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Controllable analog emulator for power system analysis

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ABSTRACT

This paper details the development of a controllable analog emulator for power system analysis. The emulator consists of reconfigurable analog hardware for power system emulation and a digital computer, along with associated software, for configuration, control, calibration and data acquisition. The analog hardware is fully controllable via the software interface. System parameters, initial conditions, integration, faults and contingencies can be created or altered via the software with no changes or manual intervention to the analog hardware. This advance overcomes one of the larger drawbacks of older analog computers, which was the need for manual configuration and calibration. The emulation methodology is presented in this paper as well as power system modeling, both theoretical and in analog hardware. The software interface and control is also presented. To validate the operation of the emulator two examples are shown from a prototype emulator. The first being a steady state power flow solution, the second computes the critical clearing time of a generator fault for transient stability.

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1. Introduction

With current technology the computation of large power systems is time intensive. There are numerous analog and digital computation methods currently utilized but they fail to meet the growing computational demands of power systems, particularly in system operations. For example, transient stability is a continued field of research [1–3] with much focus on faster, more efficient calculation techniques. The power grid is expanding which is increasing the necessity and complexity of contingency studies. Current techniques often rank [4] contingencies and only perform analysis on a subset of the scenarios assumed to be more dangerous. Faster calculation techniques will allow for more thorough contingency analyses. Economic analyses are also demanding a tremendous computational burden. Traditional digital methods are too slow to solve the aforementioned demands quickly at a reasonable cost. Cluster and parallel computing techniques have been proposed [5,6] but the cost increases exponentially with the size of the system and the increase in computation performance does not increase at this same rate. Conversely, existing analog simulators can easily simulate the power system in real time but consist of many analog components and require manual intervention to setup and configure the system for each calculation. A controllable real-time computation tool, or faster than real-time, is preferable.

Currently, digital simulation is the prevalent method for several reasons. These include (i) the emergence of personal computers (PC) has made this technology reliable and easy to operate, (ii) advances in very large scale integration (VLSI) technology have allowed the development of new parallel computers with performance comparable to that of supercomputers at a fraction of the cost, and (iii) the highly programmable nature of digital computers. In digital simulation the set of algebraic expressions, which describe power system behavior, are discretized and software algorithms (such as Newton–Raphson) utilize input parameters to calculate the steady-state solution. Presently for large-scale systems, studies are performed with several types of massively parallel computers [7–12]. The use of digital simulation analysis is seriously inhibited by lengthy computational times inherent to the iterative algorithms they employ and the large cost of hardware and operating costs of massively parallel digital computers. New technological developments have facilitated research in the further development of analog computational tools to achieve fast computations at lower cost.

A new approach has been proposed as to how analog technology may be utilized to perform analysis for large power systems [13,14]. In addition, recent work has developed general purpose analog processor for use in conjunction with a digital computers [15] to improve computational performance. The main advantage of analog computers is their shorter computational time. In this

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work, through the use of reconfigurable analog tools such as operational transconductance amplifiers (OTAs), accompanying circuit models for power system components such as generators [16], transmission lines [17], loads [18], and control and data acquisition circuitry and software, a fully controllable analog emulator for power system analysis has been developed. This emulator is suitable for transient and steady-state power system analysis. Example applications for this tool would be transient stability and contingency analysis.

The next section of this paper provides an overview of the DC emulation methodology utilized in this power system emulator. Following this, details of the power system emulator are presented. An overview is then provided on the power system models in the DC emulation environment. In addition, the associated analog hardware realizations of these models are shown. Next, a summary of the data acquisition, control and calibration of the hardware is presented along with the software interface to the emulator. This is followed by the presentation of a couple examples, discussion and conclusion.

2. DC emulation

The emulator presented here utilizes a DC emulation method for power system analysis. This emulation method has been proposed in [13] and is reviewed here for an understanding of the emulator presented in this paper. This approach utilizes multiple DC resistive networks to emulate an AC power system network in rectangular coordinates with DC voltages and currents. With fixed resistor values this emulation method assumes a constant system frequency, although with the hardware realization of these networks parameters can be varied based on frequency, temperature, or other factors. The DC emulation is based on the following equation solved in rectangular coordinates:

$$\begin{aligned}\mathbf{I} = \mathbf{Y}\cdot\mathbf{V} &= I_{\mathrm{Re}} + jI_{\mathrm{Im}}\\ &= (Y_{\mathrm{Re}}V_{\mathrm{Re}} - Y_{\mathrm{Im}}V_{\mathrm{Im}})\{\text{real current}\} + j(Y_{\mathrm{Im}}V_{\mathrm{Re}} + Y_{\mathrm{Im}}V_{\mathrm{Re}})\\ &\quad\times\{\text{imaginary current}\}\end{aligned} \tag{1}$$

where the subscripts "Re" and "Im" refer to real and imaginary components respectively. A diagram of the emulation networks highlighting the voltages applied to each network is shown in Fig. 1.

