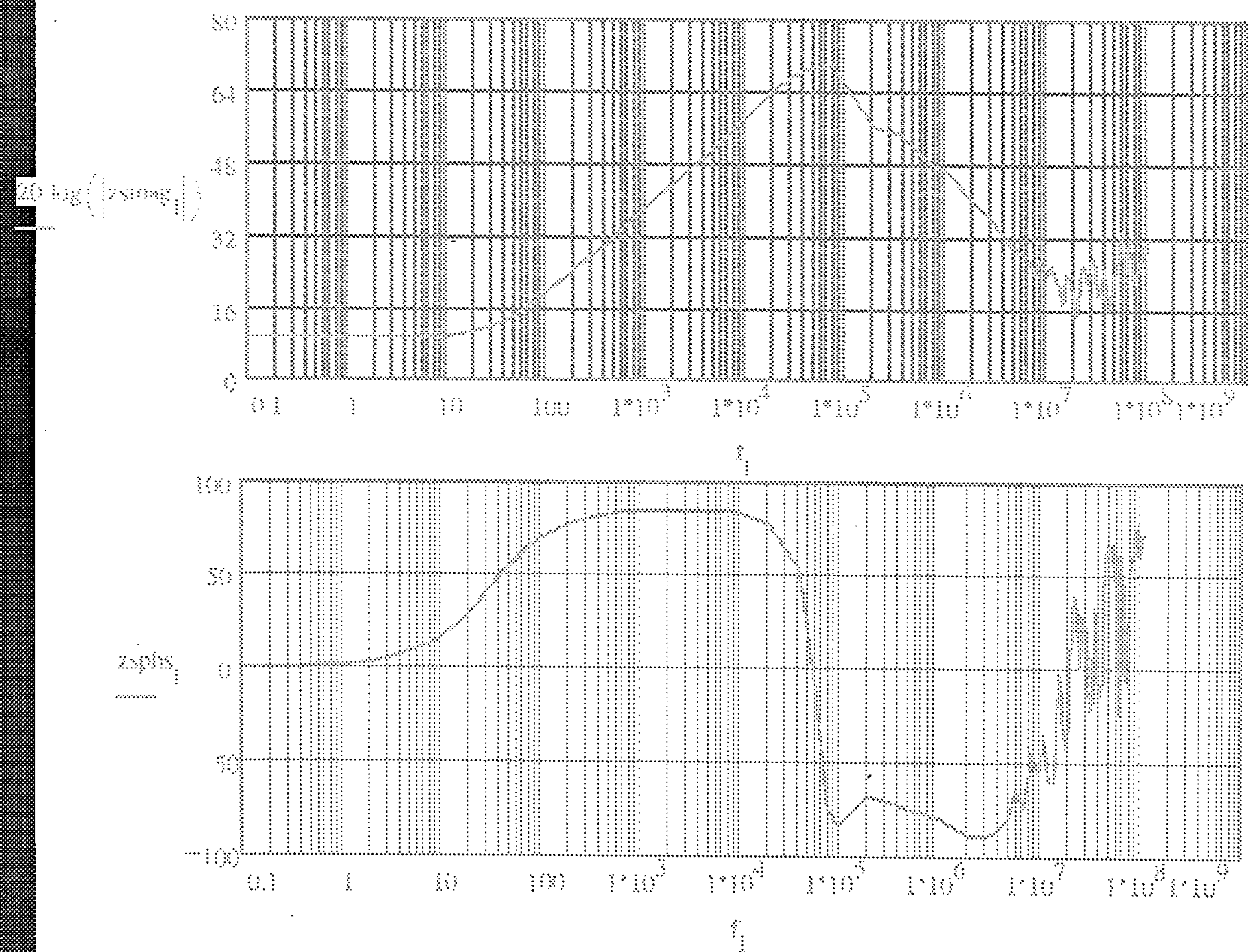
$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ v_f \end{bmatrix} = \begin{bmatrix} z_{ss} & z_{sa} & z_{sa} & z_{sf} \\ z_{sa} & z_{ss} & z_{sa} & z_{sf} \\ z_{sa} & z_{sa} & z_{ss} & z_{sf} \\ z_{sf} & z_{sf} & z_{sf} & z_{ff} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \end{bmatrix} + p\lambda_{abcf}$$

$$\lambda_{abcf} = \lambda'_m \begin{bmatrix} \sin\theta_r & \sin(\theta_r - \frac{2\pi}{3}) & \sin(\theta_r + \frac{2\pi}{3}) & 0 \end{bmatrix}^T$$

