Transient Stability Studies using SMIB Emulator

Samuel Jadhav, Nigel Goveas, Akshay Krishnapurkar, Neethi Thomas
BE Students, Dept. of Electrical Engg.
Fr. C. Rodrigues Institute of Technology
Navi Mumbai, India

Divya M
Assistant Professor, Dept. of Electrical Engg.
Fr. C. Rodrigues Institute of Technology
Navi Mumbai, India
divya.m@fcrit.ac.in

***Abstract* - Power system based subjects form an integral part of undergraduate level Electrical Engineering course. The course curriculum contains laboratory experiments where, both software and hardware experiments are conducted. Due to the availability of dedicated power system software packages like ETAP, PSS SINCAL, PowerWorld, PSCAD and MATPOWER, software laboratories are very popular. Even though they are expensive and time consuming to operate, hardware laboratories give hands-on experience. In this paper, an analog emulator that can be used for transient stability studies of a Synchronous Machine connected to Infinite Bus (SMIB) is presented. Firstly, transient stability model of an SMIB based on swing equation was modeled and simulated using MATLAB [1]. Then, an analog model of the same was modeled and simulated in Multisim [2]. It was observed that the analog model results are satisfactory when compared with the real mathematical model. Also the analog model was 5000 times faster than that of a real system. Finally hardware for analog emulator was implemented. When tested for the transient response of the system settling to the steady state solution, it is observed that output of the emulator saturates. In order to avoid this, external circuit has to be incorporated.**

Index Terms - Synchronous machine connected to infinite bus (SMIB), power system stability, power system emulator

I. INTRODUCTION

Software and hardware laboratories are vital ingredients of any power system curriculum. Compared to software laboratories, hardware laboratories have not penetrated into undergraduate level teaching. Hardware setups are expensive to build and time consuming to operate. Also various meters are required to monitor and record data. Manual configurations are required for interconnecting various devices [3, 4].

Software laboratories have some limitations when applied for power system experiments. Software packages are problem-specific. For steady state analysis of power system, software packages based on power flow solvers are used whereas time domain solvers are to be used for dynamic analysis of power system. They suffer from convergence errors since power system models are non-linear. Large number of iterative calculations required in such case results in large computation times. Also, system equations are linearized which is not recommended. They follow finite clock period that results in quantization error [5, 6].

Digital simulation is the popular method used to solve set of nonlinear differential equations and yields precise results. But it takes a lot of time to simulate a solution [6-8]. An analog emulator solves a set of nonlinear differential equations by using continuous electrical signals instead of discrete signals [9]. Analog computation can perform various non-linear analysis much faster than other methods [10].

In this paper, an analog emulation model for a SMIB is presented. Section-II explains mathematical model of transient stability of a power system. Modeling of swing equation using MATLAB is described in Section-III. In Section-IV, the analog emulator model for SMIB is simulated using Multisim and the results are presented. Details of hardware implementation are elaborated in Section-V and concluding remarks are given in Section-VI.

II. TRANSIENT STABILITY ANALYSIS

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most of the system variables bounded so that practically the entire system remains intact [11]. There are three forms of stability conditions viz. steady state stability, transient stability and dynamic stability. Steady state stability is the ability of a power system to maintain synchronism between machines within the system and external tie-lines, for small and slow normal load fluctuations. Transient stability of a power system is defined as the ability of the system to remain in synchronism during the period following a large and sudden disturbance and prior to the time when speed governors can act while dynamic stability is its ability to remain in synchronism after the initial swing, until the system has settled down to its new steady state equilibrium condition [12].

