

Interactive Object-Oriented Simulation of Interconnected Power Systems Using SIMULINK

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Abstract—An object-oriented power system simulation environment is constructed using the SIMULINK dynamic system modeling software. The environment is well suited to educational purposes, because the user interface is interactive and intuitive with a graphical, object-oriented model representation. For small system studies, a model is constructed in block diagram form with one block for each system component. For large scale simulations, the dynamics of portions of the network can be combined into collective blocks, with parameters managed as data arrays accessed indirectly using string mnemonics. The advanced numerical capabilities built into SIMULINK provide an excellent simulation engine for the nonlinear models. Off-line analysis is available through the extensive capabilities of the MATLAB environment.

Index Terms—Block diagram form, dynamic system modeling software, large scale simulation, MATLAB, nonlinear models, object-oriented modeling, off-line analysis, SIMULINK.

I. INTRODUCTION

THE USE of computer simulation tools is essential in power system studies. Software tools are widely used by utilities for transient event simulations, power flow studies, stability analysis, and operational planning. Most of the commercially available software packages are, however, designed to work with large power system models. The use of such tools is often cumbersome and not well suited to the small power system studies used for educational purposes. This paper presents a new power system simulation tool that uses an interactive, object oriented interface in the *SIMULINK* [1] modeling environment.

SIMULINK is a window oriented dynamics modeling package built on top of the MATLAB numerical workspace. The MATLAB environment has also been used to develop analysis tools for small scale power system studies [2]. However, the SIMULINK environment has the advantage that models are entered as block diagrams with an intuitive graphical interface. Model parameters are entered in menus and can be changed interactively during a simulation. Simulation results can be viewed during the simulation and then exported to the MATLAB workspace for subsequent off-line analysis. While the simulation is not *real time*, the immediate feedback of the interactive simulation environment provides the user with far

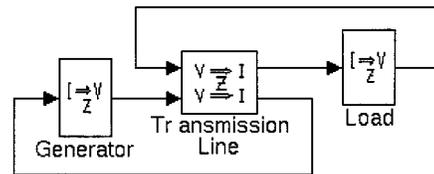


Fig. 1. A SIMULINK-based schematic of a two-bus system.

more intuition about simple system dynamics than batch-mode simulations.

The SIMULINK modeling environment consists of a library of basic building blocks, which can be combined to form a dynamic model. Groups of blocks can be combined into single customized blocks to form highly specialized modeling constructs. The modeling environment described in this paper consists of a library of customized blocks for power system components that are easily connected to form a power system model. Models are constructed in block-diagram form, with a separate block, or object, used for each generator, load, and transmission line in the simulated system. The connections between blocks in the model reflect a phasor representation of voltage and current, and the connections are structured so that Kirchhoff's voltage and current laws are satisfied. The simulation models only one phase of a three-phase system, so the simulated dynamics reflect the system dynamics only under balanced conditions. The software can be developed to simulate unbalanced conditions based on the modeling method presented in [3].

Fig. 1 shows a simple two-bus power network modeled in SIMULINK. Apparent in the model are the basic elements of the system: a generator, transmission line, and load. The generator and load blocks are single input, single output blocks with a voltage output given a current input. The transmission line block has two inputs and two outputs, which connect the generator to the load by outputting current given the voltage input. With this connection methodology, the structure of the network is apparent in the block diagram representation of the system model. For small power systems, the block diagram can be read like a network diagram, with each connection consisting of a voltage-current pair.

This intuitive interface makes it very simple to create and modify simulation models for small power networks. As the typical learning time for the SIMULINK graphical interface is on the order of a day, the simulation tools are well suited to educational use. The numerical simulations shown in this paper are typical results of homework exercises and course term-projects done by a first-year graduate student at MIT.

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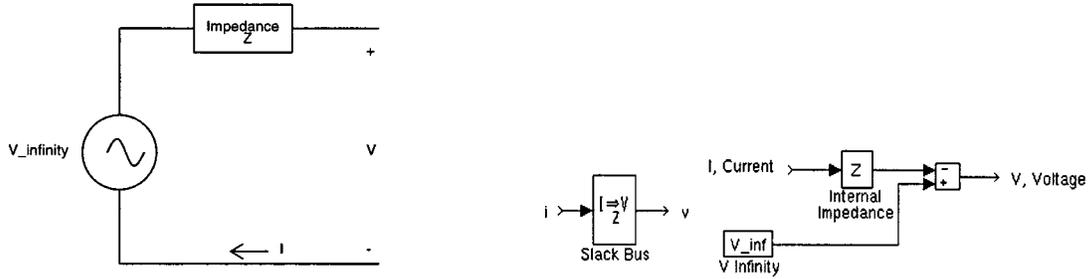


Fig. 2. Model for slack bus and its SIMULINK block.