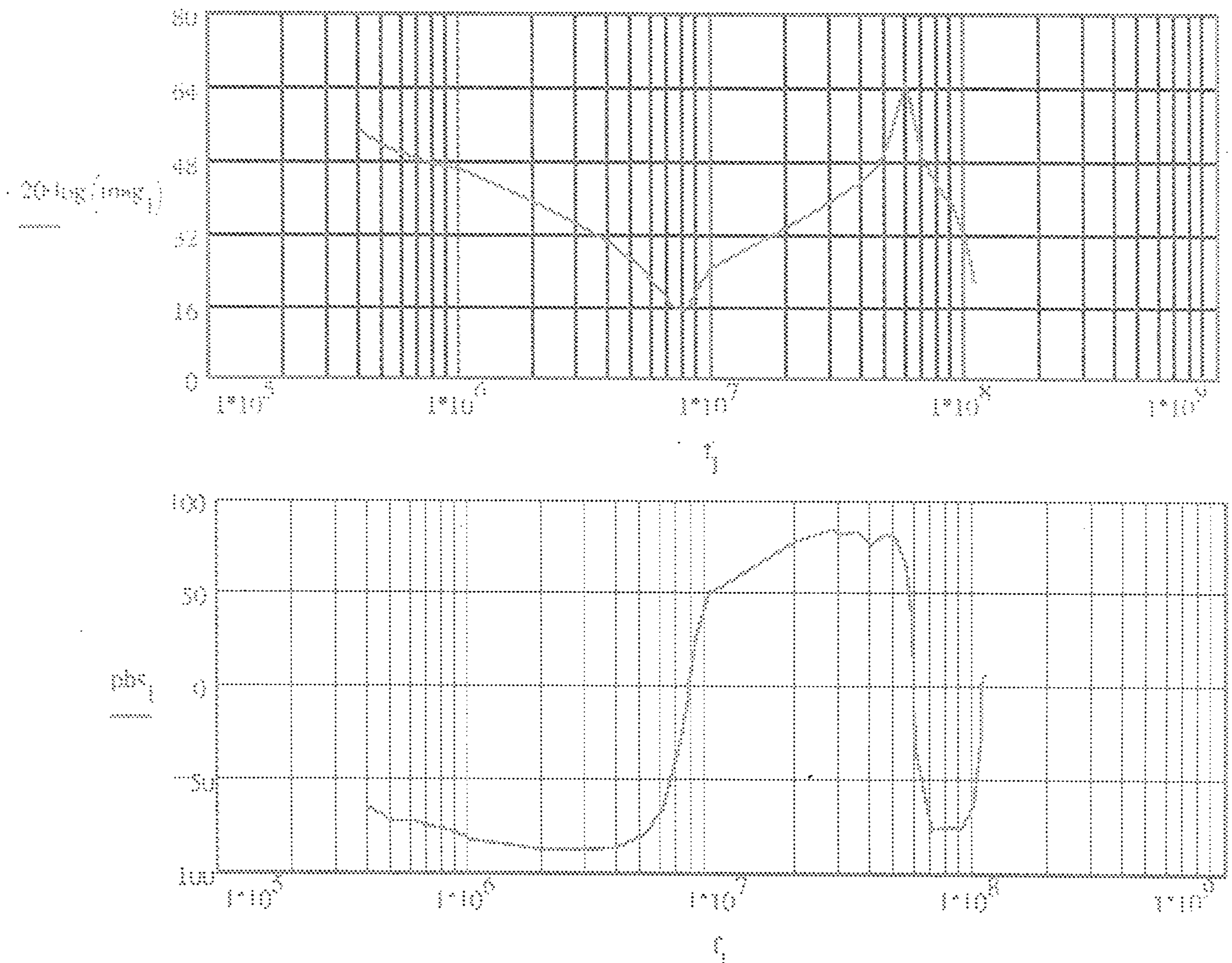
Wide Bandwidth QD Model



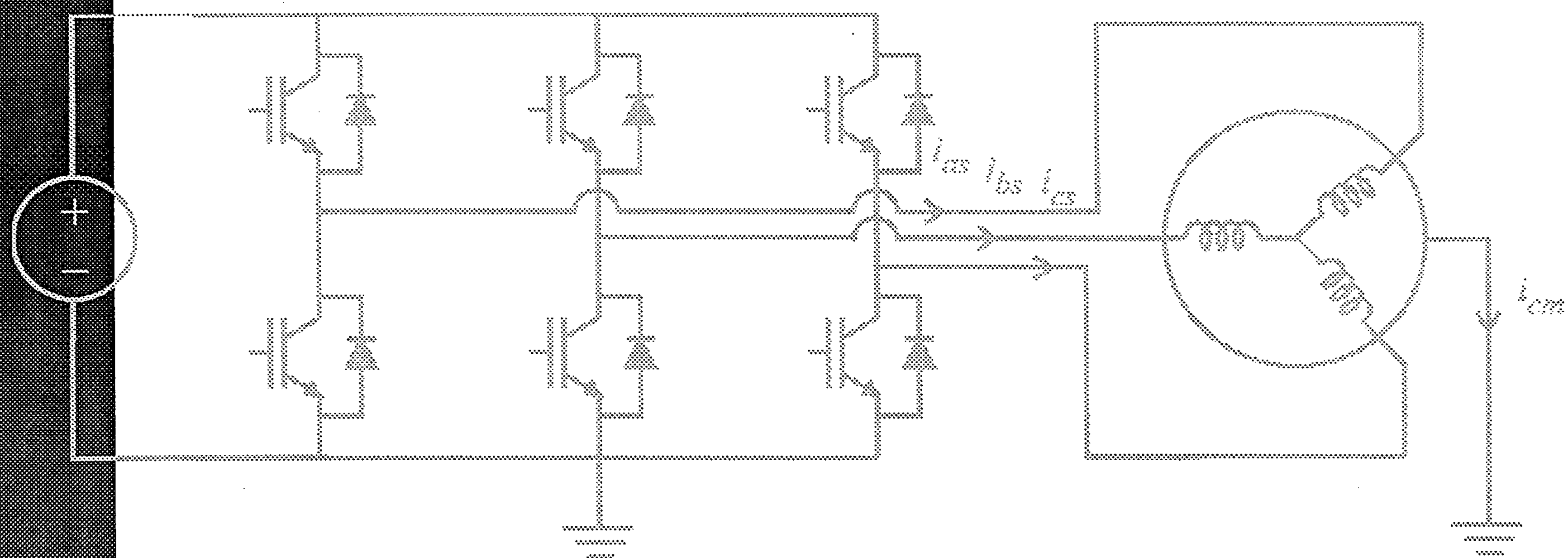
Q/D - Axis Impedance



Common Mode Impedance

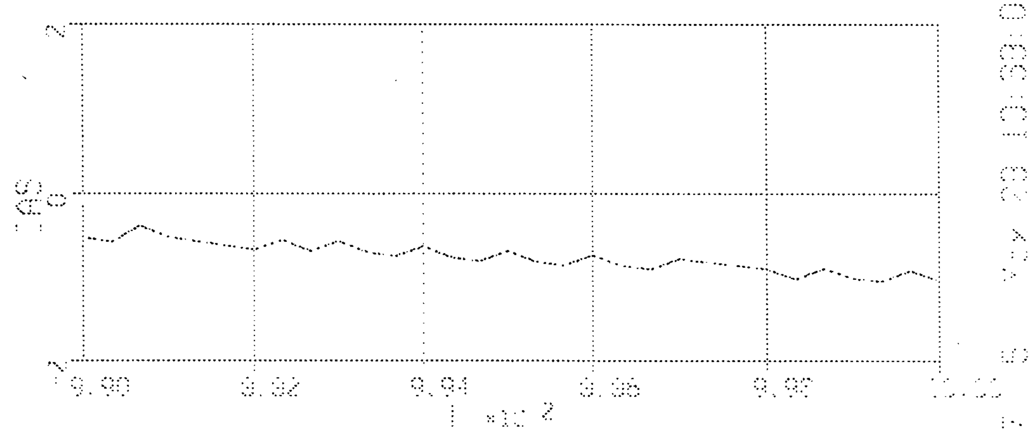


Sample Drive System

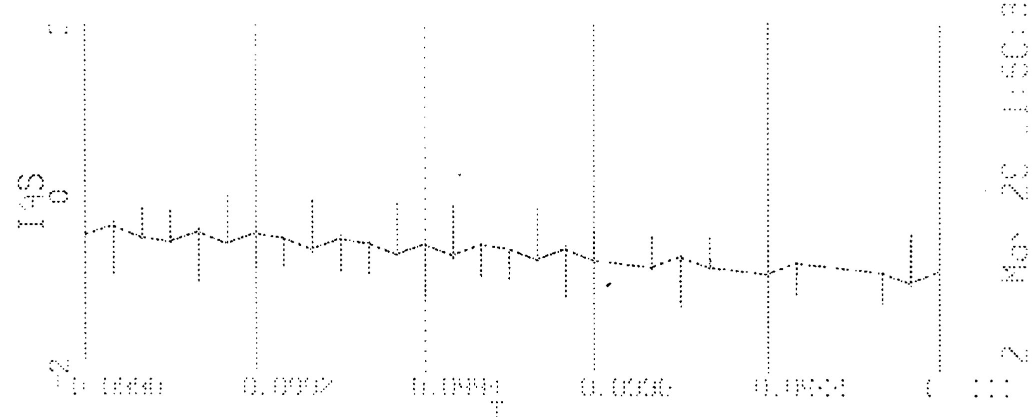


Standard and HF Simulation Mode

Standard Model



