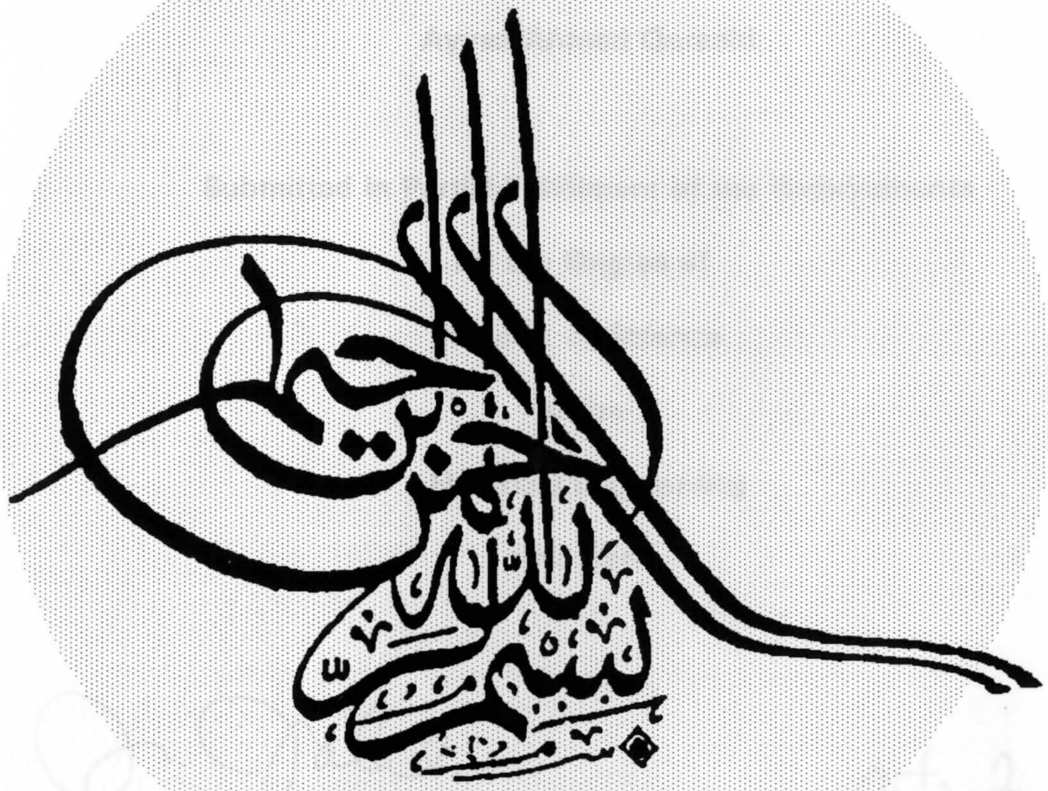

"... and say "O my Lord increase me in knowledge ..."

The Sublime Quran (20:114)

HARMONIC EFFECTS ON TRANSIENT STABILITY

BY

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ABSTRACT

Harmonic Effects On Transient Stability

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Master of Science, Electrical Engineering

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In this paper, the effects of harmonics on transient stability of an electrical power distribution system are studied for three-phase short circuit on different locations of the distribution system.

Harmonics decrease magnitude of voltage and increase magnitude of current of an electrical distribution system. The power flow program is executed so that the frequency, amplitude and phase shift of a particular harmonic could be studied. The Swing Equation and the Runge-Kutta method are used to determine the critical clearance angle and critical clearing time for the three-phase short circuit of the modeled distribution system. The abrupt operating characteristics of solid-state relays are used to prevent the deterioration in the system. The effects of 5th harmonic on an electric power system are reduced more than 20% by adding a double tuned filter, which improves the transient stability of the system.

ACKNOWLEDGMENTS

I would like to first extend my sincere thanks to Dr. Jalal Jalali, my mentor and thesis advisor, for giving me patience, understanding, constant support and countless hours of guidance, as I worked on my thesis project with him.

It is a pleasure to acknowledge and thank the committee members Dr. Salvatore R. Pansino and Dr. Philip C. Munro for reviewing my thesis. I would also like to take this opportunity to thank Anna Mae Serrechio, department secretary, who always is encouraging and takes time in helping all students in the Electrical Engineering Department.