II. VECTOR NOTATION FOR CIRCUIT EQUATIONS

In order to build models for the generator, load, and transmission line, it is first necessary to convert the basic circuit equations from phasor notation to a two-dimensional vector notation, since SIMULINK does not accept complex-valued states. Throughout the paper, we will use the following notation to represent vectors and matrices:

$$\mathbf{v} = \begin{bmatrix} V_r \\ V_i \end{bmatrix} \quad (1)$$

$$\mathbf{i} = \begin{bmatrix} I_r \\ I_i \end{bmatrix} \quad (2)$$

$$\mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (3)$$

$$\mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \quad (4)$$

where the r and i subscripts denote, respectively, the real and imaginary parts of phasors. Using this notation, the basic circuit equations become, for an impedance

$$\mathbf{v} = \mathbf{Z}\mathbf{i} \quad (5)$$

$$\mathbf{Z} = \mathbf{R}\mathbf{I} + \mathbf{X}\mathbf{J}. \quad (6)$$

For an admittance

$$\mathbf{i} = \mathbf{Y}\mathbf{v} \quad (7)$$

$$\mathbf{Y} = \mathbf{G}\mathbf{I} + \mathbf{B}\mathbf{J}. \quad (8)$$

For real and reactive power

$$P = \mathbf{v}^T \mathbf{i} \quad (9)$$

$$Q = \mathbf{v}^T \mathbf{J}\mathbf{i}. \quad (10)$$

Now that we have the fundamental circuit equations in vector form, we are ready to introduce SIMULINK models of system components.

III. SIMULINK-BASED REPRESENTATION OF STANDARD COMPONENTS IN POWER SYSTEMS

Elementary power systems involve generators, transmission lines and loads. To illustrate use of SIMULINK for their representation with various degrees of model accuracy, we describe first a menu of blocks representing several generator models. Similarly SIMULINK blocks representing both constant impedance and constant power (PQ) load are described.

Finally, two different SIMULINK blocks representing transmission line models are given.

A. Model of a Generator

The simplest generator model is a slack bus, shown in Fig. 2. It consists of an independent voltage source and an internal impedance \hat{Z} . This impedance can also be taken to be zero. The block is designed by viewing a slack bus as shown in Fig. 2.

The matrix equation for the slack bus is

$$\mathbf{v} = \mathbf{v}_\infty - \mathbf{Z}\mathbf{i}. \quad (11)$$

The “swing” type generator model [4], [5] is the simplest model capturing only the real power dynamics and assuming constant voltage magnitude. However, the angle of the voltage source is a state variable, θ , which changes according to the following inertial equation:

$$2H\ddot{\theta} + B\dot{\theta} = P_{\text{mech}} - P_{\text{elect}}$$

where H is the inertial time constant and B is the damping factor. The complete SIMULINK block diagram for the swing-type generator model is given in Fig. 3.

The most complex model of generator dynamics illustrated here is based on the following fourth-order two-axis model:

$$\dot{\delta} = \omega - \omega_o \quad (12)$$

$$\dot{\omega} = -\frac{\omega_o}{2H} \left[D \frac{\omega}{\omega_o} + E'_d i_d + E'_q i_q - P_{\text{mech}} \right] \quad (13)$$

$$\dot{E}'_q = \frac{1}{T'_{d0}} [-E'_q - (x_d - x'_d) i_d + E_{fd}] \quad (14)$$

$$\dot{E}'_d = \frac{1}{T'_{q0}} [-E'_d + (x_q - x'_q) i_q]. \quad (15)$$

The generator terminal voltage is given by

$$E_d = E'_d - r_a i_d + x'_q i_q \quad (16)$$

$$E_q = E'_q - r_a i_q - x'_d i_d. \quad (17)$$

Note that the generator voltage and current are Park transformed and therefore in the machine frame of reference. These quantities are related to the network voltage \mathbf{v}_n and network current \mathbf{i}_n by

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin \delta & -\cos \delta \\ \cos \delta & \sin \delta \end{bmatrix} \mathbf{i}_n \quad (18)$$

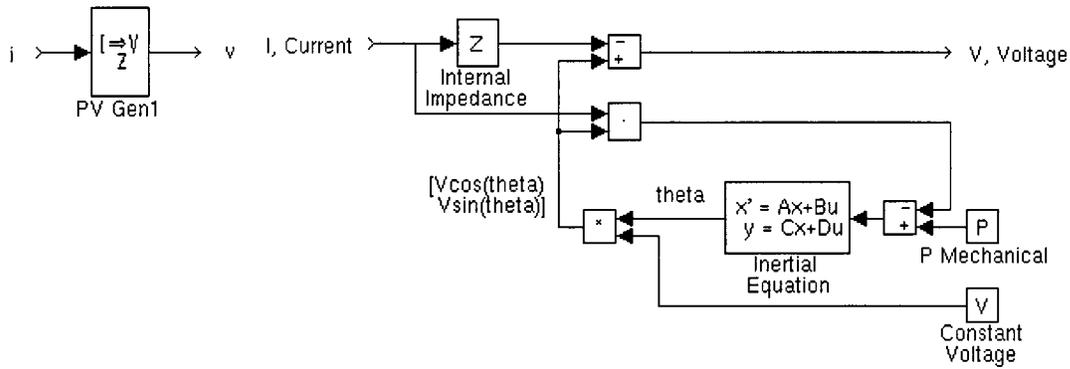


Fig. 3. Model for the swing-type generator.

