Automatic Governor for Tie-line Control : A Teaching Tool

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***Abstract*—Power transmission between interconnected systems is a major concern in the present electrical engineering context and is of utmost importance to Electrical Engineering undergraduates. A voltage scaled power system simulator with two interconnected areas has been designed, for educational purposes, using vacuum circuit breakers, a diesel generator, a motor-generator set, transmission lines, bus bars, loads etc. Synchronization of two areas and a power controller of the tie line between the two areas have been implemented. In addition, students can learn about different interactions, such as synchronous and isochronous operation of generators with large systems. This paper finally discusses the possible experiences of interconnected power systems that undergraduate students could be exposed to.**

***Keywords*— Power System Simulator; Synchronous; Isochronous; Governor; Transmission; Inter-connected Systems; Tie-Line Power; VFD**

I. INTRODUCTION

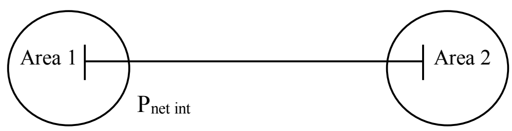
A power system plays a major part in social, economic and industrial development of a country. It is important for Electrical Engineering undergraduates, as future engineers, to study about power systems in both theoretical and practical approaches [1]. Constructing a Power system simulator inside the Electrical Engineering department was done with the purpose of providing the practical experience to the undergraduates about the real power system. This Power system simulator is a voltage scaled model of a part of the power system which has been constructed using real vacuum circuit breakers, transformers, generators, relays and other equipment. An operating voltage of 110V has been used for safety.

Though power system simulation software such as HYPERSIM Power System Real-Time Digital Simulator [2], PSMS™ [3], and PSCAD are available to simulate power systems, students can't get the hands on experience about the operation of the real power systems. Power system simulator which is developed in the university premises will give the students the practical knowledge about the operation of the power system. Students would be able to get familiar with each component of the power system simulator which is an advantage over the power system simulation software. There are number of real power system models developed in the world such as PST 2200 [4] power system simulator laboratory to offer a good experimenting environment. It won't be financially feasible to implement that type of a simulator in University of Moratuwa.

This paper presents the implementation of the automatic governor for tie line power flow control, which has extended the capacity of doing experiments using the power system simulator. It has given the opportunity to undergraduates to understand the theories and practical problems related with tie line power controlling between two areas. Also students will get a knowledge about the behavior of an integrated system.

For satisfactory operation of a tie line between two utilities as shown in fig. 1, the power flow in the tie line between the two areas should be controlled and the system frequency should be maintained within the allowed limits, despite of the changes in loads and generation.

This is achieved by control of the generation in each area. Governors are introduced to the generators to achieve these goals. Such a control system with two governors each with two inputs, the system frequency and the net power flow in the tie line perform the control action as illustrated in table 1.



ΔP_{L1} – Load change in area 1
ΔP_{L2} – Load change in area 2

Fig. 1. Two Area System

TABLE I - TIE-LINE FREQUENCY CONTROL ACTION FOR TWO AREA SYSTEM [5]

$\Delta\omega$	$\Delta P_{net\ int}$	Change of the load	Control Action
+	+	ΔP_{L1} – ΔP_{L2} 0	Decrease P_{gen} in system 1
–	–	ΔP_{L1} + ΔP_{L2} 0	Increase P_{gen} in system 1
+	–	ΔP_{L1} 0 ΔP_{L2} –	Decrease P_{gen} in system 2
–	+	ΔP_{L1} 0 ΔP_{L2} +	Increase P_{gen} in system 2

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II. POWER SYSTEM SIMULATOR

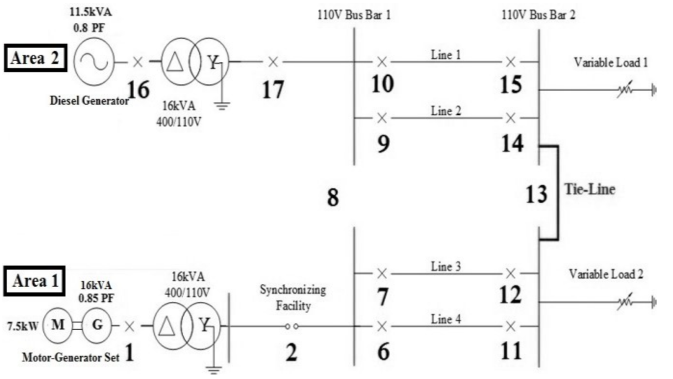

Fig. 2. Single Line Diagram of the Power System Simulator with Tie-Line Control Mode

In the Power System Simulator, shown in Fig. 2, there are 17 vacuum circuit breaker panels, incorporated with relays and these panels are connected using high current cables.