High Frequency Model

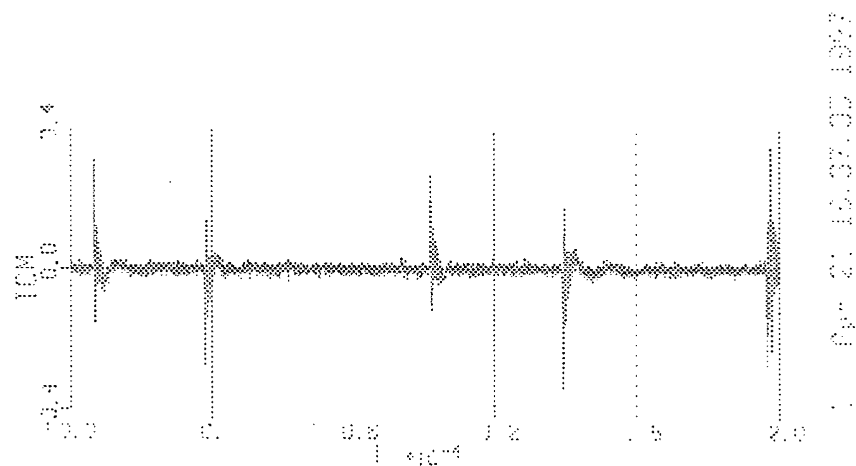


Eigenvalues vs. Mode

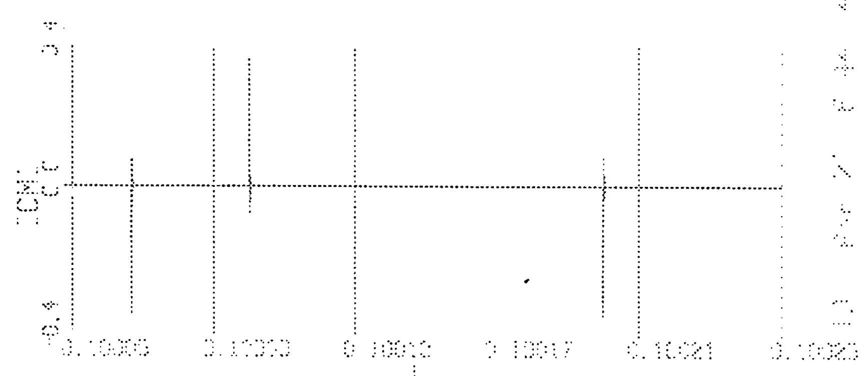
- Low Frequency Mode (1000 rpm):
  - -223 +/- j209.4
- High Frequency Mode (1000 rpm):
  - -223 +/- j209.4
  - -5.37e6 +/- j4.69e7
  - -1.59e7 +/- j7.34e7
  - -1.59e7 +/- j7.34e7