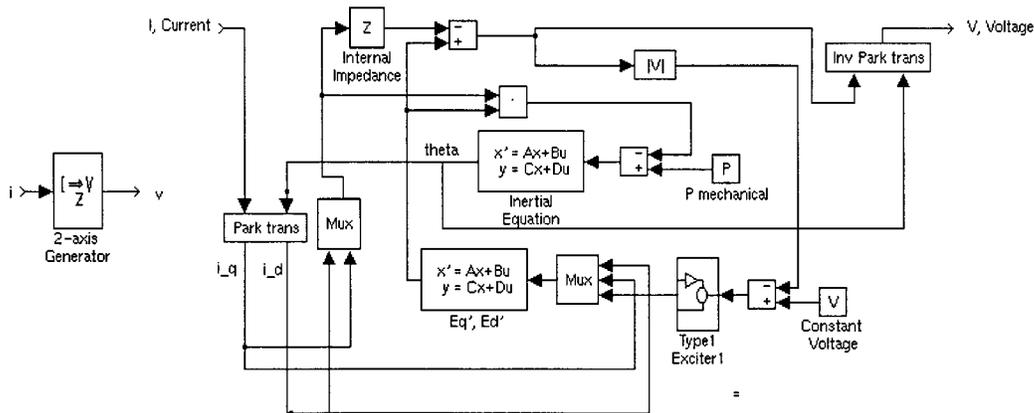


Fig. 4. Complete SIMULINK block for the two-axis generator model.

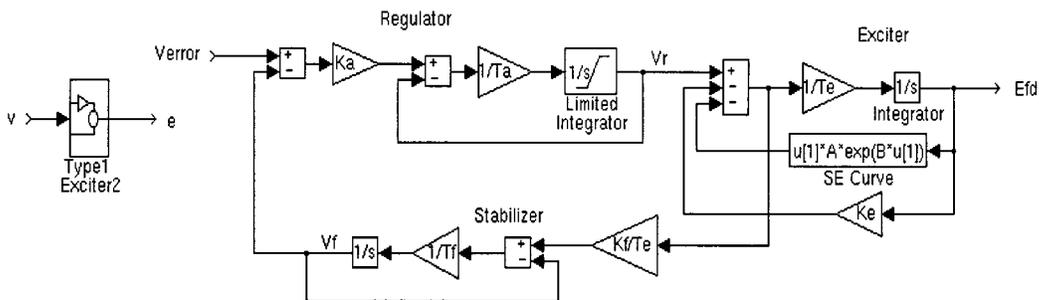


Fig. 5. State-space subblock representing dynamics of the IEEE Type 1 exciter in the swing-type generator.

$$\mathbf{v}_n = \begin{bmatrix} \sin \delta & \cos \delta \\ -\cos \delta & \sin \delta \end{bmatrix} \begin{bmatrix} E_d \\ E_q \end{bmatrix}. \quad (19)$$

The field voltage E_{fd} is controlled by a third-order Type I IEEE exciter, and the mechanical power P_{mech} is assumed to be constant. Fig. 4 shows the SIMULINK representation of the two-axis generator model, while the state-space subblock for the IEEE Type 1 exciter is shown in Fig. 5.

These block representations are typical of generator model complexity used for academic studies. However, once the basic SIMULINK library is available, new blocks of various complexity could be added.

1) *Generator Model with Torsional Shaft Dynamics:* One embellishment of the generator model given above is to include the dynamics of the shaft connecting the rotor to the turbines.

Such a model has been developed in SIMULINK. The dynamic equations for this model are given in [6], [7].

2) *Generator Model with Governor:* Another addition to the basic generator model is to include the dynamics of the governor unit. In this model, P_{mech} is no longer constant but instead is given by

$$P_{mech} = P_m + P_{ta} + e_{TA} \quad (20)$$

where P_m is the constant mechanical power corresponding to the base load at 60 Hz, and P_{ta} and a are state variables of the turbine and the governor, respectively, and have the following linear¹ dynamics [5], [8]

$$\dot{P}_{ta} = \frac{1}{T_u} [-P_{ta} + K_t a] \quad (21)$$

¹A nonlinear version is equally possible.

$$\dot{a} = \frac{1}{T_g} \left[-ra + \frac{\omega^{ref} - \omega}{\omega_o} \right] \quad (22)$$

ω^{ref} is the setpoint for the governor. This quantity is typically controlled at the secondary level in response to the area-wide frequency deviations from the nominal [5], [8].

B. Model of a Load

The next step is to develop a model of a load. Two static load models are used; constant impedance and constant power. A diagram applicable for both load models is shown in Fig. 6. In the constant impedance model, \mathbf{Z} is obviously treated as a fixed quantity; therefore, the constant impedance load is represented by the equation

$$\mathbf{v} = -\mathbf{Z}\mathbf{i}. \quad (23)$$

To simulate the load behavior of a constant power load, the admittance $G + jB$ of the load becomes a state variable with the following dynamics:

$$\dot{G} = \frac{1}{\tau} [P^{ref} - P] \quad (24)$$

$$\dot{B} = \frac{1}{\tau} [Q^{ref} - Q] \quad (25)$$

τ is a time constant (typically 0.1 s), while P^{ref} (Q^{ref}) are the desired constant real (reactive) power for the load. P and Q are the instantaneous real and reactive power at the load. In these equations, a positive P implies power supplied to the network; therefore, for a load, P^{ref} will be negative.