The power system simulator is divided into two areas using a tie line with breaker 13 at one end to separate the two utilities.

In one area a 16 kVA synchronous generator driven by an induction motor is connected, and in the other area an 11.5 kVA diesel generator is connected as the source of power. The motor-generator set is controlled through a variable frequency drive and the governor action is obtained using the programming facility Arduino Due. Two generator transformers (16kVA, 3 phase, 400V/110V, Dyn11, 50 Hz) convert the generated voltage to the 110V voltage of the power system simulator which has four scaled transmission line models constructed with wire wound inductors and capacitors.

III. GOVERNOR OF THE MOTOR GENERATOR SET IN AREA 1

A. Design of a Load Bank

The Loading of the Power System Simulator (PSS) is done using load banks. A simple controllable load bank was designed and constructed to meet the requirements. Since the system needs to be loaded to at least 20% capacity, a load exceeding 2.5 kW is needed.

Since the PSS accommodates loads at 3phase, 110 V, the design had this as a main constraint. Thus, a 4.5 kW load bank was designed with the use of 9 Nos. of 0.5 kW, 110V Halogen lamps. Three lamps are connected in delta arrangement to give three 1.5 kW 3phase loads, which can be switched separately as shown in Fig. 3.

The three phase electronic energy meters, obtained for the power measurement in the two areas and in the tie line, had meter constant of 400 impulses/kWh.

$$\text{Time between two impulses} = \frac{1}{400} \times 3600\ \text{s/kW}$$
$$= 9\ \text{s/kW}$$

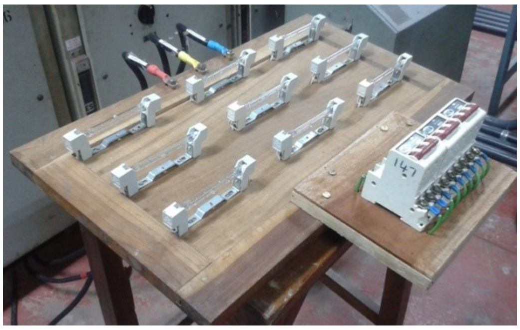

Fig. 3. 3-phase Halogen Lamp Load

Thus for a 2.5 kW load, time between 2 successive impulses is 3.6 s. Thus a minimum time of 3.6 s would be required to measure power immediately when the load varies.

B. MATLAB Simulation of Isochronous Governor Mechanism

When implementing the isochronous governor mechanism, first a MATLAB simulation was carried out using typical values for generator time constant, turbine time constant and damping constant since it is difficult to find the actual values [6]. Fig. 4 illustrates the MATLAB block diagram which was used or the simulation of isochronous operation. When a step load increase is applied at t=10s, the change in system frequency is obtained as shown in the Fig. 5.

C. Implementation of Isochronous Governor Mechanism in Area 1

As the prime mover of Area 1 is an induction motor controlled through a variable frequency drive (VFD), in order

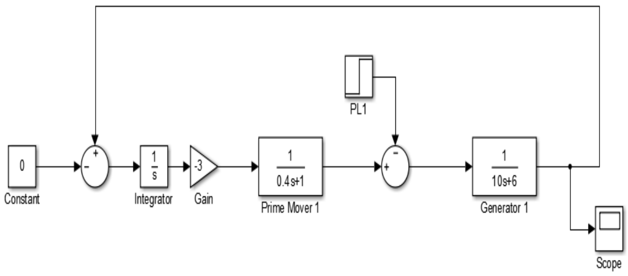

Fig. 4. Matlab Block Diagram for Isochronous Governor

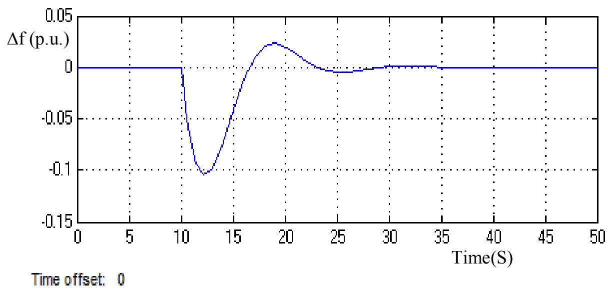

Fig. 5. Simulated Frequency Response

to control the output of the synchrnous generator, the VFD has to be controlled. The rotor speed of the synchronous generator is obtained through a rotary encoder (OMRON E6B2-CWZ6C Rotary Encoder) which is coupled to the generator shaft. An Arduino Due programming environment is used which outputs the control signal to the VFD. The arrangement of the equipement in the motor-generator set is shown in Fig. 6.

