Insight into Reconfigurable Analog Emulation of the Classical Generator Model

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Abstract- **This paper suggests an approach to implement a reconfigurable generator model with operational transconductance amplifiers (OTAs). This analog circuit will be used with other reconfigurable circuits, i.e. transmission lines and loads, to achieve power system analysis by means of circuit emulation. The advantage of using this method will allow for reduction in the computation time that is needed for solving load flow operating points based on numerical calculations for various power system configurations. An example will be provided to give insight into the proposed emulator's capabilities as well as possible limitations.**

I. INTRODUCTION

With the deregulation of the electric power industry, there has been an increase in the need to develop a real-time computational tool with very high speed to determine the operating points of the network. Currently in the power industry, static load flow analysis is based on the power flow equations. These analyses use a sequential method, which make the simulation process very slow in complex networks and is greatly dependent on the size of the power system network.

An approach using an analog VLSI chip for simulation of power system behavior was introduced by Fried et al [1]. The concept introduces the idea of transient stability analysis with the advantages of shorter computation time than current digital simulations and smaller size and cost than discrete analog emulators. This approach allows for immediate results of the transient behavior independent of the size of the power network, while maintaining relatively small size and low cost. One of the main disadvantages of this method is the limited accuracy due to the implementation of the analog VLSI chip.

When designing an analog VLSI chip, if the parameters cannot be changed for different power system configurations, the technology becomes limited for only one network solutions. Gu et al, [2] presented a concept to use the VLSI technology for transient stability analysis like Fried, but with the ability to reconfigure the system parameters, so the general VLSI chip can be used for a variety of power system configurations. Hence, the approach does not limit the fabricated chip to just one power system.

This paper proposes an approach to realize the classical generator model used in the previous mentioned papers [1]-[2], and implement it with operational transconductance amplifiers in a highly programmable printed circuit board (PCB) that can perform the emulation of the generator model in a very short time. With the selection of this model, both static and dynamic characteristics can be studied. In this paper, concentration will concern the solution of static states to be used in an equivalent load flow environment.

The goal is to design and prototype a printed circuit board using operational transconductance amplifiers (OTAs) [3] to model the behavior of a classical generator model. This board will use analog and digital control signals to initialize and reconfigure the parameters that are based on the power network. Fig. 1 represents how the interface between the generator module and a computer will be applied to allow for the control and data acquisition of the power system. The computer will be needed to apply control voltages to the module, collect the data from the load flow solution, and post-process any information that may need to be calculated.

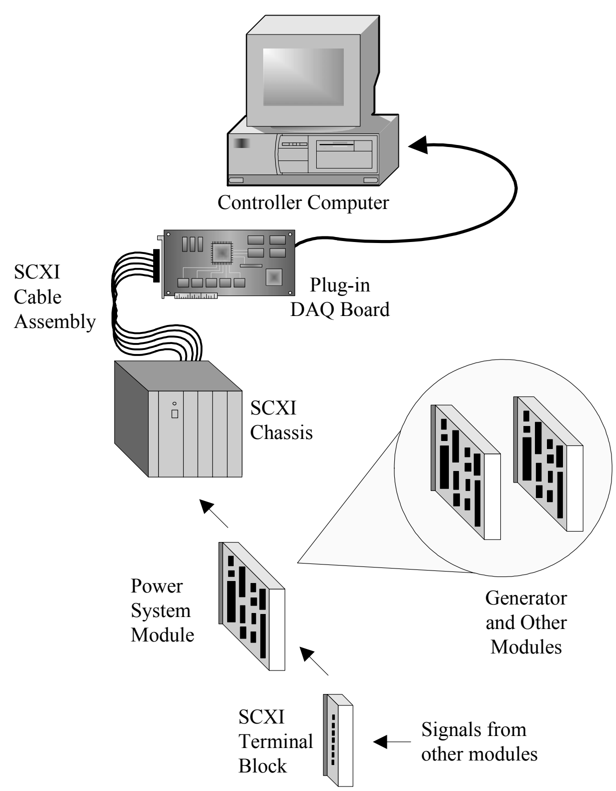

Fig. 1. Circuit Module Design for Emulation

Consideration will be given to issues involving underlying functional description of generator dynamics, its analog equivalent representation, and circuit component selection. In addition, issues involving the accuracy of this method and the source of inherent errors in analog computation of generator behavior will be investigated.