Initial Hardware Comparison

Measured



Simulated



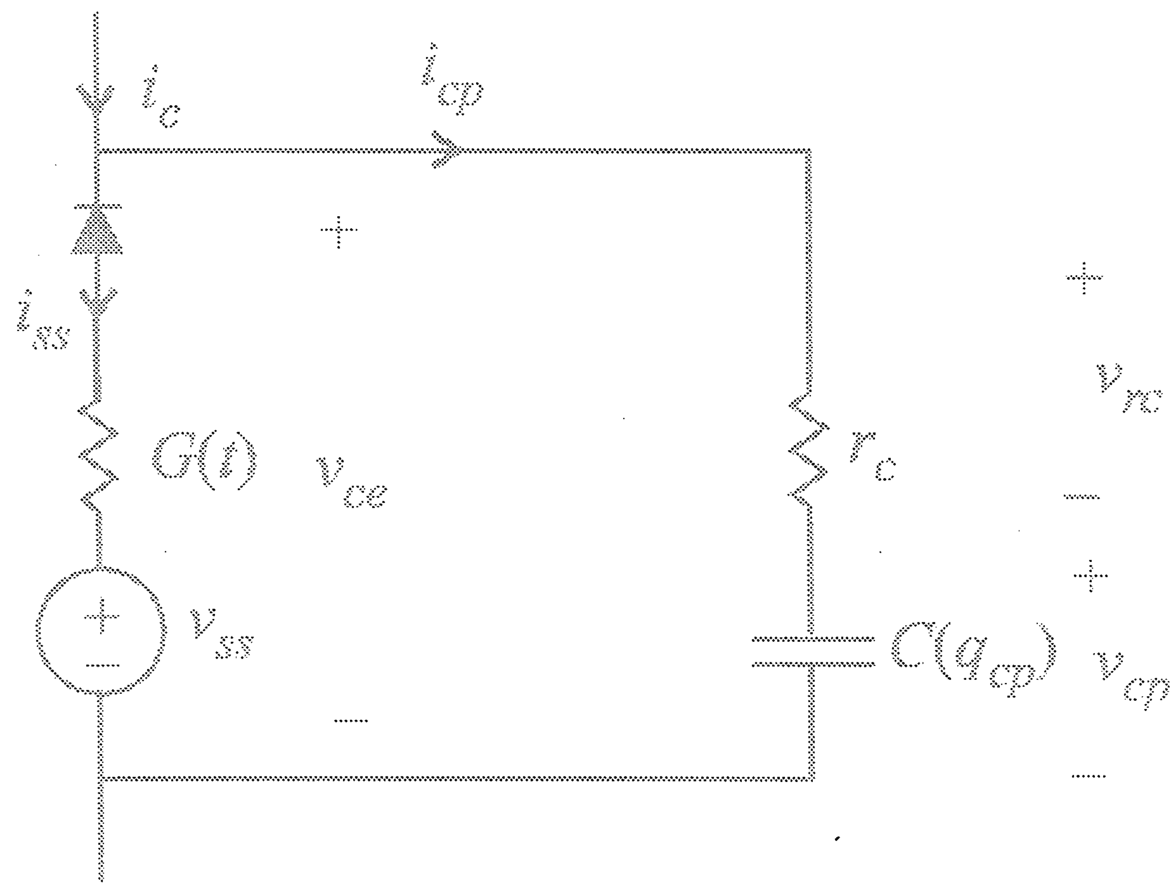
Model Discrepancies

- Amplitude Correct
- Frequency Different
- Actual Response Richer

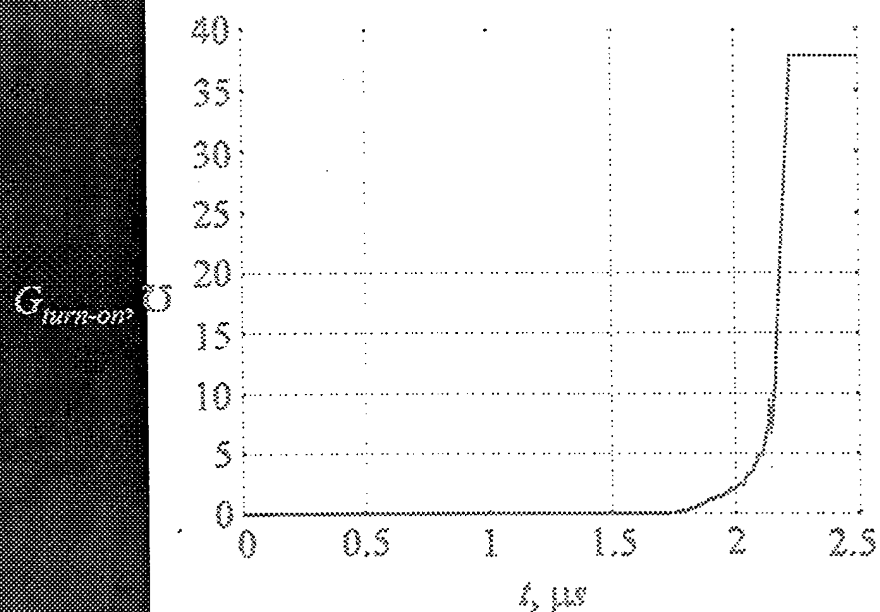
Semiconductor Modeling

- Basic Approaches:
  - Physics Based Models
  - Behavioral Models

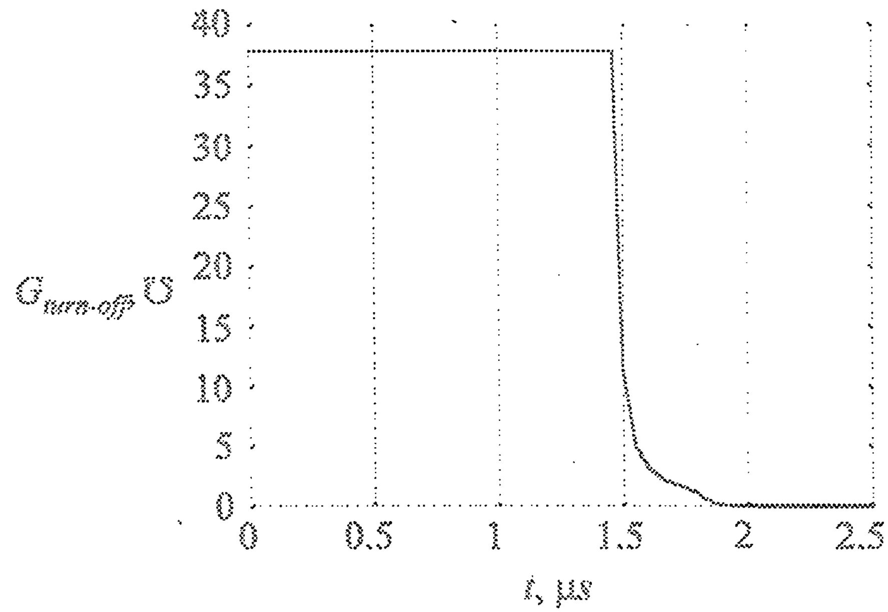
New Behavioral IGBT Model



Conductance Profiles

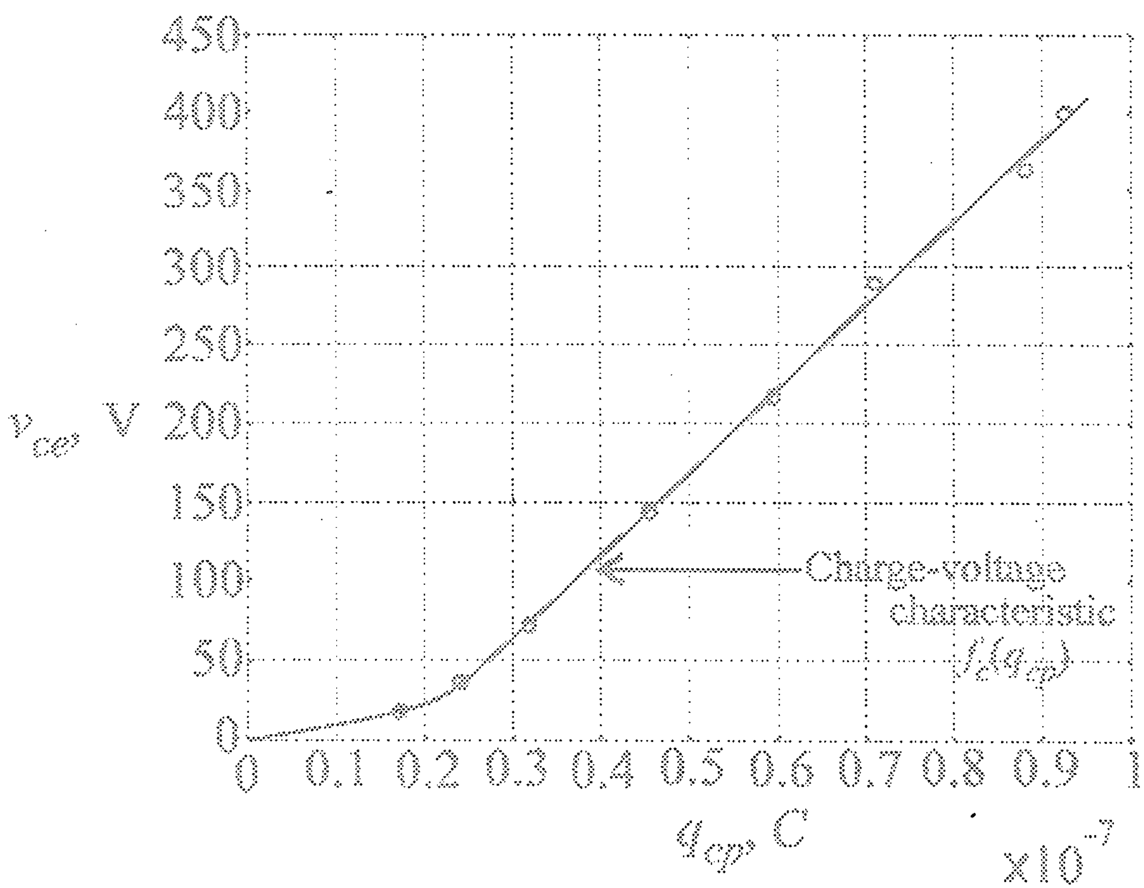


Turn On

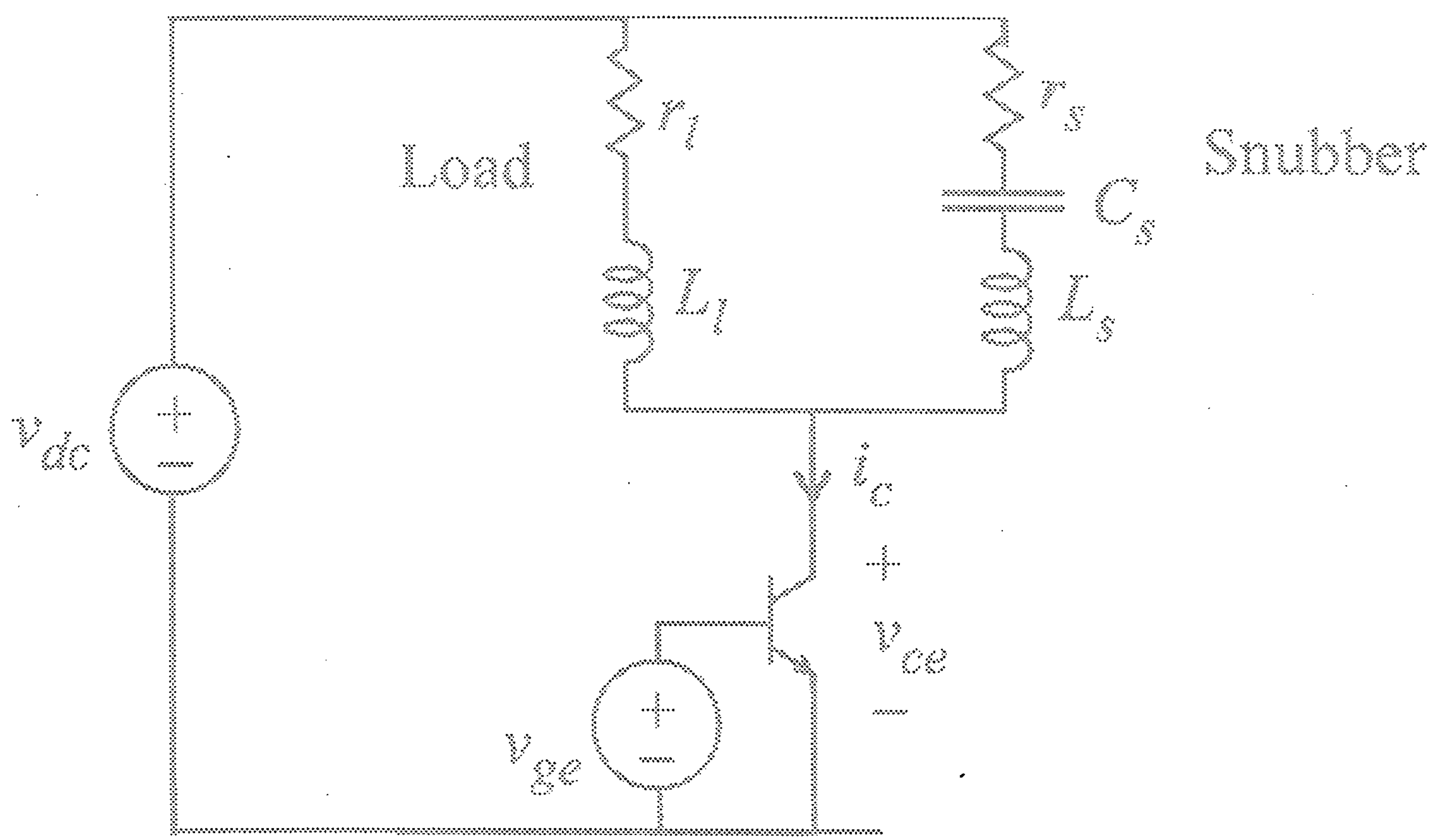


Turn Off

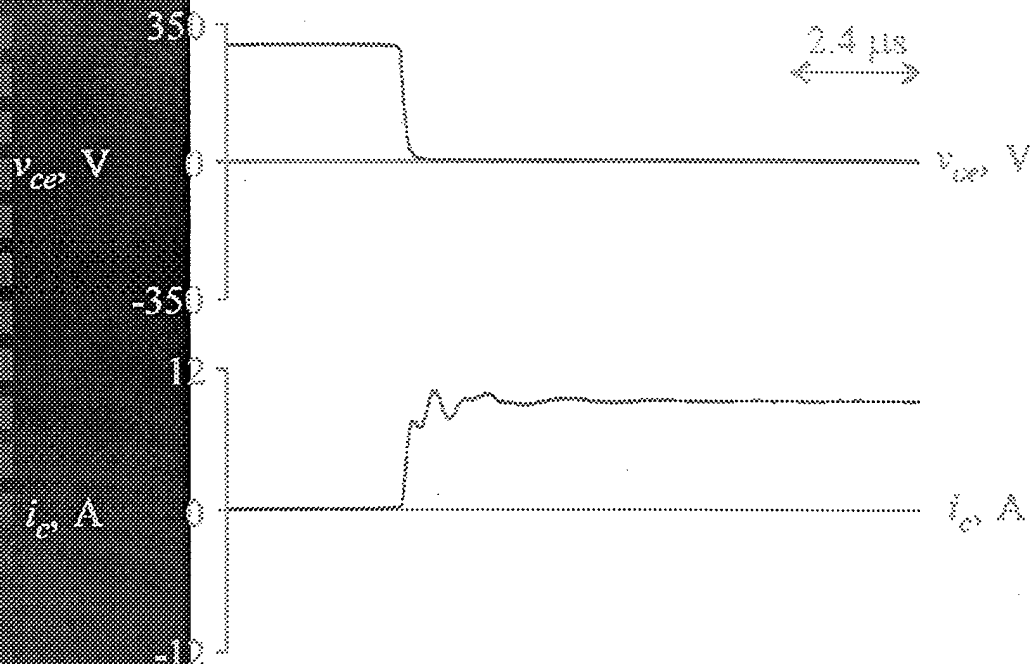
Capacitance Profile



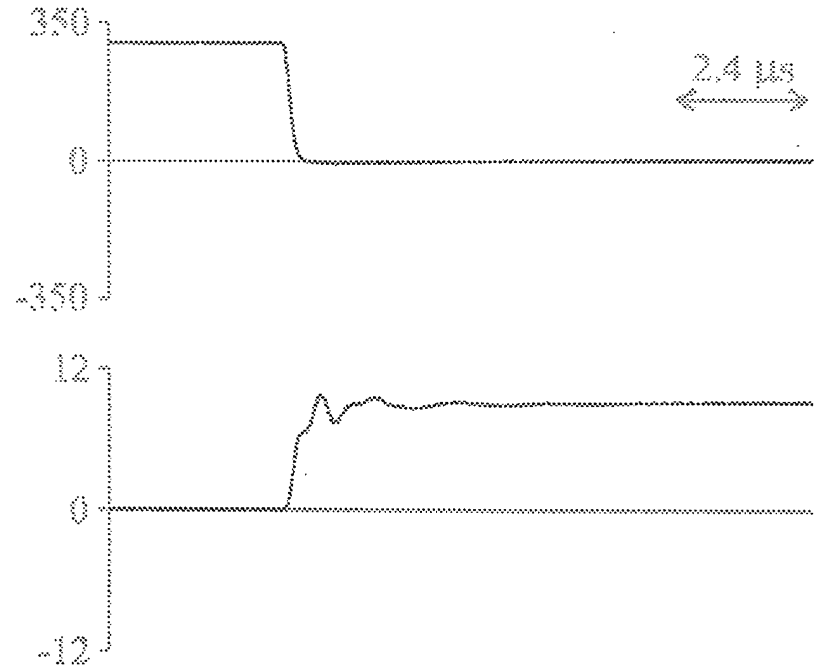
Validation Test Set Up



Turn-On Waveforms

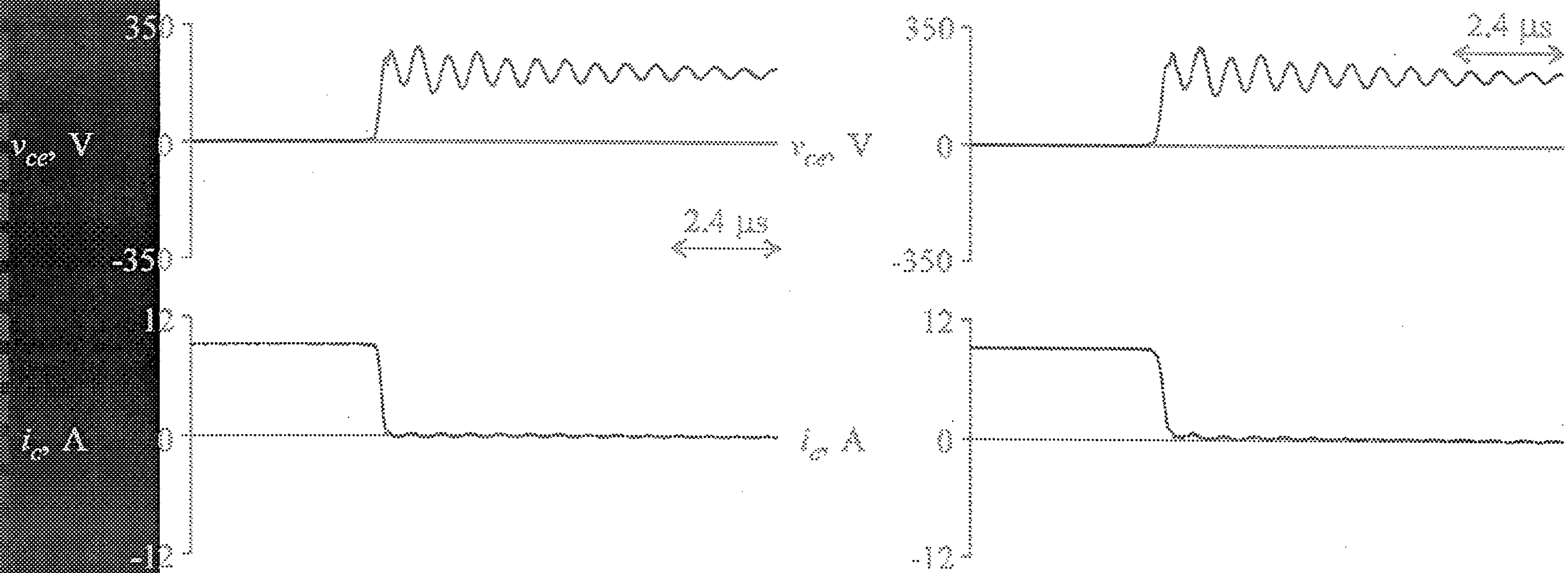


Predicted



Measured

Turn Off Waveforms



Predicted

Measured

Work For Next Time

- Behavioral Diode Model
- Complete Dual Mode Simulation of SM-PMSM Drive
- Extend Analytical Approach to Induction Motor

Focus Groups

Computational performance

Model standards

Visualization tools

Evolution of simulation technology

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Focus Group Objectives

1. Obtain at least one concrete result that can be reported back to this body after lunch

2. Establish framework for addressing pertinent questions in a public forum
   e.g. Come together as a publication task force?

Computational Performance

Oleg Wasynczuk

- What levels of performance should the VTB target?
- What are reasonable expectations of the problem size, the degree of detail that will be sought, and the time that an engineer is willing to wait for an answer?
- Benchmarks based on experience with existing tools are useful.

Model Standards

Charles Brice

- What standards should exist or are necessary to ensure that models are interoperative?
- How many restrictions can be imposed without becoming too burdensome?
- Are such standards compatible with other existing standards?
- How many lines will be needed in the "Backplane" definition to use a typical model?

Visualization Tools

Sakis Meliopoulos

- What specific visualization options should be provided?
- What should be the default data presentation format?
- Should there be a standard visual display (e.g. line graph), regardless of the data being plotted, or should the type of display be keyed to the type of data? Should this key be defined at the same time as the backplane variables are defined?