When the generator is running at synchronous speed, a 4.5 kW load is switched on at t = 9s and it is switched off at t = 26s as shown in Fig. 7.

When the load is switched on, the system frequency drops along with the speed of the synchronous generator. Speed is sensed by the rotary encoder and it is read by the Arduino program. Then, a voltage proportional to the reduction of speed is applied to the VFD which ultimately controls the induction motor (prime mover). With the voltage input, the power output of the induction motor starts to increase which in turn reduces the rate of decrease of speed. When the power output of the induction motor exceeds the load power, speed starts to increase and finally returns to its reference value and reaches steady state.

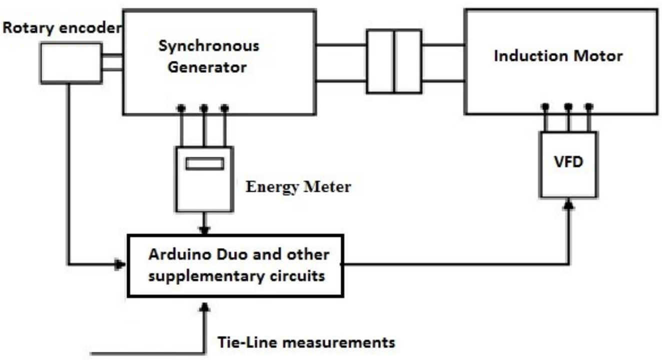

Fig. 6. Arrangement of Equipment in Motor-Generator set

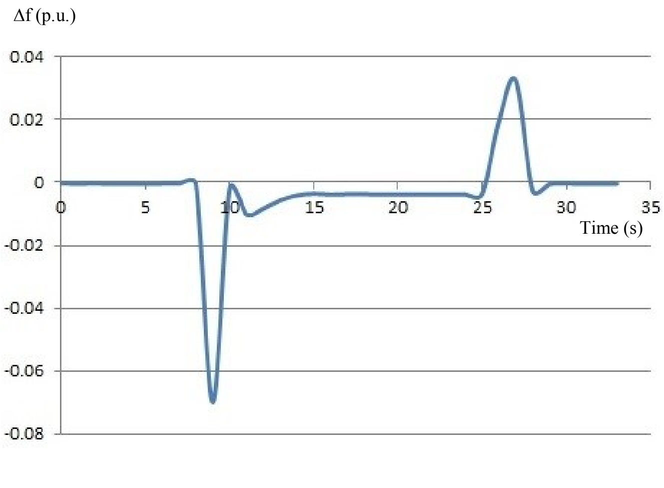

Fig. 7. Actual Frequency Response of the Governor

Laboratory experiments on isochronous and synchronous governor operation of synchronous generator are provided using motor-generator set in area 1. For a step load change, the frequency variation depends on the parameters of the control block diagram of isochronous operation. Undergraduates can observe how frequency varies with the change of these parameters, which is also helpful in understanding control systems theories.

With the droop characteristics introduced using programming facility, undergraduates are exposed to the relationship between the power and frequency of the synchronous governor.

IV. Diesel Generator Side Governor in Area 2

As the second generating unit, a single phase, 11.5kVA, 0.8 PF diesel generator was available. As the PS simulator is three phase, a winding conversion to 3-phase was done, as shown in Fig. 8 as this generator had this facility.

A. Cable Selection

As the PS simulator is designed to withstand full voltage short circuits, the cable had to be properly rated. The cross section of the power cable connecting diesel generator and the existing power system simulator is an important factor which determines the current carrying capacity. To calculate the optimal cross section of the cable, calculation was done considering both the minimum cross section required to withstand fault current for 1 second and minimum cross section required to withstand the normal continuous current.