Analog emulation is essentially a solution to a problem of scaling. In other words, since the goal is to eventually mimic large scale power system behavior on a PC board and eventually a VLSI chip. One must resolve scaling in time as well as in parameter space. Benefits include enormous computation speedups and appropriate component selection based on power handling capability.

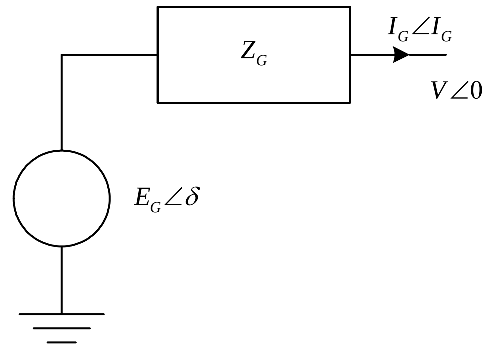

Fig. 2. General Model of Classical Generator

II. GENERATOR MODEL

The classical generator model that will be used in the power system 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_G representing the transient reactance of the generator X'_d. The generator consisting of these elements can be seen in Fig. 2.

The main challenge of applying the model described is the unknown electrical angle, δ. In order to compute the electrical angle, we first must model the dynamics of the generator. 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 method to solve for the electrical power output of the generator will be calculated in rectangular form. By converting the polar notation to rectangular form, only the real and imaginary components will be necessary. Keeping this in mind, solving for the electrical power output, can be found by solving for the real part of the complex power, which can be written as

$$\mathrm{Re}\{S\} = \mathrm{Re}\{E_G \cdot I_G^*\} \tag{2}$$

$$P_e = E_{G,real} \cdot I_{G,real} + E_{G,imag} \cdot I_{G,imag} \tag{3}$$

where the real and imaginary parts of the internal generator voltage are $E_{G,real} = |E_G|\cdot\cos\delta$ and $E_{G,imag} = |E_G|\cdot\sin\delta$, respectively. Substituting the rectangular components of the voltage and current, the calculation for the electrical output power of the generator model can be rewritten as

$$P_e = |E_G| \cdot \cos\delta \cdot \mathrm{Re}\{I_G\} + |E_G| \cdot \sin\delta \cdot \mathrm{Im}\{I_G\} \tag{4}$$

The realization of the electrical output power will be vital to the generator model because this will need to be applied directly into the swing equation for the calculation of the electrical angle. Fig. 3 corresponds to a block diagram depiction of the functionality of the generator swing equation. After deriving the electrical power delivered by the generator, the electrical angle will update and modify the real and imaginary part of the internal generator voltage E_G. By subtracting the electrical output power and the damping factor from the mechanical input power, this will yield the angular acceleration of the generator.

Since damping is neglected (or D=0), the only change needed to be determined is the difference between the mechanical input power and the electrical output power. After factoring in the generator inertia coefficient, by taking two integration steps of the angular acceleration, the solution of the electrical power angle can be calculated in the following form.

$$\delta = \frac{1}{M}\iint \left(P_m - P_e(\delta)\right)\, dtdt \tag{5}$$

Even though there are many different representations of generator models available, the accuracy does not increase significantly [4] when using a more complicated model. The swing equation allows for a simplified non-linear description of the dynamics of a classical generator with sufficient precision.

