ANALOG EMULATION USING A RECONFIGURABLE CLASSICAL GENERATOR MODEL FOR LOAD FLOW ANALYSIS

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Abstract – This paper is concerned with the development of a generator model using analog circuits for load flow emulation. Using analog emulation for power system analysis allows for reduction in computation time compared to currently used numerical methods. The proposed generator model will include reconfigurable parameters using operational transconductance amplifiers (OTAs). The design is capable of reconfiguring system parameters and emulating load flow calculations. The circuit module currently being developed will be used with other reconfigurable circuits, i.e. transmission lines and loads.

Keywords: generator model, analog computation, reconfigurable emulation

1 INTRODUCTION

Deregulation of the electric power industry has created new challenges to maintaining quality and reliability of the electric power system. With these new challenges, comes the need for new computation tools to study the behavior of the power system network. In order to quickly assess the system performance, the development of a real-time computational tool with very high speed to determine the operating points of the network is required.

Static load flow analysis, which is based on the power flow equations, is one method currently used by the industry. The problem at hand is that these analyses solve using a sequential method, which make the simulation process very slow in complex networks. The speed of the digital computer to solve for static load flow is greatly dependent on the size of the power system network. An alternative method to solve static load flow is using an analog computer to emulate the behavior of the power system, instead of using model equations to simulate the network.

In the past two decades, silicon-on-insulator complementary metal oxide semiconductor (SOI CMOS) technology has become a major technology for integrating VLSI systems using a low-supply voltage [1]. Along with the progress in the CMOS technology, CMOS devices have been scaled down continuously and the corresponding power consumption has also been decreased, which have triggered advances in the circuit design techniques for various designs and applications. The association between CMOS circuits and VLSI chips is becoming increasingly easier to implement.

With these advances, Fried et al [2], proposed an approach using an analog VLSI chip for simulation of the behavior of power systems. The paper introduces the concept of transient stability analysis with the advantages of shorter computation time than current digital simulations and smaller size and cost than discrete analog emulators. One of the main disadvantages of this method is the limited accuracy due to the implementation of the analog VLSI chip.

Using an analog VLSI chip can be limited if the fabricated chip is only useful for one power system configuration. Gu et al [3], presented a concept to add reconfigurable parameters using switches and analog voltages to change the system configuration and parameters.

A main advantage of analog emulation compared to Real Time Digital Simulators (RTDS) [4] is that the former incorporates faster than real time calculation, since RTDS perform transient calculations in real time. In addition, complex systems may not be easily implemented on RTDS because the calculation of parallel algorithms must be decoupled, whereas the analog emulator mimics the real power system, inherently parallel, and the load flow solutions are simply extracted.

Using the techniques presented based on previous work [5], this paper will present the next step of the actual design of a prototype for a reconfigurable generator model for multiple static load flow calculations with the ability to change power system parameters.

The goal is to design a prototype of a classical generator model using CMOS technology that will emulate the behavior of a generator in the power system, which may eventually be integrated into a VLSI circuit design. This board will use analog and digital control signals to initialize and reconfigure the parameters that are based on the power network. Figure 1 represents the proposed interface between the generator module and the computer to facilitate data acquisition and control of system parameters. This will later expand to other power system sizes for static load flow calculation, using transmission lines and load models, which are also currently in development.

Attention will first address issues involving fundamental functional description of the generator dynamics, its analog equivalent representation, and CMOS component selection. In addition, issues involving the accuracy of this method and the source of inherent errors in ana-

log computation of generator behavior will be investigated.

Analog emulation is essentially a solution to a problem of scaling. To accomplish this, one must resolve scaling in time as well as in parameter space. Benefits of scaling include enormous computation speedups and lower circuit voltages and currents to minimize power consumption of CMOS devices.