C. Model of a Transmission Line

The transmission lines are usually modeled as π -sections consisting of resistors, inductors, and capacitors that have the following voltage–current relations [5], [9], [10]:

$$\hat{V}_R = \hat{Z}_R \hat{I}_R \quad (26)$$

$$\hat{V}_L = L \frac{d\hat{I}_L}{dt} + \hat{Z}_L \hat{I}_L \quad (27)$$

$$\hat{I}_C = C \frac{d\hat{V}_C}{dt} + \hat{Y}_C \hat{V}_C. \quad (28)$$

Typically, the time constants of transmission lines are short, so the time derivatives can be ignored for time intervals of interest. The resulting constituent relationships between the voltage and current phasors are algebraic, not dynamic. However, in SIMULINK, such algebraic constraints for transmission lines require that an iterative numerical solution be found at each simulation time step. This algebraic iteration increases processing time and can cause numerical instability. The numerical problems caused by the algebraic relationships can be avoided by including the time derivatives in the phasor equations, so the constituent relationships remain dynamic. Although the time constants of the dynamic relationships are extremely fast, the variable-time-step numerical techniques built into SIMULINK provide very good simulation speed once initial transients decay.

The basic model for the transmission line is shown in Fig. 7. It consists simply of a resistor and an inductor in series. Shunt

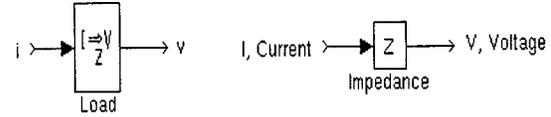


Fig. 6. Model of the load.

capacitance can also be included, if needed. The state equations for the line are

$$\dot{I}_{r1} = \frac{1}{L} [V_{r1} - V_{r2} - RI_{r1} + XI_{i1}] \quad (29)$$

$$\dot{I}_{i1} = \frac{1}{L} [V_{i1} - V_{i2} - XI_{r1} - RI_{i1}]. \quad (30)$$

Note that $\dot{\mathbf{i}}_2 = -\dot{\mathbf{i}}_1$.

A dynamic model is also included for a transmission line with series capacitive compensation. This model has four states and evolves according to [6], [7]

$$\dot{I}_{r3} = \frac{\omega_o}{X} [V_{r1} - V_{r3} - RI_{r3} + XI_{i3}] \quad (31)$$

$$\dot{I}_{i3} = \frac{\omega_o}{X} [V_{i1} - V_{i3} - RI_{i3} - XI_{r3}] \quad (32)$$

$$\dot{V}_{r3} = \frac{1}{C} I_{r3} + \omega_o(V_{i3} - V_{i2}) \quad (33)$$

$$\dot{V}_{i3} = \frac{1}{C} I_{i3} - \omega_o(V_{r3} - V_{r2}). \quad (34)$$

The derivation of this model is also based on time-varying phasors; the details can be found in [6] and [7].

To demonstrate relevance of representing transmission lines using recently developed time-varying phasor algebra, the difference between the two responses obtained by means of two models, i.e., an algebraic model and the model based on time-varying phasor algebra, is shown in Fig. 8 for the system shown in Fig. 9. The more theoretically sound dynamic model allows for detecting unstable subsynchronous dynamics, while simulations using an algebraic model fail to detect this type of instability. This is just one example of using SIMULINK blocks of various accuracy for simulating dynamic phenomena of interest.

D. Interconnected System

The SIMULINK representations of individual devices described above fit very nicely when combined to form a power system model. In the transmission line model, the current is a state variable, while the voltages at each end are inputs which control the current dynamics. In the generator and load models, the current is an input while the voltage is an output of either an algebraic or a dynamic system. Note that current in the models is always defined as flowing into transmission lines and out of generators and loads. At buses where two or more transmission lines meet, the current flowing from the generator or load is the sum of the currents in the individual lines. The combination of the component models into a model for the interconnected system forms a stiff dynamic system that can be simulated using the “Gear” algorithm in SIMULINK.

A SIMULINK setup of an interconnected system is illustrated on the three bus system given in Fig. 10. Its SIMULINK representation is also shown in Fig. 10.