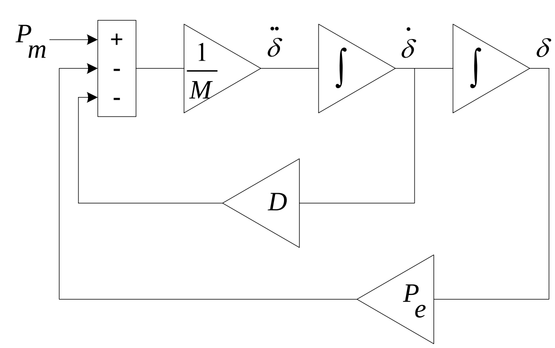

Fig. 3. Swing Equation Functional Block Diagram

III. FUNCTIONAL ANALOG COMPUTATION

In order to provide the analog implementation of the algorithm described in the previous section, an approach to simulating the block diagram needs to be realized. To study the behavior of the generator model, functional blocks will be used to represent the algorithm. Before implementing every component in an actual circuit, the input/output relationship of the block diagrams will be analyzed before modeling the circuit with actual circuit devices. Fig. 4 represents the block diagram of the analog behavioral model of the generator.

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. Voltages, V_m and V_e, are used to control the currents that represent the mechanical and electrical power, respectively. The difference between these two currents is the input into a double integrator, with a gain of the double integral related to the inertia coefficient of the generator, the time scaling parameter for computation speedup, and the scaling of parameter space.

The time scale factor is a constant which will represent a computational speedup of τ times faster than the real-time system. With this advantage, we can include the time scale factor in the solution of the electrical angle (5) which is capable of scaling the computation time of emulator in the following manner.

$$\delta = \frac{\tau^2}{M} \iint \left(P_m - P_e(\delta)\right) dtdt \qquad (7)$$

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

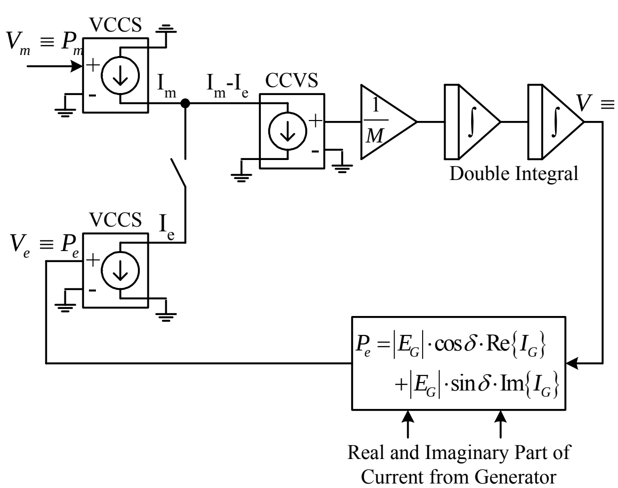

Fig. 4. Analog Behavioral Model of Generator

Another scaling procedure that needs to be concentrated on is actual parameter scaling of the electrical angle to a voltage. Introducing the desired voltage, υ to be represented as a voltage in the circuit that is equivalent to π radians, (7) can be rewritten as the following equation.

$$\delta = \frac{\tau^2}{M} \frac{\upsilon}{\pi} \iint \left(P_m - P_e(\delta)\right) dtdt \qquad (8)$$

After solving the electrical angle with the swing equation, the output of the double integrator is used to calculate the real output power of the generator based on the complex current drawn by the network and load models. Other network and load models are being developed in a similar fashion to simulate a 3-bus power system with two generators, three transmission lines, and one load.

Consequently, the generator circuit module has to provide four terminals, two inputs and two outputs. The outputs are the real and imaginary parts of the generator voltage which are fed into the network module, based on the work of Carullo et al [5].

The inputs will be the real and imaginary currents that are drawn from the generator by the network. The current drawn from the generator real and imaginary voltage sources are used to calculate the complex current drawn from the generator.

This is used to calculate the real electrical power output of the generator module and accomplished using two analog multipliers and an adder circuit which can be seen in the actual circuit of the generator module in Fig. 5.