This paper is presented in a manner to describe how the generator model is developed, scaled, and represented as an analog emulator. An example with results will validate the model design and the circuit operation of the analog emulator.
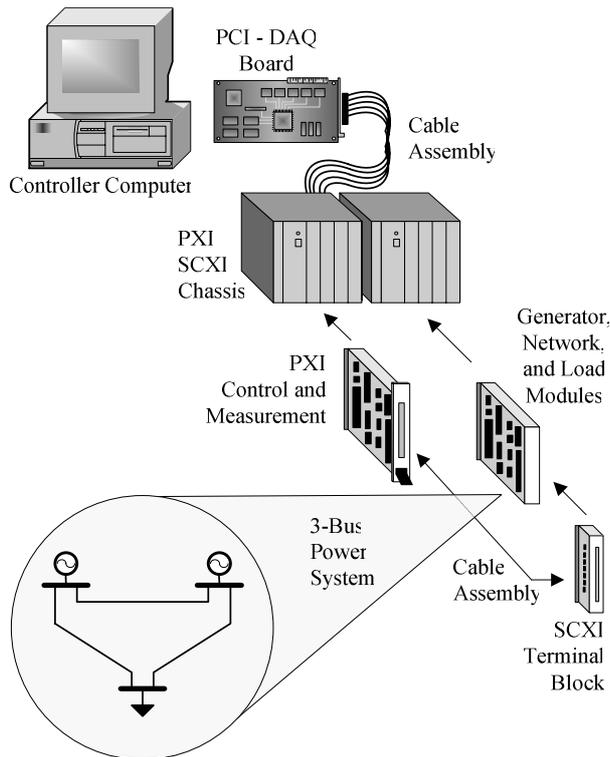

Figure 1: Power System Emulator Hardware Setup.

2   GENERATOR MODEL

The proposed circuit is based largely upon the classical generator model. This section presents a short review of the basics behind the generator model developed and scaling of the model to an appropriate analog circuit.

2.1 Classical Generator Model

The classical generator model that will be used for this paper consists of a voltage source behind an impedance, where $V\angle 0$ represents the generator terminal voltage, $E\angle\delta$ denotes the internal generator voltage and angle, and Z representing the transient reactance of the generator X'_d. The generator consisting of these elements can be seen in Figure 2.
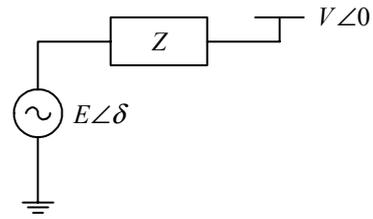

Figure 2: Classical Generator Model.

With this model, the electrical angle, δ, is unknown, and therefore, needs to be computed. In order to determine the electrical angle, we decided to capture the dynamics of the generator within our model. The simplified mechanical equation that governs the motion of the generator rotor, describes the swing between the mechanical and electrical angle, otherwise known as the swing equation,

$$M\ddot{\delta} + D\dot{\delta} + P_e(\delta) = P_m \tag{1}$$

where M is the generator inertia coefficient, D is the damping coefficient, P_e is the electrical power output, and P_m is the mechanical input power. The solution we seek, the load flow, corresponds to the steady state solution of this equation.

In order to simplify the calculation required in the analog circuit, the electrical power output of the generator will be solved in rectangular form. With converting the polar notation to rectangular form, only the real and imaginary components will be necessary and the calculation for the electrical output power of the generator model can be rewritten as the following equation.

$$\begin{aligned} \mathrm{Re}\{S\} &= \mathrm{Re}\{V\cdot I^*\} \\ P_e &= E_{Real}\cdot I_{Real} + E_{Imag}\cdot I_{Imag} \\ P_e &= |E|\cdot\cos\delta\cdot\mathrm{Re}\{I\} + |E|\cdot\sin\delta\cdot\mathrm{Im}\{I\} \end{aligned} \tag{2}$$