This block diagram reflects the basic process of meeting network constraints using SIMULINK. This is done by defining

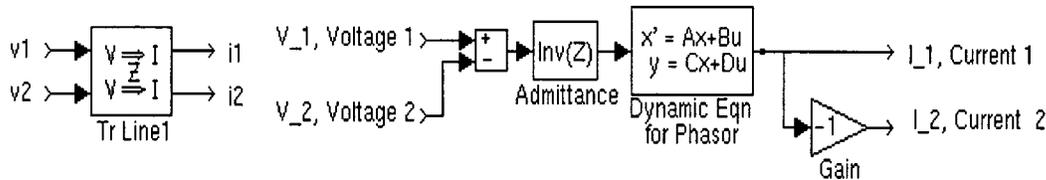


Fig. 7. Model of a transmission line

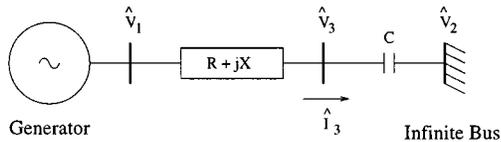


Fig. 8. System used to demonstrate the effect of the transmission line model chosen.

KCL imposed constraints at the cutsets where any two “objects” (typically an equipment component and a transmission line) connect. Similarly, the KVL imposed constraints are defined around the loops involving three devices only, two equipment components and one transmission line at the time. Because of this the KVL constraint is implicitly met by defining the constituent relationship of a transmission line. KCL, on the other hand, requires that the sum of currents going into all transmission lines directly connected to any bus i equal the injected current by the equipment at bus i .

Typical responses of the system at different points at the system are shown in Fig. 11. SIMULINK offers simple plotting methods.

Fig. 12 shows system response for two different load models, i.e., constant impedance and constant power.

IV. USE OF SIMULINK FOR FREQUENCY CONTROL

Generally, load flow computations assume the existence of a slack bus on the system. However, in practice, no such device exists on the interconnected system. Consequently, the system frequency will deviate from 60 Hz due to differences between the nominal generator power output and the load power drawn from the system [5]. A SIMULINK model of the system is capable of analyzing this phenomenon without using a slack bus. This model can be used to calculate the Jacobian of the load flow equations.

To illustrate this process, a six-bus Ward–Hale configuration will be considered. The network will have two generators, three constant power loads, and one constant impedance load. The two-axis generator model with governor dynamics will be used in SIMULINK to represent each generator. If the governor setpoints for both generators are set to 60 Hz, then for a given set of generator and load power specifications, the resulting system frequency will settle to some value, but not necessarily 60 Hz (Figs. 13 and 14). This result is due to a structural singularity of the system [5], [11]. However, by adjusting the governor setpoints, it is possible to bring the system frequency back to 60

Hz. To do so, the governor setpoint for each generator is chosen as

$$\omega^{ref} = r\omega_o \left[\frac{P_{elec} + D - P_m}{K_t + e_T} \right] + \omega_o \quad (35)$$

where P_{elec} is the electric power output of the generator in the original system which has all governor setpoints at 60 Hz. The choice of governor setpoints using (35) causes the dynamics of each generator given by (13), (21), and (22) to reach an equilibrium at 60 Hz without changing the electrical power output of the generators.

It is possible to determine a governor setpoint value such that the system will settle at 60 Hz. After choosing the appropriate setpoint values for the generators, the system response is shown in Figs. 15 and 16. In a more general case, where loads are constantly changing, it is possible to develop a secondary level control methodology to continuously adjust the governor setpoints so that the system frequency is maintained at 60 Hz [5].

As mentioned earlier, the SIMULINK model of the system may be used to find the Jacobian of the power flow equations, even though no slack bus is assumed to be present. This process has two main steps. The first step is to determine the equilibrium “point” of the system. Actually, since the system frequency in general does not settle to 60 Hz, the rotor angles will be linear functions of time when equilibrium is reached; however, the differences between the angle of different machines will remain constant. Furthermore, the states ω , P_{ta} , and a at each generator will all remain constant when equilibrium is reached. The equilibrium conditions may be found by simply simulating the system until the states settle to their equilibrium values. Once these values are known, the voltage magnitude and angle at each bus can be calculated.

The second step is to find the partial derivatives of the load flow equations and evaluate these derivatives using the bus voltages calculated in the first step. There are many ways to do this; one method is to build a purely algebraic model of the power flow equations in SIMULINK. This algebraic model simply calculates P and Q at each bus given the voltage magnitude and angle at each bus. The MATLAB function “linmod” is then applied to the algebraic SIMULINK model to calculate the Jacobian.

V. DEALING WITH LARGE SYSTEMS

For simulating larger scale systems, the need to reduce the computational effort and manage the system complexity requires a somewhat different approach. It is of interest to minimize the number of dynamic states that are carried through the simulation, and the management of machine and network data become an issue both in building and verifying the model.