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Evolution of Simulation Technology

George Cokkinides

- Where is the commercial simulation market headed?
- How will VTB compare with commercial tools (e.g. ACSL/spice)?
- What effect, if any, will DoD HLA have on engineering tools?
- What provisions should VTB make w/r to DoD HLA?

Computational Performance
Oleg Wasynczuk

Model Standards
Charles Brice

Evolution of Simulation Technology
George Cokkinides

Visualization Tools
Sakis Meliopoulos

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Focus Group Reports

VTB Annual Review

June 1997

Computational Performance

- Members - Oleg Wasynczuk, Peter Lamm, Ralph Young, Elias Glytsis
- Agree to disagree on formal framework for establishing evaluation criteria
- Computational Performance secondary to modeling detail
- Multiple "computing engines" suggested for different issues to be addressed
  - (1) EMI/EMC component-level
  - (2) Circuit protection, communication performance
  - (3) Global Ship control

  - Does not appear feasible/justifiable to have one engine for all issues

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Evolution of Simulation Technology

- Members **George Cokkinides**, Steve Pekarek, Thurman R. Harper, Myles Hurwitz, Gene Dadin, Ronda Henning, Chieng Lee, Eugene Solodovnik, Tichenor
- **HLA**
  - Keep track of HLA evolution
  - www.dmso.mil/advisor
- **Mixed Model Support**
  - ACSL/SPICE
  - SABER
  - MATHCAD/SIMULINK
- **Design Orientation**
  - parametric analysis
  - optimization
  - cost analysis
- **Tasks**
  - Monitor COTS trends
  - Monitor DOD Standards
  - Intellectual Property Issues
- **Recommended Reading:**
  - "WHAT WILL BE," M. DERTOUZOS (Harper-Collins)
  - middleware...?

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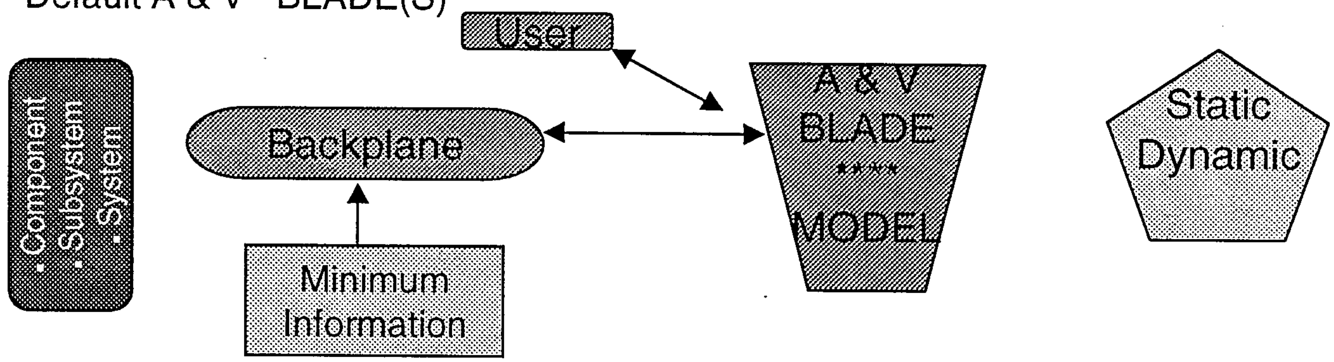
Visualization Tools

- Members:- **Sakis Meliopoulos,** Robert Pettus, Song Li, Karim Wassef, Chris King, Milad Badawi, Mike Sechrest
- Tools
  - Open GL
  - JAVA 3D
  - Programmer Imagination
- Desirable Results
  - Structure by which application users can specify animation & visualization needs
  - A. Equivalent of animation & visualization BLADES
  - B. Default A & V BLADE(S)



- Recommendation
  - Create a Visualization Working Group from the VTB/PEBB community to address A & V issues.

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Model Standards

- Members
  - **Charles Brice**, Louise Miles, Levent Gokdere, Anatoly Koleshikov, Joe Borraccini, Jeff Mayer, Vadim Popov
- Fundamental Question: What standards should be established to ensure that models are interoperative?
- Is there a fundamental reason why circuit-based models can not be coupled to differential equation based models?
  - It is an issue of methodology. Both types are converted to some kind of difference equation, so it should be possible to connect them.

Model Standards (cont)

- Should there be restrictions on the topology of the circuit or on the topology of the mathematical equations near the connection terminals?
  - There must be restrictions of various sorts. The next slide indicates some of the issues that we discussed
  - Both circuits and equations will need restrictions. We will form a group to focus on this issue over the next few months.
  - Possible chaotic behavior of some systems may cause problems at interconnections.
  - Some problems may not have easy solutions
  - Backplane definition already includes reasonable physical variables. Should these include polyphase types?
  - Should we impose a general restriction that all variables at terminals represent measurable quantities?
  - Should all models have a topological basis?
  - We should not overlook symbolic solutions of differential equations.
  - System control may impose or relax some restrictions. For example a control system may improve the response of an otherwise chaotic system.

Model Standards (cont)

- How many restrictions can be imposed without becoming too burdensome?
  - This is difficult to answer now. We may gain knowledge by getting user input later.
- Are such standards compatible with other existing standards (ACSL, Spice, Saber)?
  - We need to think about general standards for VTB models. We do not have specific answers to this question.

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Repetitive waveforms

- Members: David Taylor, Scott Sudhoff
- Problem statement: Are there efficient ways of computing waveform details, other than slow-stepping through transitions, when waveforms are repetitive in nature