The representation of the electrical output power will be essential to the generator model because this will need to be applied directly into the swing equation for the calculation of the electrical angle. The functionality of the swing equation as seen in the block diagram in Figure 3, will provide us with a layout for the generator model that will be presented in the following section.
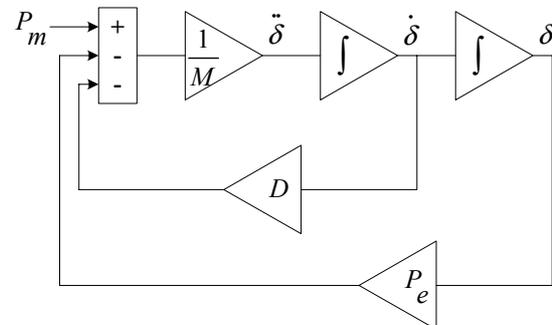

Figure 3: Swing Equation Functional Block Diagram.

With many different models representing the generator available, we will use the classical model while neglecting damping. This will simplify the non-linear dynamics of the classical generator without significantly reducing the precision of the model. Higher order complex generator models are identified to only increase accuracy by 1-2% when adding detailed modifications to the traditional classical model [6]. With these assumptions, the swing equation (1) will reduce to only the difference between the mechanical input power and the electrical output power. After factoring in the generator inertia coefficient and taking two integration steps of the angular acceleration, the solution of the electrical power angle can be calculated in the following form.

$$\delta = \frac{1}{M} \iint \left(P_m - P_e(\delta) \right) dtdt \qquad (3)$$

2.2 Scaling Parameters

In order to realize a power system using analog emulation, two different scaling factors need to transpire. The time scaling parameter for the computation speedup of the emulator, and the scaling of parameter space for the electrical angle to be represented as voltage in the circuit.

First is the introduction of the time scale factor, τ, a constant which will represent a computational speedup of τ times faster than the real-time system. This factor is directly proportional to the real time of the power system, t, for a given simulation time of the analog emulator, T. This factor always allows for the emulator to be τ times faster than any given power system. With this advantage, we can include the time scale factor in the solution of the electrical angle (3), capable of scaling the computation time of emulator in the following manner.

$$\tau = \frac{t}{T}$$
$$\delta = \frac{\tau^2}{M} \iint \left(P_m - P_e(\delta) \right) dtdt \qquad (4)$$

The time scale factor needs to be squared because of the second order nature involved in the dynamics of the classical generator model. A collaborating factor that may influence the choice of the time scale is that the error in the integration may be accentuated by long emulation times.

Another scaling procedure that needs to be addressed is actual parameter scaling of the electrical angle to voltage. Introducing the desired voltage, υ to be represented as a voltage level in the circuit that is equivalent to π radians, (4) can be rewritten as the following equation.

$$\delta = \frac{\tau^2}{M} \frac{\upsilon}{\pi} \iint \left(P_m - P_e(\delta) \right) dtdt \qquad (5)$$

With the generator model and scaling parameters defined, we can proceed to develop this model using CMOS analog devices. Before selecting the devices we need to identify the circuit parameters needed to scale

the power system to an analog circuit and the parameters needed to achieve reconfigurablity within the model.

3 RECONFIGURABLE GENERATOR MODEL

The next step of modeling addresses the concept of reconfigurablity in the generator model. This aspect will allow for the change of the system parameters for one given hardware design via external control signals. The control signals actuate the circuit parameters as opposed to the concept of adaptability which involve model parameters adapting to changing conditions. To accomplish this, the actual analog circuit representing the generator needs to incorporate a programmable analog device into model to obtain controllable behaviors of the power system.

3.1 OTA Characteristics

Instead of the typical operational amplifiers to realize some of the components needed, the operational transconductance amplifier (OTA) will be used because of its ability to control its gain by an external current (or voltage). This extends the boundaries of the basic op-amp and makes realizable designs that were previously unobtainable.

The OTA has the basic properties of a voltage-controlled current source (VCCS) and the output current is obtain by,

$$I_o = g_m \left(\Delta V_{in} \right) \qquad (6)$$

a product of the transconductance parameter and the differential input voltage.