My family deserves a special acknowledgment for their sacrifices, especially my sister, Mrs. Shagufta Anwar Qureshi. To her I express my deepest appreciation for the emotional support and understanding she so freely provided.

Finally, I dedicate my thesis to my parents: my father, (the late) Dr. Khurshid Ahmed Qureshi and my mother, Mrs. Hafeeza Begum Qureshi, whose loving and guiding force has supported me always and has given me strength to complete my studies.

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LIST OF SYMBOLS

SYMBOL	DEFINITION
E	Internal voltage of generator
E_{bus}	Total voltage at particular bus
E_p	Voltage at pth bus
f	Frequency (60 Hz)
G	Shunt conductance
H	Inertia constant of generator
H_{fv}	Voltage harmonic factor
I_{fi}	Current harmonic factor
I_1	Total current before fault
I_2	Total current during fault
I_p	Current at pth bus
I_{pq}	Current flow between bus p and bus q
I_{bus}	Total current on a particular bus
$J_{\alpha m}$	Total amount of inertia of rotating masses
P	Total real power
p.f	Power factor

$P_{ap.u}$ Rotor angular power, per unit

$P_{ep.u}$ Electric power output of generator plus electric losses, per unit

$P_{mp.u}$ Mechanical power supplied by prime mover minus mechanical losses, per unit

P_g Real power of generator

P_l Real power of load

P_p Real power present at pth bus

P_{gp} Real generating power flows into pth bus

P_{lp} Real load power flows out of pth bus

P_{tp} Real transmitted power flows out of pth bus

Q Total reactive power

Q_g Reactive power of generator

Q_l Reactive power of load

Q_p Reactive power present at pth bus

Q_{gp} Reactive generated power flows into pth bus

Q_{lp} Reactive load power flows out of pth bus

Q_{tp}	Reactive transmitted power flows out of pth bus
S_p	Complex power flowing into the pth bus
T_a	Net accelerating torque of generator
T_e	Electrical torque for the total three phase electrical power output of generator, pulse electrical losses
T_m	Mechanical torque supplied by prime mover minus retarding torque due to mechanical losses
w	Angular frequency
w_m	Rotor angular velocity, rad/s
$w_{m\ syn}$	Synchronous angular velocity of rotor
X	Reactance
Y_{pq}	Line admittance
Y'_{pq}	Total line charging admittance
Y_{bus}	Bus admittance matrix
Z_{bus}	Bus impedance matrix

GREEK LETTERS

α_m	Rotor angular acceleration, rad/s
α	Control angle or delay angle
μ	Overlap angle
δ	Rotor angle
δ_m	Rotor angular position with respect to a synchronous rotating reference
Θ_m	Rotor angular position with respect to a stationary axis

LIST OF FIGURES

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CHAPTER I

POWER SYSTEM

1.1 OVERVIEW

The main purpose of this research is to find the effects of harmonics (especially the 5th harmonic) on the transient stability and to find the filter's values which can suppress the harmonics generated by the ac/dc converter, and keep the network in the stable condition during the fault.

This paper is divided into six chapters to discuss the details of the research.

1) This chapter explains the background of power distribution system and the power flow program.

2) Chapter #2 explains the transient stability and the swing equation. It also discusses the Runge-Kutta method to find the critical clearance angle for swing equation, which is very important for transient stability.

3) Chapter #3 explains the three-phase short circuit and the calculations for transient stability. The calculations involve the Thevenin equivalent circuits.

4) Chapter #4 explains the production of harmonics by the ac/dc converter, and also discusses the overlap and delay angle due to commutator.

5) Chapter #5 explains about filters and how to find the values of certain

filter for certain harmonic.

6) Chapter #6 explains the results, in the form of tables and graphs, of the research.