Each of the four current components seen in (1) is represented in emulation by a DC voltage dropped across a resistive element. This results in four DC resistive networks. Power injections into the resistive network are modeled as dependant voltage sources.

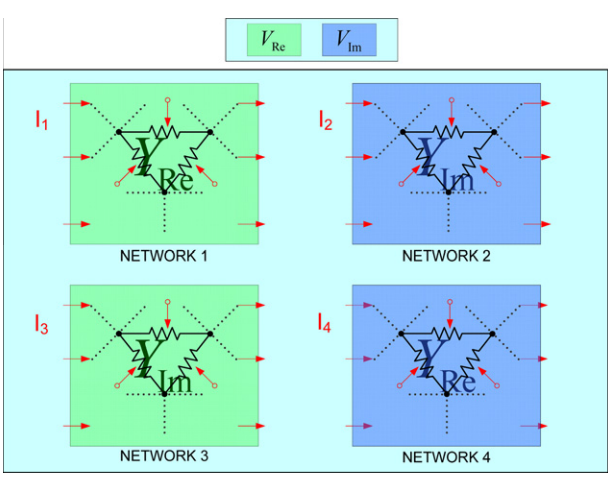

Fig. 1. DC emulation networks.

3. Power system emulator

The power system emulator is shown in a block diagram form in Fig. 2. The emulator consists of a digital computer with custom software designed for data acquisition and control of the analog emulator, data acquisition and control circuitry and the analog emulation hardware. The next subsections provide details of each component of the emulator.

3.1. Power system model

The power system model utilized in this emulator is broken up into three main components: generators, transmission lines, and loads. There is ongoing research developing other components, such as transformers, but the emulator presented here consists of these three elements. The interconnections of these three elements result in the power system model for emulation. The generators and loads are represented as dependent DC voltage sources and the transmission lines as resistive networks whose parameters are relative to line parameters. The generators and loads excite the networks with real and imaginary DC voltage components and the states (voltages and currents) of the resistive networks provide the AC power flows through the network. These components were modeled mathematically within the DC emulation environment and then controllable analog circuits were constructed based on these models.

3.2. Transmission lines

Transmission lines constitute the power system network in the emulator. Lumped equivalent models are employed. A pi model is shown in Fig. 3. To translate this into the DC emulation scheme the line parameters are separated into real and imaginary components. This yields the resistor values for the DC emulation networks. For the series elements [17]:

$$\begin{aligned}R_{\mathrm{Re}(ij)} &= \frac{1}{\mathrm{Re}\{Y_{ij}\}} = \frac{R_{ij}^2+X_{Lij}^2}{R_{ij}}\\ R_{\mathrm{Im}(ij)} &= \frac{1}{\mathrm{Im}\{Y_{ij}\}} = \frac{R_{ij}^2+X_{Lij}^2}{X_{Lij}}\end{aligned}. \tag{2}$$

For the shunt elements:

$$\begin{aligned}R_{\mathrm{Re}(ik)} &= R_{\mathrm{Re}(jk)} = \frac{1}{\mathrm{Re}\{Y_{jk,ik}\}} = r_{jk}\\ R_{\mathrm{Im}(ik)} &= R_{\mathrm{Im}(jk)} = \frac{1}{\mathrm{Im}\{Y_{jk,ik}\}} = \frac{-1}{\omega C_{jk}} = -X_{C_{jk}}\end{aligned}. \tag{3}$$

The emulation networks can be constructed based on the line parameters and Eqs. (2) and (3). The topology of each DC network will mimic the topology of the power system. For example, for the pi model shown here the analogous section DC emulation network will have a pi form. For a network of many transmission lines the required resistance values and network topology are developed in the same fashion.

In circuit form a network of resistors, or potentiometers, would require manual intervention to configure and alter the emulator for a given computation. In addition, there is a requirement for negative resistance when modeling shunt capacitive elements of the transmission lines. A hardware design with active devices that achieves remote reconfigurability and negative resistance has been developed. The circuits are OTA-based reconfigurable variable positive and negative resistive circuits.

OTAs are voltage controlled current sources (VCCSs) with a controllable transconductance gain (g_m). More specifically, $i_o = g_m v_{in}$ where i_o is the output current and v_{in} the input voltage. The gain is controllable via a bias current (i_{abc}). A double ended OTA variable resistor [19] based on the LM13700 OTA is shown in Fig. 4. The LM13700 was utilized due to its low cost and