The transconductance, g_m, can be increased or decreased as a function of the input voltage by varying the amplifier bias current, I_{abc}, according to this equation.

$$g_m = \rho \cdot I_{abc} \qquad (7)$$

The transconductance of the device can be considered as a gain and is dependent on a non-linear device constant, ρ and the amplifier bias current as seen in (7) [7]. Ideally, the desirable gain of an OTA would always be constant, with a linear input output relationship. Since this is not the case, measures will need to be considered because of the errors that will result from the non-linear transconductance of the OTA. To ensure that the operation of the OTA is within a linear operating region, scaling of system parameters to appropriate current and voltage levels is required. The remaining analysis in this paper will assume this to be so.

3.2 Circuit Parameter Transformation

To achieve the difference between the mechanical input power and the electric output power on a circuit, power is quantified as current. This introduces a circuit scaling parameter, K_p, a constant ratio between the circuit current and the real world power quantity as seen below.

$$K_p = \frac{I_{max}}{P_{max}} \qquad (8)$$

The analog circuit developed to solve the swing equation of the generator will consist of two first-order integrators built using OTAs [7]. The output of the double integration process is voltage, V, representing the electrical angle and is calculated in the following manner analogous to (5).

$$\delta \equiv V = \frac{g_{m1} \cdot g_{m2}}{C_1 \cdot C_2} \iint \left(I_m - I_e(V) \right) \, dt dt \qquad (9)$$

In this equation, the $I_e(V)$ represents electrical power which is dependent on the electrical angle. The components C_1 and C_2 are the values of the integration capacitor needed in the first and second integrators, respectively. The transconductance parameters, g_{m1} and g_{m2}, are the gains of the first and second OTAs in the double integration process. In connection to scaling described in section 2, these values can be reconfigured using the amplifier bias currents to correspond to various generator characteristics and a given range of speedup times.

3.3 Analog Generator Model

In order to provide the analog implementation of the algorithm described in the previous section, an approach to simulate the block diagram of the swing equation (3) needs to be realized. A functional block diagram of the generator behavioral model is made up of voltage-controlled current sources (VCCS), current-controlled voltage source (CCVS), amplifiers, integrators, and various other components that determine the electrical output power of the generator. Figure 4 represents the block diagram of the analog behavioral model of the generator.

Similar to I_e, the current, I_m, is used to quantify mechanical power. The difference between this current and I_e, is used as the input into the double integrator scaled as voltage. The voltage output of the double integrator is equivalent to the electrical angle given by (5). By definition, electrical power output is dependent on generator terminal voltage and current. Upon calculation of the electrical power, $P_e(\delta)$, it will be scaled to a corresponding current value, $I_e(V)$, and the process updates itself until a possible stable steady-state solution is attained.
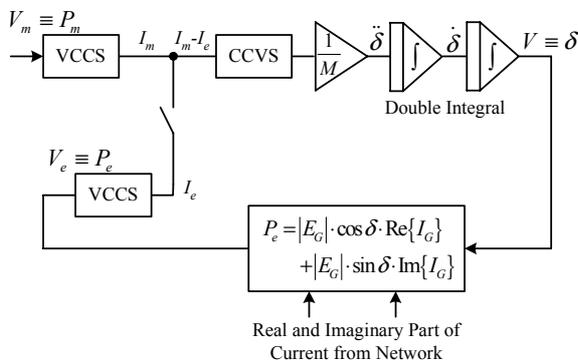

Figure 4: Generator Model Functional Block Diagram.

To achieve this operation on a circuit, appropriate CMOS devices must be selected. Considerations used for selection include minimal device power consumption, suitable device operating ranges, and transconduc-

tance. The devices selected for this model will use commercial off-the-shelf (COTS) CMOS components including the National Semiconductor LM13700 OTA [8] and the Analog Devices AD639 Trigonometric Converter [9].