1.2 INTRODUCTION

An electric power system can be defined as a network of interconnected components which convert non-electrical energy continuously into the electrical form, transmit the electrical energy over potentially great distances, transform the electrical energy into a specific form subject to close tolerances, and convert the electrical energy into a useable non-electrical form. The major elements of a power distribution are shown in figure 1.2.1

1.3 GENERATOR

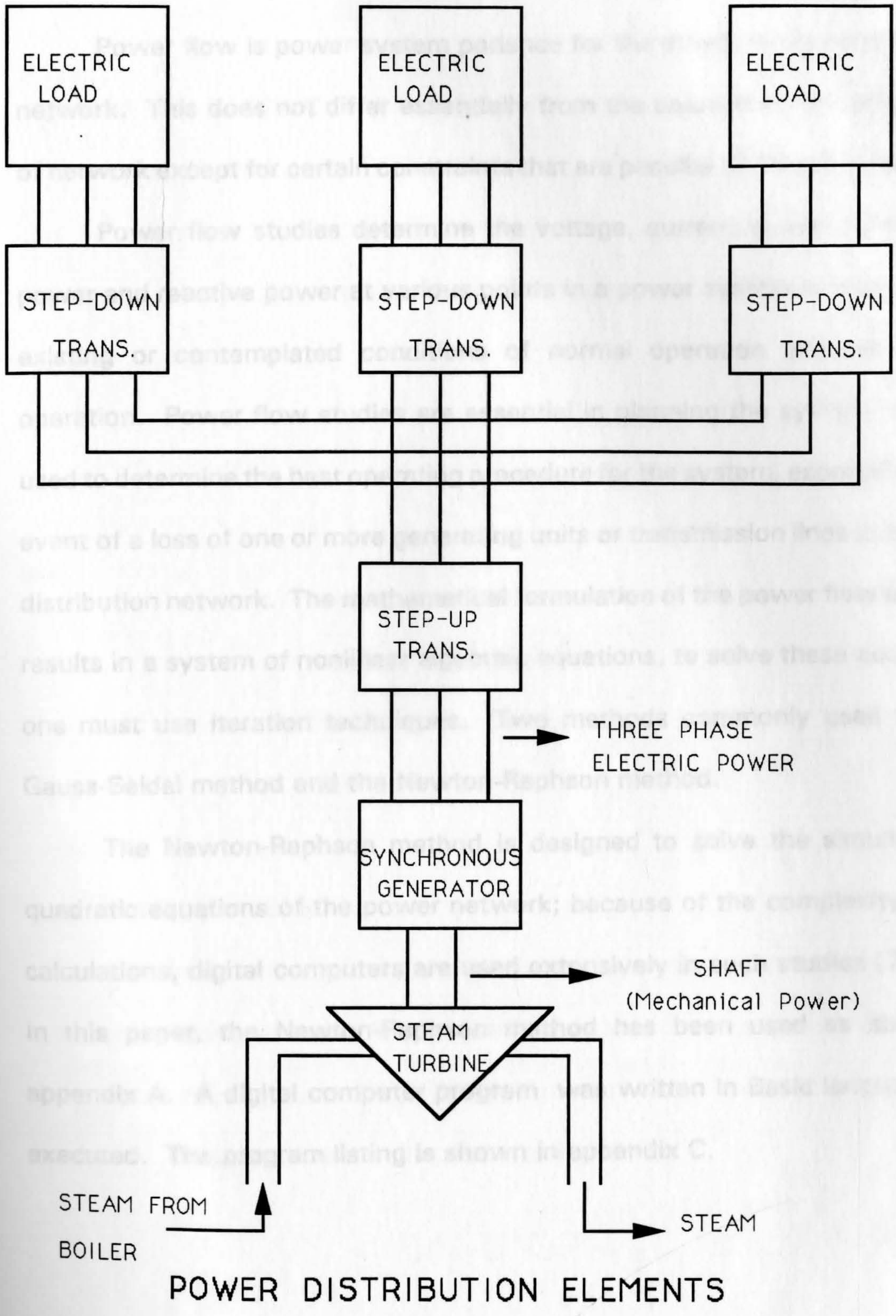
The main purpose of the generator is to convert mechanical power into electrical power, usually in the form of three-phrase electricity. Nearly all generators are operated in a manner that will produce voltages that vary sinusoidally with respect to time. The generator output power is a function of the mechanical power applied to its shaft, which also is a function of the rotor angle that the field poles maintain relative to the revolving magnetic field in the stator. In a power system, all generators are electrically connected. The system frequency and voltage are determined by the combined action of all the generators. The total real output power of two synchronous generators is given by

$$P=\frac{E_1 \times E_2}{X}\sin\delta \qquad (1.3.1)$$

And the total reactive output power is given by

$$Q=E_1 \times E_2 \times \cos\delta - \frac{|E_1|^2}{X} \qquad (1.3.2)$$

E_1 and E_2	internal voltages of two generators
δ	phase difference of these voltages
X	reactance



POWER DISTRIBUTION ELEMENTS

FIGURE 1.2.1

1.4 POWER FLOW

Power flow is power system parlance for the steady-state solution of a network. This does not differ essentially from the solution of any other type of network except for certain constraints that are peculiar to the power system.