Rated current $(I_B) = \frac{11.5 * 10^3}{\sqrt{3} * 400} = 16.59$ A

Using correction factors at 30° C of $C_a = 1$, $C_g = 0.873$, $C_i = 1$

Derated current rating for cable $= \frac{I_B}{C_a * C_g * C_i} = 19.0$ A

Theoretical minimum short circuit withstand cross section $= \sqrt{\frac{I^2 * t}{k^2}} = \sqrt{\frac{587.6^2 * 1}{115^2}} = 5.11\ \text{mm}^2$

Maximum permissible voltage drop $V_{d,max} = 2.5\% = 5.77$ V

Since the actual length of cable from breaker to diesel generator is 40m, for a current of 16.59A, the maximum allowable voltage drop per meter per ampere should be less than

$$\frac{5.77 * 10^3}{16.59 * 40} = 8.695\ \text{mV/A/m}$$

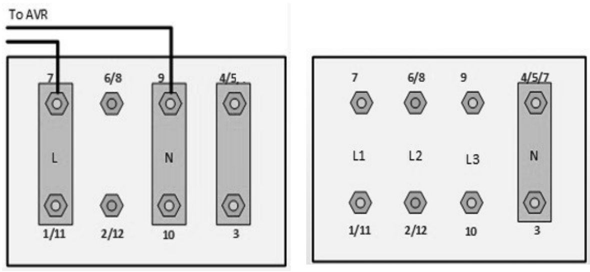

Fig. 8. Winding Conversion Before And After

From standards, for the selected installation method and an Aluminum/XLPE/PVC insulated cable, a cross-section of 16 mm^2 satisfies this criteria and has a voltage drop of 2.8 mV/A/m [7].

B. Implementation of Isochronous Governor Mechanism for the Diesel Generator in Area 2

The engine governor controls engine speed according to the fluctuations of the load connected to it. To meet the requirements of the automatic governor for tie-line controlling, the existing mechanical governor of the diesel generator was replaced by an electronic governor designed to give the required droop by controlling the fuel flow rate using a servo motor.

V. TIE-LINE CONTROL GOVERNOR

Power transmission from one area to the other area through the tie line is controlled by the tie line control governor. It acts as a frequency controlling governor for each area. Two generators which are currently connected to the power system simulator are governed by its action (i.e. frequency control generators). Each of the two generators' surplus power capacities after serving loads, will act as control reserves for each area respectively. In a situation of more distributed generators addition in each area, their surplus power capacities will act as dispatchable reserves while part of its capacity is consumed by loads. If load change in each area is below its control reserve (i.e. the surplus power capacity of the generator which is governed by tie-line control governor) the total load change is taken by that frequency controlling generator. If load change is higher than its control reserve the dispatchable generators will be manually dispatched according to a dispatch plan which is constructed considering availability of generators, economy, etc. until balance load change can be borne by frequency control generator. Therefore following analysis and implementation of tie line control governor in a power system simulator which only have frequency controlling generators in each area will be valid for more distributed generators attached systems also.

A. Synchronization of the Two Areas

It is necessary to synchronize the two islands as the tie line controlling has to be carried out.

Fig. 9 shows the synchronization facility between the two areas, with details around the synchronizing breaker being detailed in 3 phase.

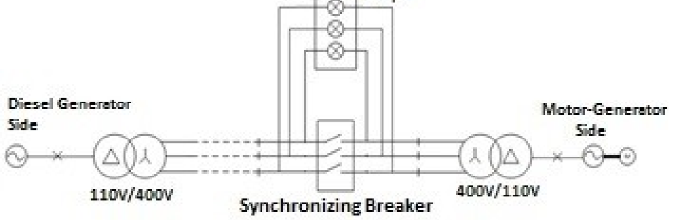

Fig. 9. Synchronization of Two Areas

The excitation voltage of the AVR of the motor-generator set is adjusted so that voltage magnitude of the breaker at motor-generator side is closely matched to breaker terminals coming from diesel generator side. Synchronization has been implemented at 110V level, rather than at the generator voltage of 400V, considering the safety of the students operating this synchronizing facility.

Frequency and the phase angle equalization process has been achieved through the aid of three dark lamp method shown in Fig. 10. This method has been used because it illustrates the principle of synchronization well to the student.

During the synchronization process the speed of the diesel generator is increased or decreased by adjusting load reference setting of the diesel generator, until the frequency of two areas are close to each other. This can be observed through the three lamps being brighten and darken slowly. And breaker is closed when all three lamps are darkened (Phase angles are also equalized now). To avoid slipping of the poles, the breaker is closed when the three lamps are almost stabled in dark.

With the interconnected generators each operating in synchronous mode, load sharing depends upon the droop characteristic of each governor. Undergraduates are provided with the opportunity to observe load sharing and its behavior using a controllable droop setting.