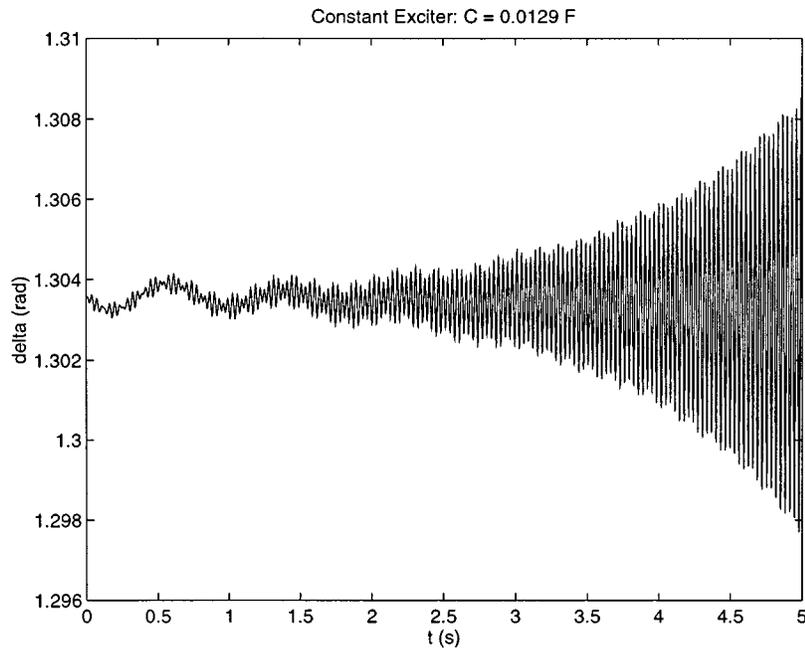


Fig. 9. Response as a function of line model chosen.

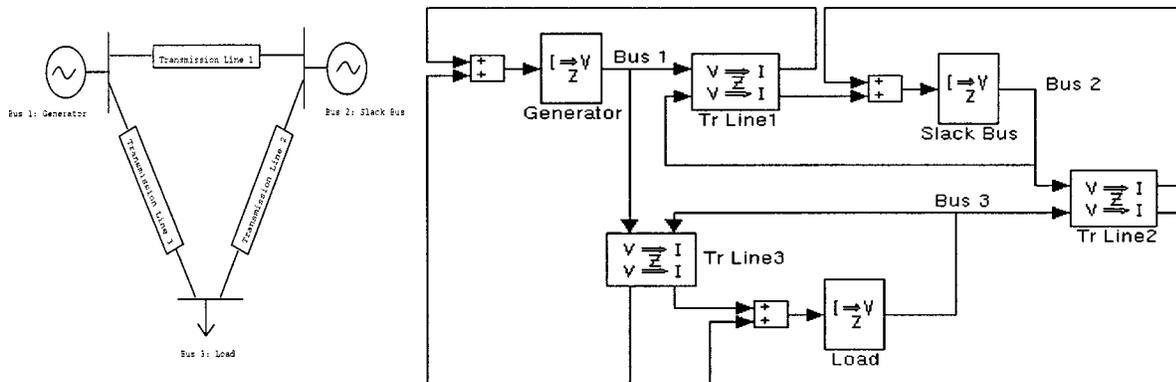


Fig. 10. The three bus system and its SIMULINK block diagram.

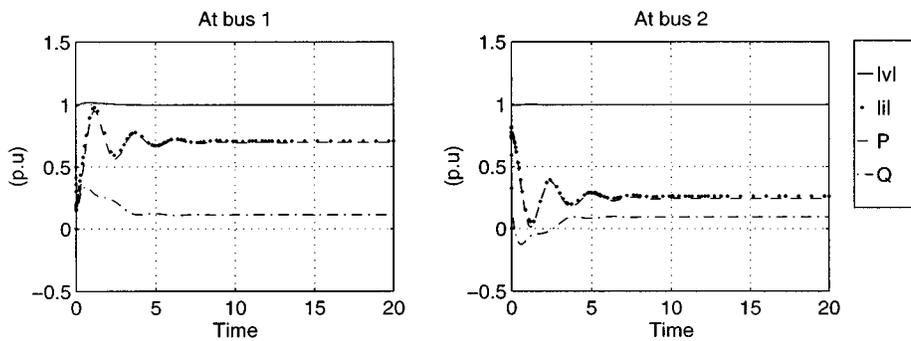


Fig. 11. Time domain response of variables at bus 1 and at bus 2.

Complexity is managed by storing machine data in matrices that are serviced by a number of special-purpose routines. Each subsystem block is indexed by two identifiers, one of which indicates its type (round-rotor generator, static VAR compensator, etc.) and one which locates its parameters in the data array.

This approach serves the dual purpose of making access to the data convenient, while isolating the raw data structure from both the user and the simulation model. New model types are accommodated by assigning an unused system type identifier to the block, defining its particular raw data structure and giving it a

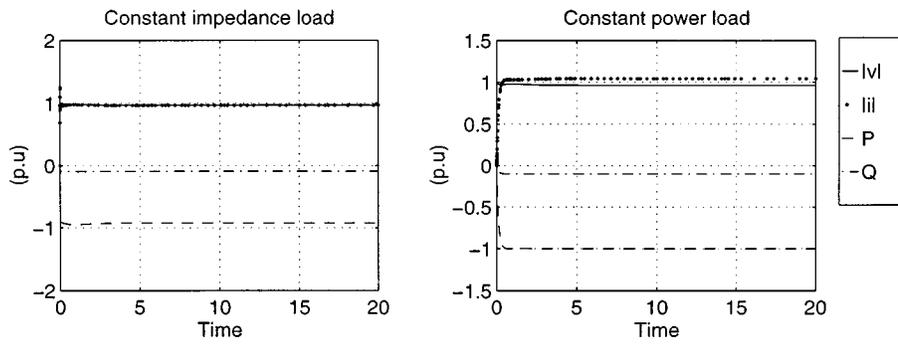


Fig. 12. Comparison of system response for two different load types.