Power flow studies determine the voltage, current, power factor, real power and reactive power at various points in a power system network under existing or contemplated conditions of normal operation and emergency operation. Power flow studies are essential in planning the system and are used to determine the best operating procedure for the system, especially in the event of a loss of one or more generating units or transmission lines in a power distribution network. The mathematical formulation of the power flow problem results in a system of nonlinear algebraic equations, to solve these equations, one must use iteration techniques. Two methods commonly used are the Gauss-Seidal method and the Newton-Raphson method.

The Newton-Raphson method is designed to solve the simultaneous quadratic equations of the power network; because of the complexity of the calculations, digital computers are used extensively in such studies [7,9,10]. In this paper, the Newton-Raphson method has been used as shown in appendix A. A digital computer program was written in Basic language and executed. The program listing is shown in appendix C.

1.5 POWER SYSTEM EQUATIONS

a) NETWORK PERFORMANCE EQUATIONS

Equations to describe the performance of the network of a power system can be developed by using the bus admittance matrix (Y_{bus}) or the bus impedance matrix (Z_{bus}) representation of the network. The nodal analysis approach yields:

$$E_{bus}=Z_{bus}\times I_{bus} \qquad (1.5.1)$$

and

$$I_{bus}=Y_{bus}\times E_{bus} \qquad (1.5.2)$$

b) BUS EQUATIONS

In power flow problems, there are four quantities associated with each bus given in the network. Any two of the four will be independent variables to be specified, whereas the other two remain to be determined. The real power and reactive power at any bus p are given by

$$P_p-jQ_p=E_p{}^*\times I_p \qquad (1.5.3)$$

and the current on the bus p is given by

$$I_p = \frac{P_p - jQ_p}{E_p^*} \qquad (1.5.4)$$

The complex power flowing into bus p is given by

$$S_p = (P_{pg} - P_{lp} - P_{tp}) - j(Q_{gp} - Q_{lp} - Q_{tp}) \qquad (1.5.5)$$

c) LINE FLOW EQUATIONS

After the interactive solution of bus voltages is completed, line flows can be calculated. The current on the line connecting between bus p and bus q is given by

$$I_{pq} = (E_p - E_q) \times (Y_{pq} + E_p) \times (Y'_{pq}) \qquad (1.5.6)$$

The real and reactive power flows on the line connecting bus p and bus q are given by

$$P_{pq} - jQ_{pq} = E_p^* \times I_{pq} \qquad (1.5.7)$$

1.6 DISTRIBUTION SYSTEM

In order to study the harmonic effects on the transient stability of a power system network, it is important to establish the mathematical model for the components of the power system. Transmission lines are represented by single phase equivalent pi models. The system is assumed to be three-phase, steady-state, completely symmetrical and balanced. All the input data should be given per unit on the common system MVA base.

To study transient stability in a network, it is necessary to find voltage, current and power on each bus and transmission line. This can be achieved by solving the power flow equations.