B. Modeling of the Tie-Line Control Governor

Fig. 11 illustrates the incremental model of the synchronized two areas connected with tie line which is governed by only droop characteristics of the two generators.

Fig. 10. Synchronizing Breaker

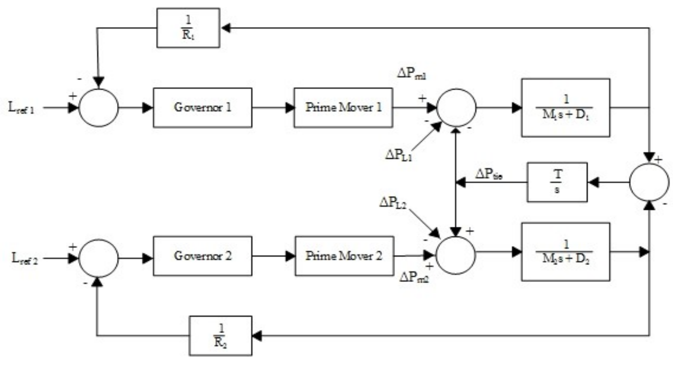

Fig. 11. Block Diagram of Tie-Line Control

This is called as primary control. There is no control over the tie line power and frequency but the balance of the generation and load exists.

If a load deviation of ΔP_L occurs in the system area 1, at steady state the frequency deviation Δf from rated value is equal in the two areas and the Tie line power flow deviation ΔP_{Tie} can be simplified to give [5] as equation (1) and (2).

$$\Delta f = \frac{-\Delta P_L}{D_1 + D_2 + \frac{1}{R_1} + \frac{1}{R_2}} \quad (1)$$

$$\Delta P_{Tie} = \frac{-(D_2 + \frac{1}{R_2})\Delta P_L}{D_1 + D_2 + \frac{1}{R_1} + \frac{1}{R_2}} \quad (2)$$

The modeling is done near nominal operating point and for small deviation from nominal values which is similar to the case of power system simulator implementation of tie line controlling. Therefore it allowed to assume each system as first order system and also to deal with power and voltage separately.

C. Modeling Calculations for the Step Changes

Sample calculation for a load increase of 2kW ($=\Delta P_L$)

$$\Delta f = \frac{-2}{0.6 + 0.9 + \frac{1}{0.2} + \frac{1}{0.1}} = -0.12\text{Hz}$$

$$\Delta P_{Tie} = \frac{-(0.9 + \frac{1}{0.1}) \times 2}{0.6 + 0.9 + \frac{1}{0.2} + \frac{1}{0.1}} = -1.32\text{kW}$$

It can be seen in the Fig. 12 that with the increase of load, frequency deviation became higher. Also tie line power is reduced as it is feeding area 2 and now the area 1 needs to be fed by a fraction of that amount. Both the generators have increased the power generation to supply the extra load.

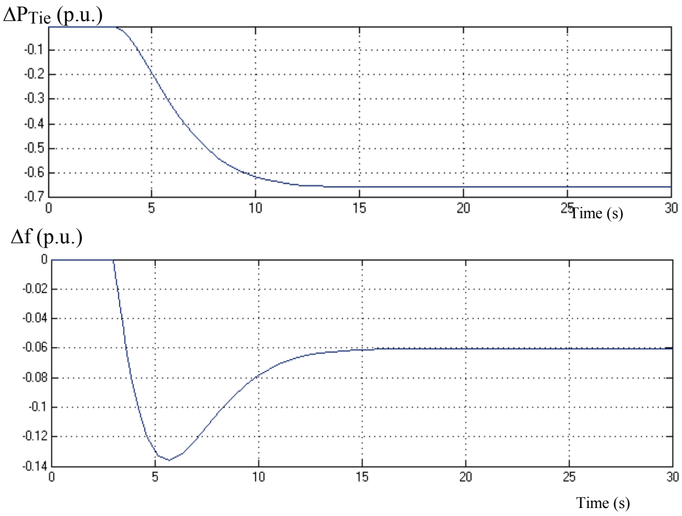

Fig.12. Variation of Frequency and Tie-Line Power

D. Introduction of Area Control

Use of area control in the power system simulator is to restore the balance between load and generation in each area [8]. Any increment or decrement of load is taken by generator in the respective area. For this, the control inputs are taken as change in frequency and change in tie line power. These two inputs are linearly related as Area Control Error (ACE) to load reference set point of each generator as equation (3) and (4).