Power system stability can be modeled as a second order nonlinear differential equation known as swing equation, given in Eq.1 [7].

$$M\frac{d^2\delta}{dt^2} = P_m - P_e \text{...(1)}$$

$$\text{Electrical power, } P_e = \frac{\left|E'\right|\left|V\right|}{X_T}\sin\delta \text{................................(2)}$$

$$\text{Angular momentum, } M = \frac{GH}{\pi f} \text{......................................(3)}$$

δ = Rotor angle

P_m = Mechanical power input

E = Excitation voltage

V = Infinite bus voltage

X_T = Transfer reactance

H = Inertia constant

G = Machine rating

f = freuency of the system

Transient stability is included in large signal analysis. In this type of analysis, the system is analyzed for its stability following large and sudden disturbances like short circuits, fault clearing, sudden change in load etc. Transient stability analysis is carried out for short durations of around 1s where nonlinearities of the system cannot be neglected. Hence nonlinear mathematical models need to be considered for the analysis. After a disturbance, if the system rotor angle δ goes through a maximum value and starts to reduce, the system is regarded as stable. It is unstable if the rotor angle continues to increase.

III. TRANSIENT STABILITY STUDIES USING MATLAB

Transient stability studies based on swing equation is presented in this section. Fig.1 shows MATLAB SIMULINK modeling of swing equation.

System inputs are mechanical power - P_m, excitation voltage - E, infinite bus voltage - V and system transfer reactance - X_T. Outputs are acceleration power - P_a, rotor acceleration - α, relative rotor speed - $\Delta\omega$ and rotor angle - δ. Various disturbances were introduced to understand the stability characteristics of the system.

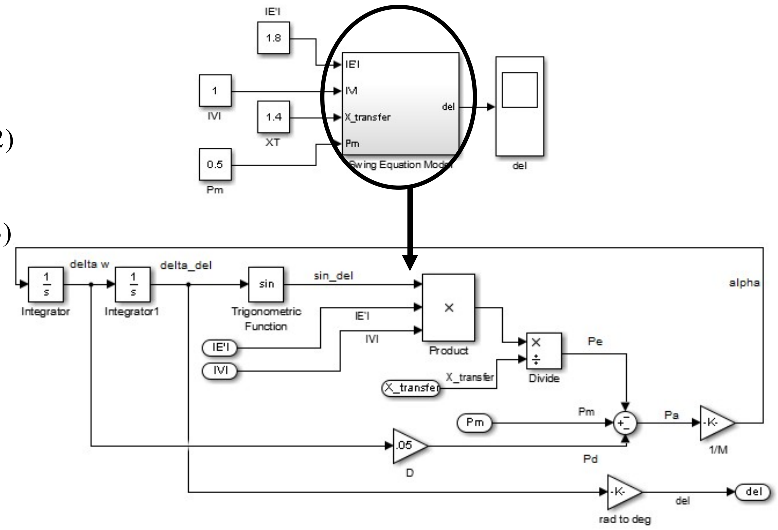

Fig. 1 Swing equation model of power system.

System parameters are:

$$P_m = 0.5\,pu,\; E = 1.8\,pu,\; V = 1\,pu,\; X_T = 1.4\,pu$$

Fig.2 and Fig.3 show the effect of three phase fault at the end of a line of a double circuit transmission system.

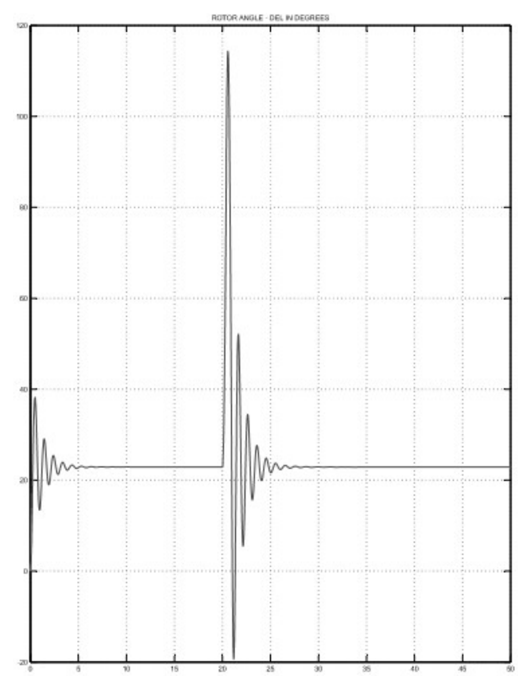

Fig. 2 Stable system with clearing time of 20 cycles.