Having the devices selected, an example of the analog emulator will be discussed, along with emulation results and recommendations for future development.

4 IMPLEMENTATION EXAMPLE

With the generator model developed, scaling parameters defined, and device components selected, the circuit will be tested on a power system example.

4.1 Power System

The model above in Figure 4, will be used in a simple power system problem [10]. For this example, the generator will be delivering power to an infinite bus through a transmission line and the solution of the electrical angle can be seen as described in equation (3).

The calculation of the steady-state solution of the electrical angle of the generator can be found by solving the instantaneous generator power for the system,

$$P_m = \frac{|E||V|}{(X'_d + X_L)} \sin \delta^o$$

$$P_m = P_{e,\max} \sin \delta^o \qquad (10)$$

where $|E|$ is the internal generator voltage, $|V|$ is the bus voltage, X'_d is the transient reactance of the generator, and X_L is the line reactance. For a given mechanical input power, the steady-state solution of the electrical angle can be found with given system parameters.

4.2 Analog Emulator

The analog circuit for the single-machine power system will consist of four OTAs, a trigonometric converter, and resistors and capacitors as seen in Figure 5. The controllable gains need to be calculated in order to fit the circuit to the power system, which will be dependent on the selection of the resistor and capacitors in the circuit. The selection of the resistor values will be needed to scale the parameters to proper voltage levels for the OTAs to function within their linear operating range. The capacitor selection will determine the integration time of the circuit.
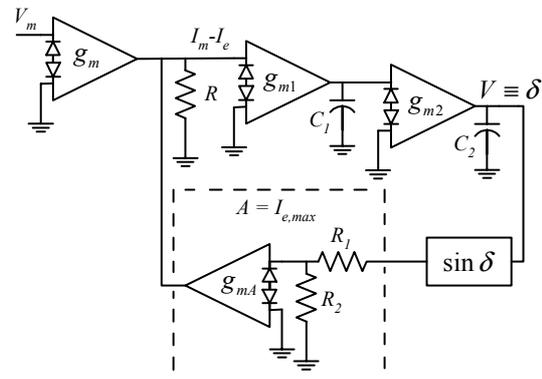

Figure 5: Single-machine CMOS Analog Emulator.

The gain representing the maximum electrical power output, $P_{e,max}$, is transformed into the maximum current gain parameter A, which equivalent to $I_{e,max.}$. The maximum allowable current parameter will be controlled through the gain of an OTA, g_{mA}. This can be changed for different power system parameters in the following manner from equations (8) and (10).

$$A = K_p \cdot P_{e,max}; \quad g_{mA} = A \cdot \frac{R_1 + R_2}{R_2}$$

$$g_{mA} = \frac{K_p |E||V|(R_1 + R_2)}{(X'_d + X_L)R_2} \tag{11}$$

In our approach, the two gains of the OTAs within the double integrator are considered identical to one another. Using equations (5), (8), and (9), we can characterize the gains in terms of the following,

$$M = \frac{H}{\pi f_o}$$

$$g_{m1} = g_{m2} = \sqrt{\frac{P_m \cdot C_1 \cdot C_2 \cdot \tau^2 \cdot \upsilon}{K_p \cdot M \cdot R \cdot \pi}} \tag{12}$$

For equation (11), the power system parameters are directly associated with a controllable gain parameter. In equation (12), the controllable gain is directly associated with the generator inertia constant and the scaling parameters defined in equations (4) and (5). This allows for a completely reconfigurable classical generator model that provides computational speedup over conventional digital methods.

5   SIMULATION RESULTS

The proposed method for a reconfigurable classical generator model has been tested in a single-machine power system. These are only preliminary results which can later include larger power system examples. The purpose of this example is to exhibit the viability of this approach through characterization of its fundamental behavior, which will be recognizable in larger scaled systems. The results of the simulation shown are from the circuit emulator proposed in Figure 5 using PSpice and will be compared to simulation results obtained using PSpice Analog Behavior Models (ABM). This comparison is validated from previous work [11] conducted using Analog Behavior Models of sample power systems, where the results obtained compared rather favorably with traditional load flow solvers such as PSS/E and PowerWorld.