$$\text{ACE}_1 = \Delta P_{Tie} + \beta_1 \Delta f \quad (3)$$

$$\text{ACE}_2 = \Delta P_{Tie} + \beta_2 \Delta f \quad (4)$$

β could be selected upon control requirement. As our motive is to restore balances in each area they are computed using equation (5) and (6).

$$\beta_1 = D_1 + \frac{1}{R_1} \quad (5)$$

$$\beta_2 = D_2 + \frac{1}{R_2} \quad (6)$$

Suppose there is a load change in the system area 1 as ΔP_L,

By substituting values for ΔP_{Tie} and Δf we get equation (7) and (8),

$$\text{ACE}_1 = \Delta P_L \quad (7)$$

$$\text{ACE}_2 = 0 \quad (8)$$

These settings are the inputs to load reference setting, ΔL which is initially set at 0.This will override the primary control frequency regulation action and stabilize the frequency at nominal value while maintaining the balance of each area. Fig. 13 shows the modeling of area control incorporated system.

Fig. 14 shows the responses of frequency and tie line power after implementation of the control in each areas to restore balances within each. Some oscillations around the rated values can be observed. These oscillations can be further minimized by introducing derivative control for the area control.

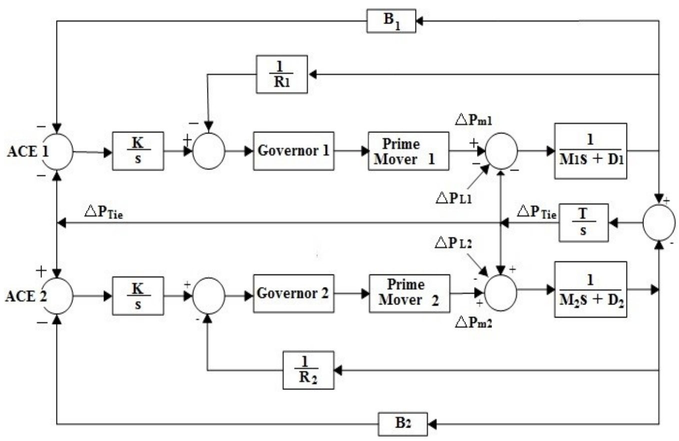

Fig. 13. Block Diagram for Tie-Line Bias Supplementary Control

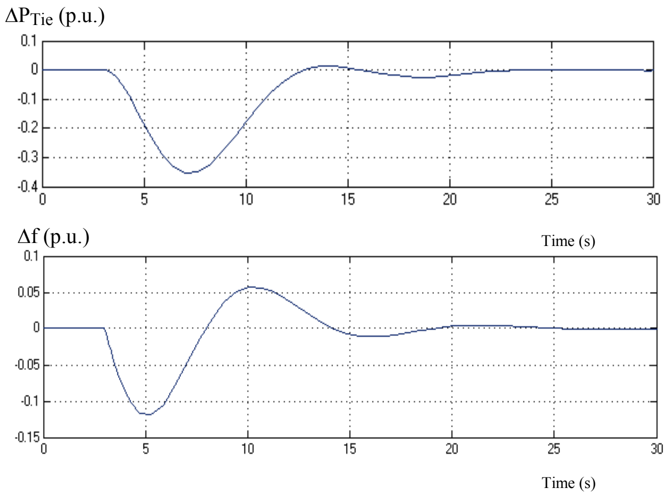

Fig. 14. Variation of Frequency and Tie-Line Power with AC

Laboratory experiments are introduced to give experience on how a load change in one area affect the other area, frequency variation of the total system and variation of the tie-line power with and without Area Control (AC). As future enhancements, attachment of more distributed generators to the power system simulator and development of a Graphical User Interface (GUI) for the loading of control parameters from a distant location are suggested.

VI. CONCLUSION

Modeling, analyzing and implementation of an automatic governor for tie-line control has been presented in this paper. Power system simulator where governor is implemented has been developed using a diesel generator, a motor generator set, transmission lines, bus bars, actual vacuum circuit breaker panels previously used in distribution substations, bus bars, loads etc. Wiring has been designed to withstand rated load currents as well as considering future expansions. Division of simulator in to two areas has been done using a tie line with a breaker at one end to have two separate utilities. Power transmission between the two utilities in the tie line is controlled and total system frequency is maintained within allowed limit. Undergraduates are given real experience on interconnected power systems' behavior and they are given chance to observe the system's responses to various changes of loads and control parameters. Laboratory experiments are designed to improve undergraduate interaction with the simulator. Simulator will serve as a useful tool for undergraduate students to study aspects of control systems as well.

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