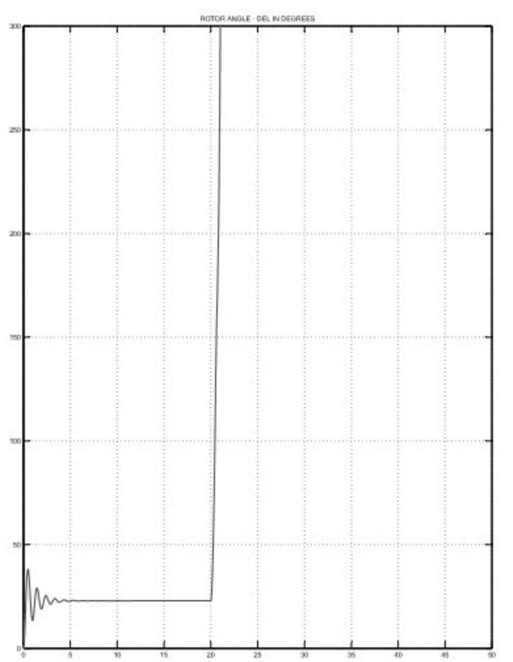

Fig. 3 Unstable system with clearing time of 25 cycles.

Initially, rotor angle stabilizes to the initial stable rotor angle. A disturbance in the form of short circuit occurs at 20s. In the first case, fault persists for 20 cycles and in the second case, it exists for 25 cycles. From Fig.3, it is observed that the system becomes unstable when the fault is cleared after 25 cycles, since the rotor angle continuously increases.

IV. Implementation of SMIB Using MULTISIM

In this work, SMIB is implemented as an analog emulator, where fundamental building blocks are developed with analog circuits representing mathematical operations and functions. The model includes second-order dynamics and damping. To create a fault so as to study the transient behavior of SMIB, a switch is introduced in the model. The analog circuit for the single-machine power system consists of four Operational Transconductance Amplifiers, a trigonometric converter, resistors, and capacitors, as seen in Fig.4.

Input to the analog emulator is a voltage V_m that represents mechanical power input P_m. It is converted to a current I_m. Current I_e, that represents electrical power P_e, is subtracted from I_m and fed to a double integrator to obtain voltage V that represents rotor angle δ**.** This is fed to a trigonometric block to obtain $\sin\delta$ which is in turn used to generate I_e.

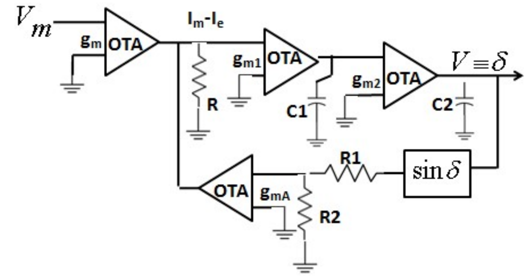

Fig. 4 Analog circuit of SMIB

Resistor R scales down the input of the double integrator from current to voltage. Resistors R_1 and R_2 are used as voltage divider to scale the input of OTA_{ma}. C_1 and C_2 determine the integration time of the circuit. They decide the computational speed up of the emulator. Multisim simulation model of the above circuit is given in Fig.5. The double integrator part is unmasked to show the connections. Various parameters and scaling factors used for the emulation are:

$C_1 = C_1 = 100nF$,

$g_{mA} = 0.0130$

Circuit scaling parameter : $K_p = 10^{-4}$

Double integrator gain : $g_{m1} = g_{m2} = 0.02184$

Time scaling parameter : $\tau = 5 * 10^3$

Use of scaling factors like parameter scaling and time scaling gives good flexibility for analog emulators. Scaling factors are constants that correlate the real world power system parameters and variables to that of the analog emulator. Using parameter scaling various physical real world quantities like power and rotor angle, are converted to emulator quantities like voltages. Time scaling allows the analog emulator to be faster or slower than the real system.