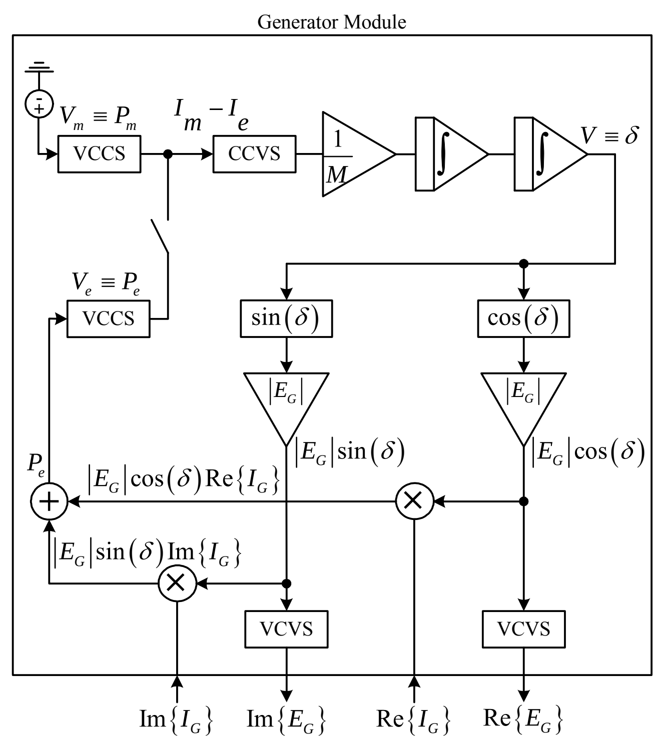

Fig. 5. Circuit Module Implementation of Generator

With the simplification of the generator using analog behavioral modeling, a final design of the module was determined after deciding the functionality needed in the model to achieve the desired characteristics of the classical generator model.

IV. RECONFIGURABLE GENERATOR MODEL WITH OTA

The next type of modeling to be completed will use the structure of the actual circuit to achieve maximum controllability of an accurate classical generator model. The desired analog behaviors that are used in the model need to be developed into the components that will be used on the actual circuit board.

With the aim to be capable of reconfiguring the generator model for use in any practical power system arrangement, a programmable device must be used to model the controllable behaviors of the physical system.

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 be controlled by an external current (or voltage). This extends the boundaries of the basic op-amp and makes realizable designs that were previously unobtainable.

Comprehension of the basic properties of the OTA in Fig. 6 can be obtained by recognizing the equivalent circuit of the OTA as a voltage controlled current source. The input to the device is a differential voltage while the output is a current. The output current is a product of the transconductance parameter and the differential input voltage.

$$I_o = g_m \left(\Delta V_{IN}\right) \tag{9}$$

The transconductance, g_m, can be increased or decreased as a function of the input voltage by varying the amplifier bias current, I_{ABC}. The transconductance of the device can be considered as a gain and is dependent on the device constant and the amplifier bias current as seen in (10). Ideally, the desirable gain of an OTA would always be constant with a linear input and 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.

$$g_m = \frac{I_{ABC}}{2 \cdot V_T} \cdot \operatorname{sec}h^2\left(\frac{\Delta V_{IN}}{2 \cdot V_T}\right) \tag{10}$$

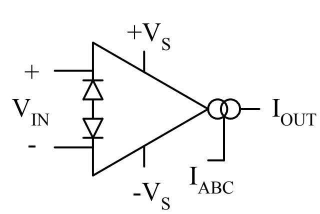

Fig. 6. Ideal Operational Transconductance Amplifier

The analog circuit needed to solve the swing equation of the generator will consist of two integrators built using operational transconductance amplifiers. The output of the double integration process is a voltage representing the electrical angle and is calculated in the following manner.

$$\delta \equiv V = \frac{g_{m2} \cdot g_{m1}}{C_2 \cdot C_1} \iint I_m - I_e\left(V\right)\, dtdt \tag{11}$$

In this equation, the $I_e(V)$ corresponds to the dependence of the electrical power 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 OTA in the double integration process. This value can be reconfigured using the amplifier bias currents to correspond to any desired generator characteristic.