- Will collaborate on techniques for efficient/fast computing

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Plans for next year

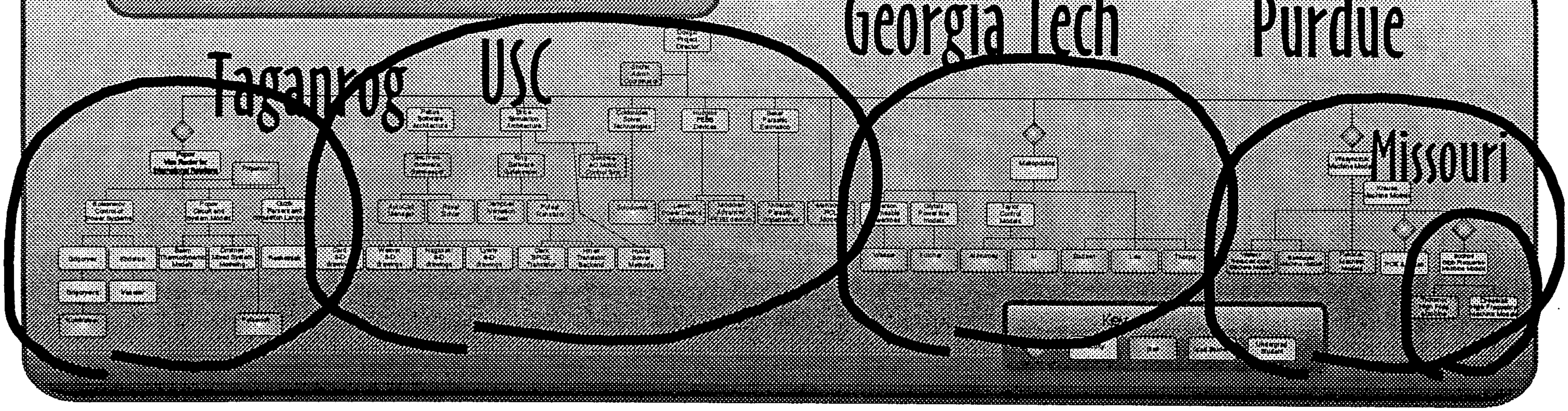
VTB Annual Review

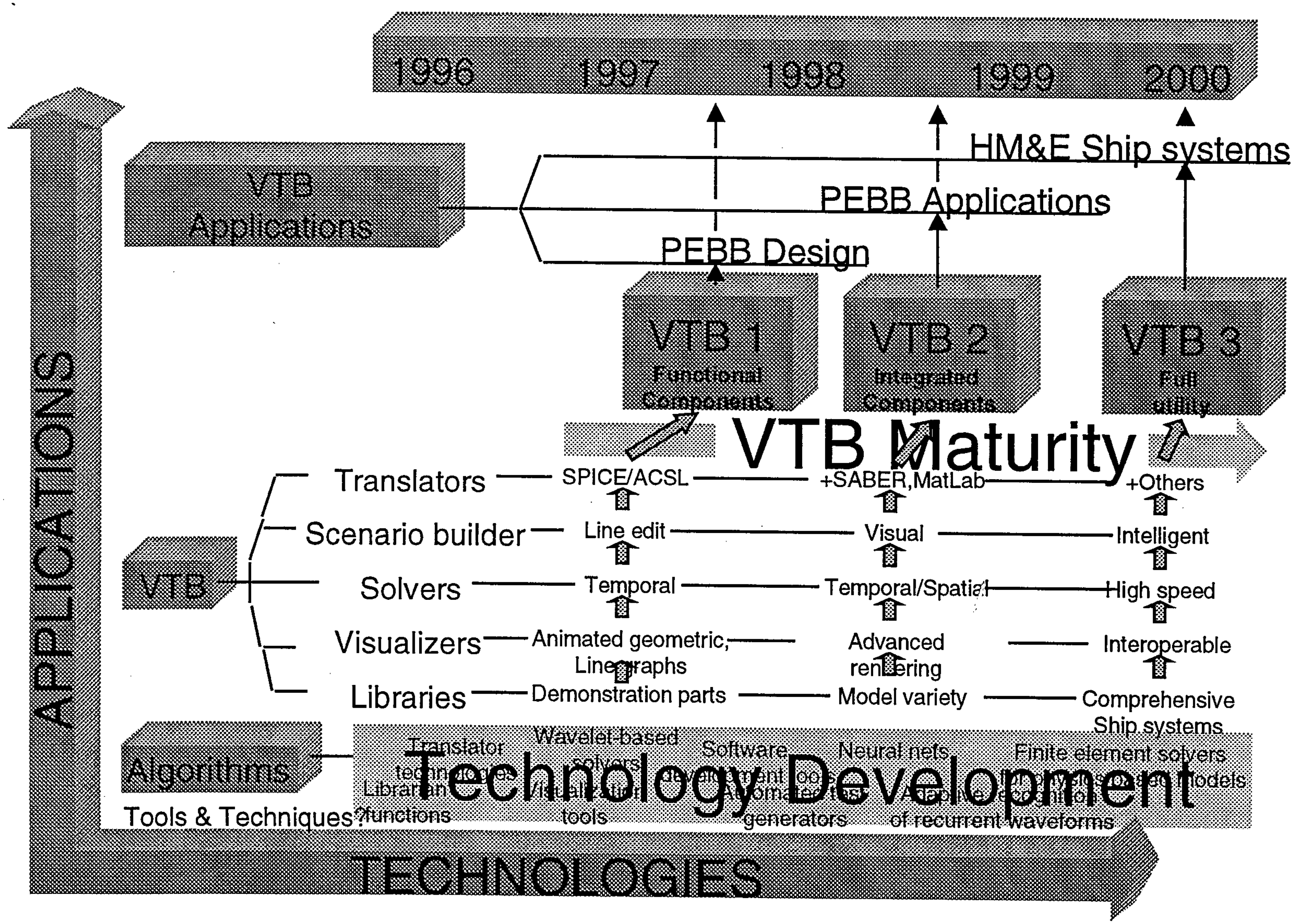
June 1997

Program Objectives

- Integrate the team's efforts
  - Develop closer relationships between team members
  - Develop plans for migration of new technologies into the VTB software

THE VTB ORGANIZATION




1996
1997
1998
1999
2000
HM&E Ship systems
PEBB Applications
PEBB Design
VTB Applications
VTB 1
Functional Components
VTB 2
Integrated Components
VTB 3
Full utility
VTB Maturity
VTB
Translators
SPICE/ACSL
+SABER,MatLab
+Others
Scenario builder
Line edit
Visual
Intelligent
Solvers
Temporal
Temporal/Spatial
High speed
Visualizers
Animated geometric, Linegraphs
Advanced rendering
Interoperable
Libraries
Demonstration parts
Model variety
Comprehensive Ship systems
Algorithms
Tools & Techniques?
Technology Development
Wavelet-based
Software
Neural nets
Finite element solvers
functions
tools
generators
of recurrent waveforms
APPLICATIONS
TECHNOLOGIES

- Finish SPICE translator
- Begin Saber translator
- Test modular model space concept
- Develop multithreaded solution methods
- Begin work on code generator for high performance
- Integrate user feedback into VTB features

- Fully integrate solver into main program
- Develop component library, including
  - building component database
  - developing distributed database manager

- Develop good models of PEBB, including controller
- Develop efficient/fast method of handling repetitive waveforms
- Develop models of advanced devices (e.g. SiC)
- Assist Harris in PEBB design/development