Integrated circuits used for the analog SMIB model are LM13700M (Operational Transconductance Amplifier), AD639 (Universal Trigonometric Function Converter) and LT1014CN (Precision OpAmp). Fig.6 and Fig.7 shows the outputs obtained for the simulation.

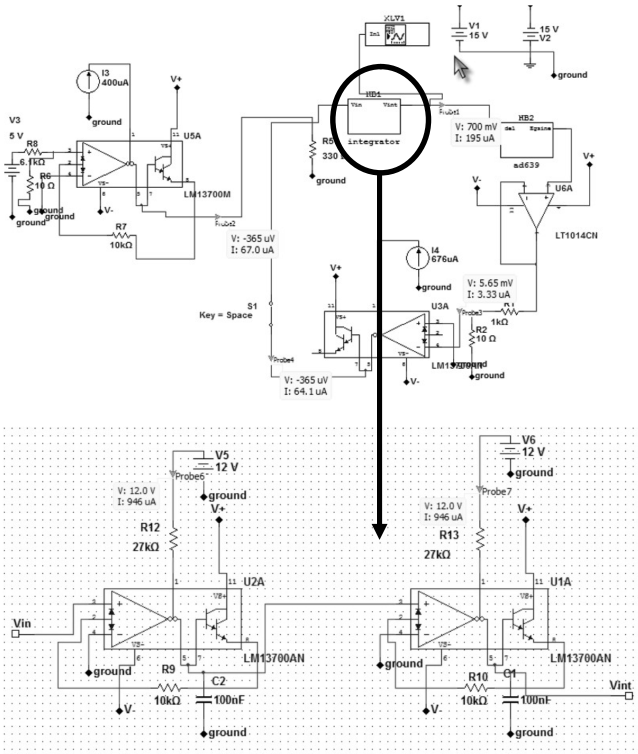

Fig. 5 Multisim model of SMIB

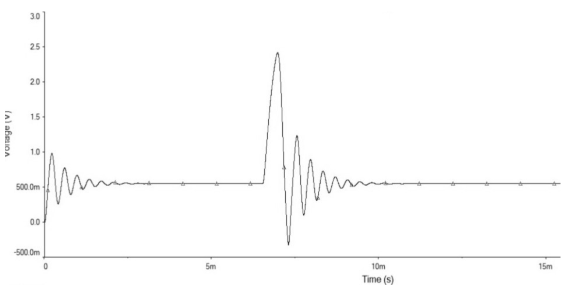

Fig. 6 Multisim simulation - Stable system with clearing of fault within critical clearing time

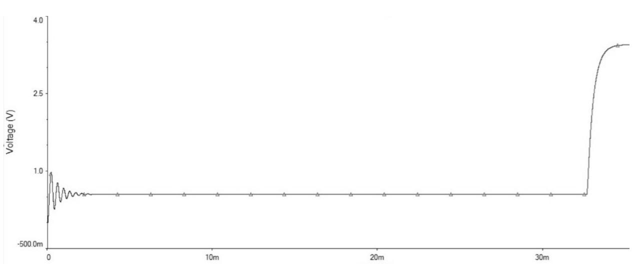

Fig.7 Multisim simulation-Unstable system with clearing of fault beyond critical clearing time

For the system considered with mechanical power input fixed to $0.5\,pu$, the transient response of the generator settling to the steady-state solution of the real world power system is given in Fig.8 and that for the analog emulator is given in Fig.9.