With equations (8) and (11), the correlation between the current representing the mechanical and electrical power in the real system can be seen with the following transformation, involving the scaling procedure needed for analog emulation.

$$\begin{aligned} I_m &= P_m \frac{C_2 \cdot C_1}{g_{m2} \cdot g_{m1}} \frac{\tau^2}{M} \frac{\upsilon}{\pi} \\ I_{e,\max} &= P_{e,\max} \frac{C_2 \cdot C_1}{g_{m2} \cdot g_{m1}} \frac{\tau^2}{M} \frac{\upsilon}{\pi} \end{aligned} \tag{12}$$

The mechanical and electrical current will need to be within the operating tolerance of the OTA and scaled accordingly. The control voltage from the computer to control the mechanical current of the generator will also need to be scaled appropriately to accommodate the limiting input voltage of the OTA with the gain controlled to get the desired and calculated required current.

Since the circuit board implemented with OTAs will not be close to ideal conditions, many issues will need to be addressed in the generator circuit. Observe that in contrast to op-amp, the OTA is often operated in open loop conditions for high-frequency operation. The major limiting factor with commercially available OTAs is the limited differential input voltage swing because of its poor linear operating range [6].

One improvement to obtain reasonable signal swings is to condition the signals before they reach the OTA. Fig. 7 shows the use of voltage dividers and buffers at the input of the existing OTA as an alternative technique to significantly improve the performance of the OTA. The setback for using this configuration is the use of the op-amps will impose a limit on the bandwidth available to the OTA and additional components will be needed in the circuit. Another way to solve this problem would be to incorporate negative feedback to operate the OTA in a closed-loop condition.

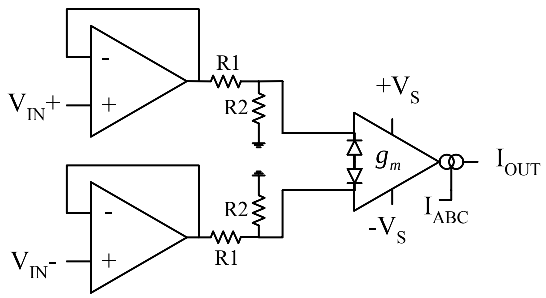

Fig. 7. Buffers at Input to OTA

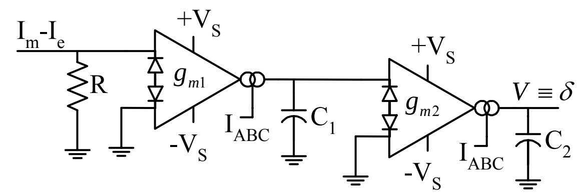

Fig. 9. Double Integrator using OTAs

An addition concern with using the OTA as the active device used in the analog circuit is the effects that noise may cause to the circuit and accuracy of the model. Because the differential input voltage of the OTA is severely limited by the linear region, any attenuation of the input signal due to noise comparable to the input signal may appear at the output and produce a serious loss in the dynamic range of the OTA structure.

Another consideration for implementing the OTAs in the generator model will be the initialization of the initial conditions of the capacitors involved in the integration process. The need to select an appropriate value will determine the speed and stability of the generator model. Incorrectly setting the initial conditions could lead to oscillations and sluggish behavior in the generator model.

Given that the OTA is a voltage controlled current source, the only devices left to model are the multiplier, adder, voltage controlled voltage source, current controlled voltage source, and the trigonometric operators [7].

V. EXAMPLE

The limited linear operating range of the OTA only applies when the device is functioning in open loop. With the open-loop gain being relatively small and the load resistance somewhat low, when the input differential voltage exceeds 25 mV, the OTA is no longer operating in the linear range, Fig. 8, and the output signal is being distorted from the non-linear behavior of the OTA stated in (10). This is the case for any amplifier bias current.

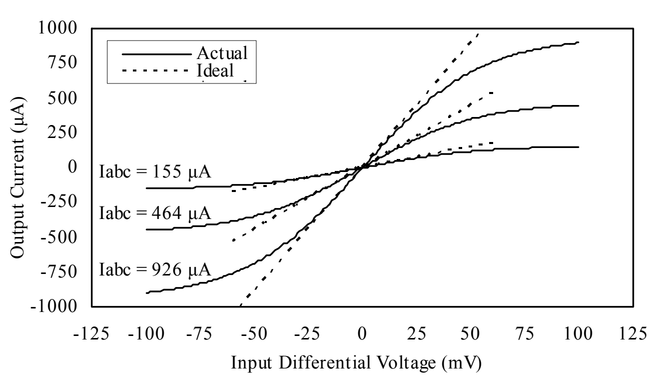

Fig. 8. Input and Output Characteristics of LM13700

To accommodate the low operating levels of the voltage and current, the generator parameters and operating points will need to be scaled down to appropriate levels for the OTA to operate in their linear range. For this case, the parameters of the integration process in Fig. 9 will be discussed to adapt to the limiting factors of the OTA.