The power system parameters and the associated circuit parameters based on the previous equations for the simulation example are listed in Table 1. For this example the mechanical input power is fixed constant at 0.5 per unit (p.u.) while the emulator solves for a steady-state solution.

The results from the power system can be seen in Figure 6a and the results of the analog emulator can be seen in Figure 6b. With both converging to approximately the same steady-state solution, we can clearly see

that the analog emulator solved from the electrical angle of the swing equation much faster than the actual power system. This clearly demonstrates the capability of the computational speedup the analog emulator possesses with respect to real-time.

Power System		Circuit Emulator	
$|E|$	1.8	C_1 (ηF)	100
$|V|$	1.0	C_2 (ηF)	100
X'_d (p.u.)	1.0	g_{m1} (mho)	0.0182
X_L (p.u.)	0.4	g_{m2} (mho)	0.0182
H (sec)	5.0	K_p	$1.0 \cdot 10^{-4}$
P_m (p.u.)	0.5	υ (V)	3.6
f_o (Hz)	60	τ	$5.0 \cdot 10^3$
		A (μA)	129
		I_m (μA)	50
		g_{mA} (mho)	0.0130

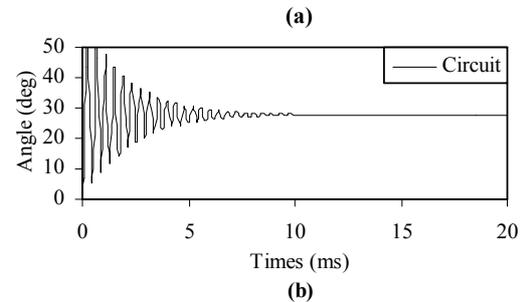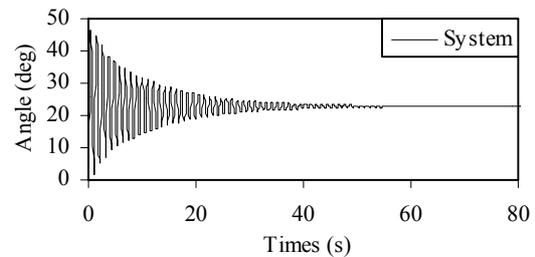**Table 1:** System and Circuit Parameters.

Figure 6: Results of Power System and Analog Emulator.

Upon closer inspection, the results of the actual angular solution are different with a large degree of error. The ABM power system model solved for the angular solution of 22.89^o, while the OTA analog emulator model solved for the angular solution of 27.79^o. The difference between the two results has an error of approximately 21~22%. Since the steady-state calculation of the actual electrical angle using equation (10) results in an angle of 22.89^o, the analog emulator seems to produce the error.

This error can be attributed to the detailed model of the LM13700 OTA that is used in the model. This off-the-shelf component is designed for high frequency applications. The circuits within the PSpice model mask the actual OTA behavior leading to errors not attributed to the OTA.

There are many methods to correct for errors produced from the non-ideal characteristics of the OTA. One method could use post-processing to correct for the offsets produced by the devices. The problem with this is that the emulation computational speedup times may be reduced to provide extra processing of data collected from the circuit.

Other methods include proposed advances in OTAs seen over the years, since the device is becoming a fundamental building block in continuous-time circuits. One such advance would be using a linear OTA with automatic offset cancellation and transconductance calibration, where the offset in the device is eliminated for high-precision performance [12].

Since this paper focuses on the study of load flow analysis of power systems, and not the intricate design of electronic devices, the offset correction method that will be applied to this example will be the post-processing of the data to correct for the offset of the devices.