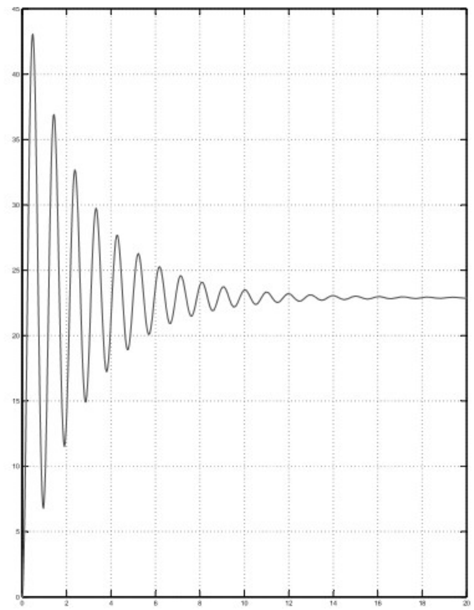

Fig.8 Real world power system-MATLAB simulation

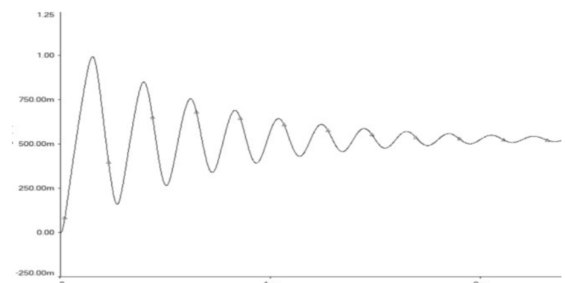

Fig.9 Analog Emulationof power system-Multisim simulation

From the above figures, it can be observed that for the selected τ , the analog emulator is 5000 times faster than the actual power system.

V. Hardware Implementation of SMIB

Operational Transconductance Amplifier (OTA) based analog SMIB emulator is implemented on bread board. OTA is used because of its ability to control its gain by an external current.OTA works as a current source with a finite transconductance gain, g_m, which is controllable through an external bias current.

It is given in Fig.10 and Fig.11 shows the transient response of the system settling to the steady state solution. The steady state solution obtained is same as that of the simulation study based on Multisim model. There is a discrepancy between software simulation and hardware results of the SMIB modeling the transient part due to offset present within the OTA.

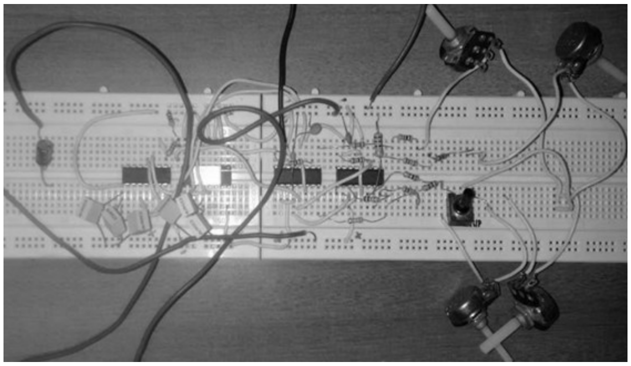

Fig.10 Hardware implementation of analog SMIB emulator

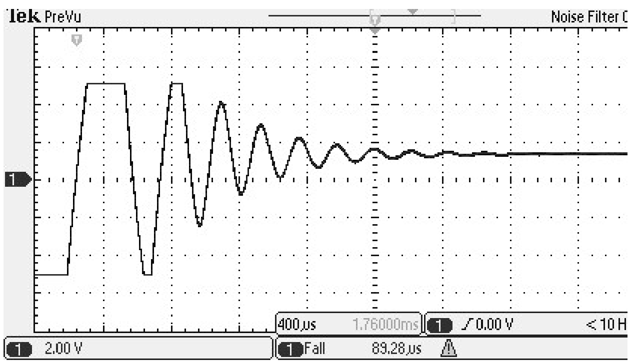

Fig.11 Transient response of SMIB emulator

Ideally, the desirable gain of an OTA, for a given bias current, would be constant, with a linear input-output relationship. Practically, this is not the case. External circuits including trimmers, compensators, and feedback circuits have to be incorporated, to avoid this problem. The design and implementation of these circuits are in progress.

VI. Conclusion

In this paper, an analog emulator of a SMIB is presented. The emulator can be used to study transient stability of a power system. The system was designed and simulated using Multisim software. Results were compared with that of a MATLAB simulation representing a real power system. Hardware of the system was implemented using OTAs, trigonometric converters, resistors and capacitors. The emulator incorporates time scaling that allows the emulator to provide solutions faster than real time solutions. This is useful in case of quick decisions like contingency analysis. The emulator can be used as a trainer simulator for students of undergraduate level.

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