Using the National Semiconductor LM13700 OTA [3] as a test circuit, selecting the components and operating levels will need to be within the device limitations. Normal operating conditions include an amplifier bias current of 5-500 µA, differential input voltage -25 to 25 mV for linearity, and an output current of -500 to 500 µA.

The first step to take is the scaling parameter of the electrical angle to a voltage. With the OTA operating voltage range in the mV range, selecting υ will especially need to be within this tolerance. Next, select the computational speedup of the emulator to be 10,000 times faster than the real power system.

The typical circuit parameters are as follows:

$\upsilon = 10$ [mV]
$\tau = 10^4$
$M = 0.027$ [s^2/rad]
$g_{m1} = g_{m2} = 3 \cdot 10^{-3}$ [A/V]
$C_1 = C_2 = 10$ [nF]
$P_m = 0.5$ [p.u.]
$P_{e.max} = 1$ [p.u.]

This example is based on the selection of the inertia coefficient of the generator, M, the transconductance of each OTA selected from a specific amplifier bias current, typical capacitor value to ensure operation within limits of each device, and typical per unit values of the mechanical and electrical power of the generator in a normalized power system.

With these parameters, the operating currents to the input of the integrator will have a mechanical power of the generator transformed into a current of 65 µA from (12). This is an attainable scaled parameter because the output of the OTA that will convert the mechanical power (represented as a voltage from the computer) to a current will be within the output range of the LM13700. Also the same can be assumed for the maximum electrical output power of the generator which will be approximately 131 µA.

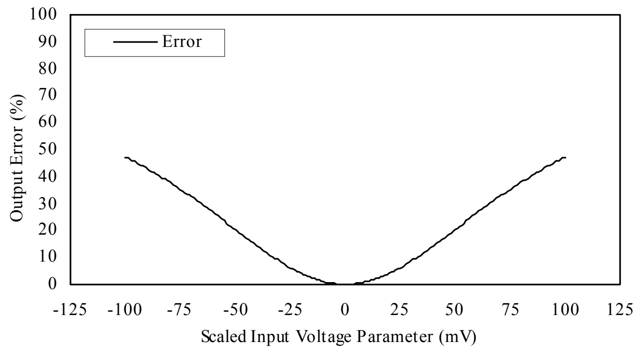

Fig. 10. Output Error for Input Voltage Conditions of LM13700

The component selection of device is critical to maintain minimal errors in the computation due to the operating conditions of the OTAs. Fig. 10 illustrates that an error in the calculations will be introduce into the circuit if the scaled voltage parameters are not within the critical tolerances of the physical device. This percentage is obtained from calculating the difference in the actual output current from the ideal output current and dividing by the ideal output then multiplying by 100. Providing that the OTA is operating in the linear region minimal errors in the analog calculation will occur.

For the practical consideration of the operational transconductance amplifier as the device used for the configurability of the generator parameters, many design optimizations will need to be taken into consideration for a realizable circuit module.

VI. CONCLUSION

Currently the load flow analysis of power systems are typical but not always, performed and simulated by numerical calculations on digital computer. The work presented in this paper will allow for reduction in computation and the ability to reconfigure models that can be used in various power system configurations.

The availability of the amplifier bias current significantly increases the flexibility of the OTA and permits the addition of controllability to a number of unique circuits and applications normally unobtainable with the conventional operational amplifier.

This work is the first step towards achieving a working prototype that will be developed on printed circuit boards and used with other network and load circuits to emulate load flow within a 3-bus power system. Larger system emulators will naturally follow from gained knowledge obtained as a result of studying such circuits.

ACKNOWLEDGMENT

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