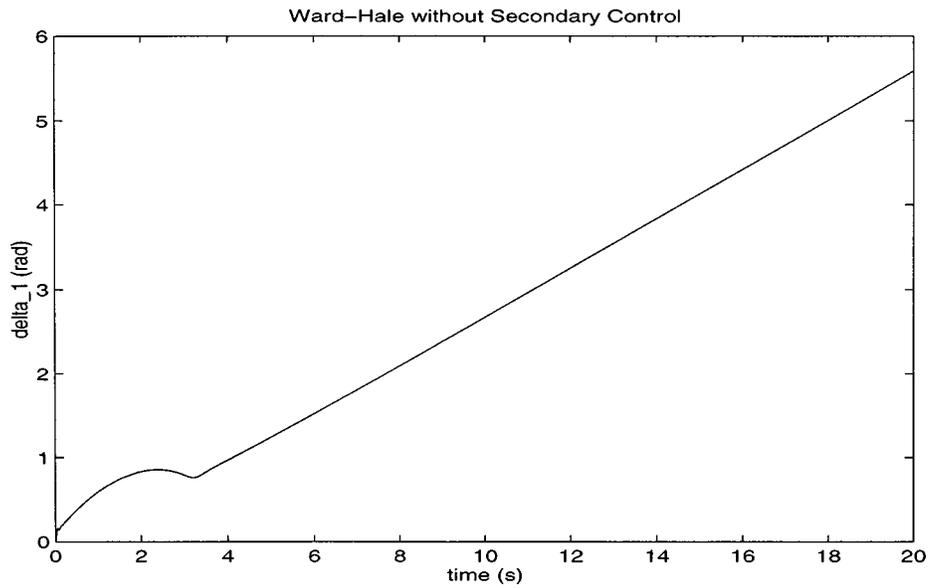


Fig. 13. Rotor angle of generator 1, without secondary adjustments.

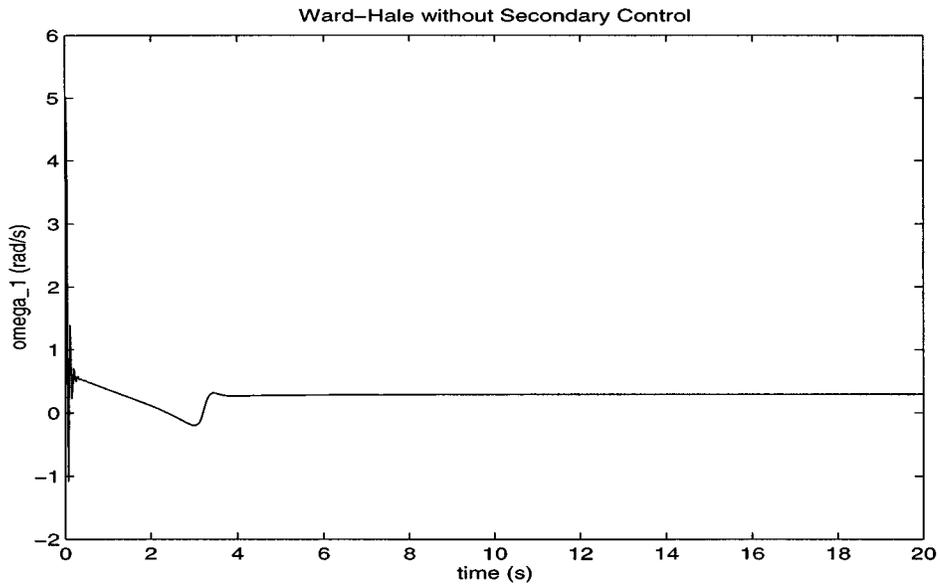


Fig. 14. Rotor frequency at generator 1, without secondary adjustments.