To correct for the offset, we set the circuit with zero mechanical input power, $P_m = 0$. The circuit emulator will provide an offset solution because the gains amplify the offsets within the devices. This angular offset solution will be subtracted from the PSpice emulator simulation for the given mechanical power. Figure 8 shows the results of the offset correction compared to the original results of the analog emulator with PSpice. With the offset eliminated from the PSpice solution, the corrected angular solution is now 22.74°, which is much closer to the desired solution. The results from this example and the errors calculated are tabulated in Table 2.
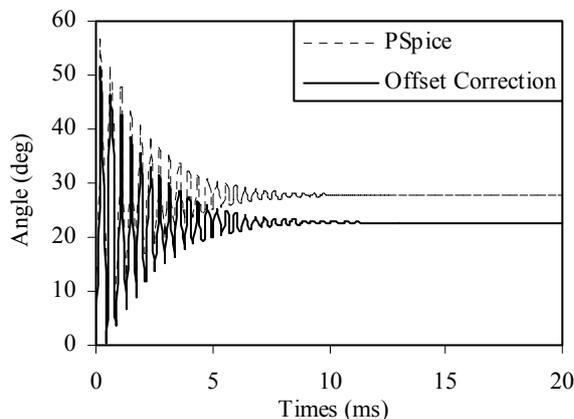

Figure 7: Results of Analog Emulator with Offset Correction.

Method	Delta (deg)	Error (%)
Calculation	22.885	-
PSpice ABM	22.886	0.00
PSpice OTA	27.787	21.4
PSpice OTA Offset Correction	22.740	0.63

Table 2: Result Comparison and Errors.

This single-machine infinite-bus power system example shows that the analog emulator achieves computational speedups over the real power system. The disadvantage of the analog circuit is that the accuracy of the circuit may not be as good as current digital computer methods for solving load flow. The results show with offset correction methods implemented, a tradeoff is made between accuracy and computational speedup.

The offset correction for this example may not be completely accurate, because the offset error of each device may be dependent upon a given input into the circuit. Further analysis on the offset correction could be used to develop a more feasible offset correction algorithm to be applied during post-processing of the data.

6   CONCLUSION

This paper explored the implementation feasibility of analog emulation of power systems using CMOS devices in a PSpice environment. The end goal is to develop a fast, programmable, and reconfigurable power system emulator on an analog/mixed signal VLSI chip. The approach provided a depiction of the end goal as well as circuit components' intricacies. Advantages and limitations of the proposed analog reconfigurable classical generator model were also highlighted.

The example provided results of the advantages of the analog emulator including the ability to reconfigure system parameters and the computational speedups achieved in the circuit. The disadvantages to this approach also were shown in terms of the relative inaccuracy of the proposed analog model. It may be noted that the emulation is only as accurate as the perceived first classical generator model. There is a strong argument in the analog computation community that errors is more linked to a precision concept as opposed to its accuracy.

This work provides insight into the problems that will need to be addressed for multi-machine systems. Since this application is designed at lower frequencies, a basic OTA model with minimal offsets could be developed without the extra control and protection circuitry. Also for larger power systems, the offsets may cancel each other out or could actually represent the physical behavior seen in real power system measurements. It is because of these and other features we stated that the analog emulator more accurately represents the behavior of the power system when compared to traditional digital linear solvers.

Further work from the results of this paper could branch off into many areas. Since the components used have device limitations, research into the limitations of the proposed analog circuit could be performed to overcome the solution limits. One method would be the introduction of initial conditions on the integrator to start at a value that may be closer to a desired stable solution. Also, more complicated models could be developed to expand this model to include damping and higher order generator models.

This work is a basic step towards achieving a working prototype that will be developed on printed circuit

boards and used with other network and load circuits to emulate power flows within various-sized power system models. Larger system emulators will naturally follow from gained knowledge obtained as a result of studying such circuits.

ACKNOWLEDGMENT

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