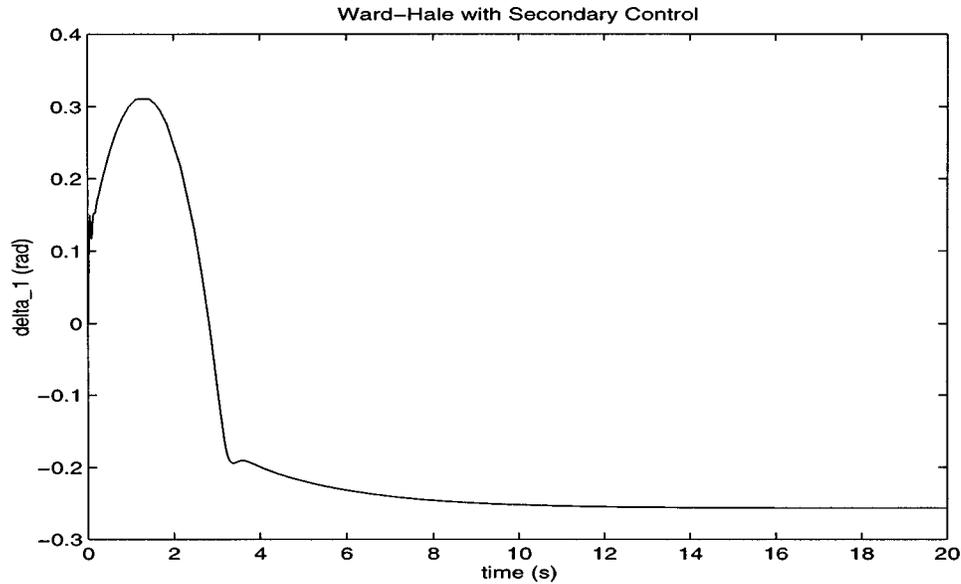


Fig. 15. Rotor angle of generator 1, with secondary adjustments.

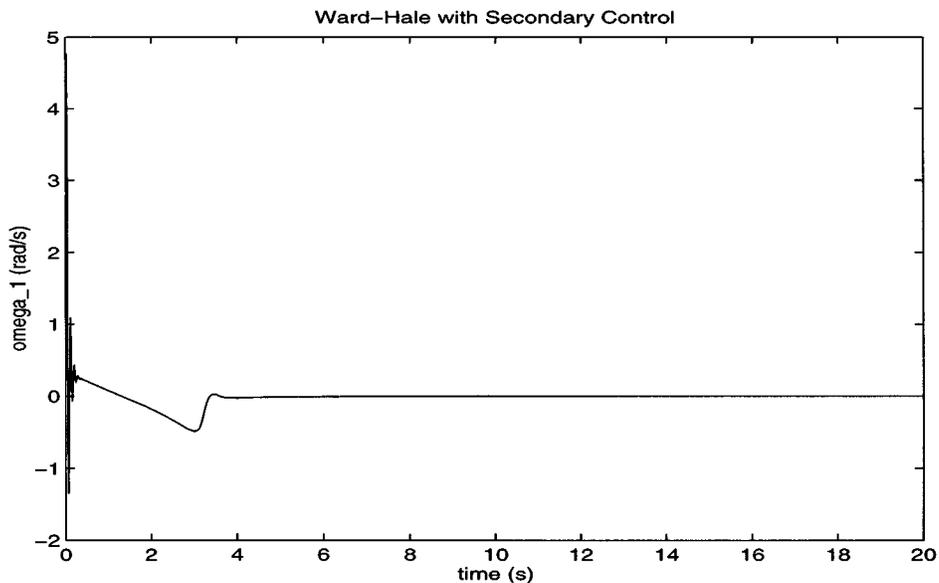


Fig. 16. Rotor frequency at generator 1, with secondary adjustments.

slot in the data array. Once this is done, the model can be used and its parameters set and retrieved at will without knowledge of the actual position or structure of the data record.

Routines are available that then initialize generic system blocks with the appropriate data, based on the machine identifier, which is the only quantity that must be entered by the user in the block mask.

In this way modularity is preserved to a great extent, however we do allow some sacrifice of subsystem data localization in order to facilitate the solution of the interconnection constraints. Because of the need to limit the number of dynamic variables in larger simulations, the transmission network is modeled in the more traditional manner, i.e., its dynamic behavior is considered to be much faster than that

of the generators, allowing its representation as a set of algebraic relations. In order to solve the network equations in one step rather than iteratively, the modularity of the system is compromised to the extent that the machine impedances are made available to the routine that calculates the network currents.

In particular, depending upon the level of detail of the generators, if transient or subtransient saliency is ignored and loads are modeled as constant impedances, it is possible to form the reduced admittance matrix and solve for the currents in a single matrix multiplication [5]. At present the simulation of a particular fault scenario is accomplished by calculating separate reduced admittance matrices for the prefault, faulted and postfault networks. These are then loaded at the appro-

appropriate time by a MATLAB routine that reads the system time and sequences the fault scenario.

As a final consideration, we note that it is important for the subsystem blocks to be initialized at the system equilibrium. Therefore routines are included in each subsystem block that calculate the equilibrium state for that block, based on the initial load-flow data. This also facilitates the recovery of linearized system matrices via the “linmod” function. The size of the larger models and the existence of multiple equilibria present obstacles to the successful determination of the system equilibrium via the MATLAB routine “trim,” but “trim” can be useful for calculating perturbed equilibria, using the initial state as a starting point. SIMULINK was shown to be a useful tool for simulating an aggregate model of the NPCC system by representing it as a system with 29 machines [12].

VI. CONCLUSION

In conclusion, a variety of simulations in this paper show SIMULINK-based time domain responses of an interconnected system with different controls present on the system. The flexibility of SIMULINK as a very useful tool for simulations of small power systems, intended to analyze specific phenomenon has been demonstrated in this paper.

For further information, the interested reader may contact Marija Ilic at ilic@mit.edu via e-mail.

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