1.7 POWER FLOW CALCULATION

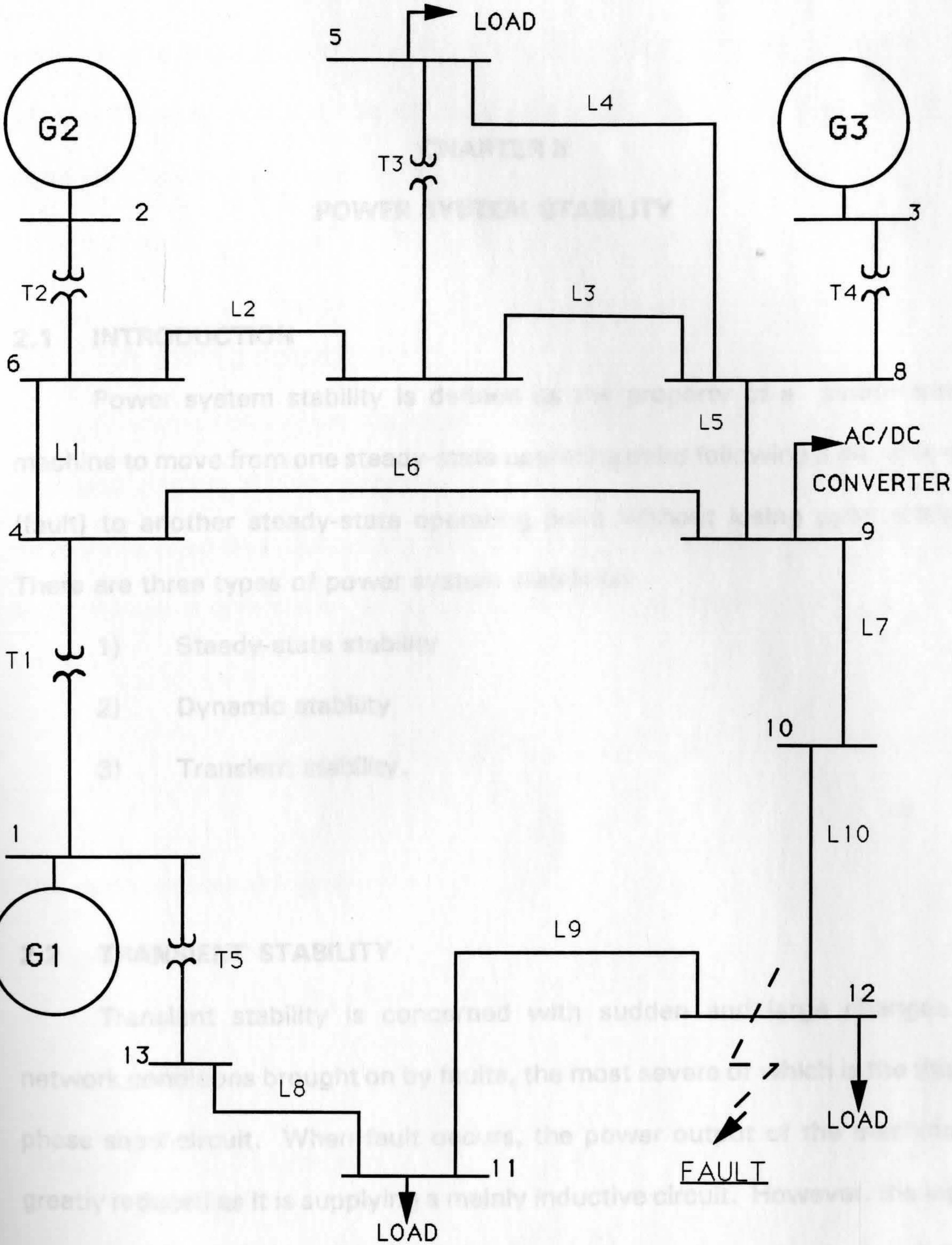
In this paper, the Newton-Raphson method has been used to calculate the voltage, current and power of buses and lines. The reactive elements of the power system are directly or inversely depending on the frequency, e.g., the transmission line's impedance is given by

$$X_c = \frac{1}{2\pi fc} \qquad (1.7.1)$$

$$X_l = 2\pi fL \qquad (1.7.2)$$

The admittance or impedance of a system varies with frequency. Therefore, it is necessary to compute the admittance or impedance matrix for each harmonic separately.

A 13-bus distribution system is assembled with three generating units connected to bus #1, bus #2, and bus #3. The ac/dc converter is connected to bus #9. Data for the system is given in appendix B. A one-line diagram of the system is shown in figure 1.7.1.



ONE LINE DIAGRAM OF 13-BUS TEST SYSTEM

FIGURE 1.7.1

CHAPTER II

POWER SYSTEM STABILITY

2.1 INTRODUCTION

Power system stability is defined as the property of a synchronous machine to move from one steady-state operating point following a disturbance (fault) to another steady-state operating point without losing synchronism. There are three types of power system stabilities:

1) Steady-state stability
2) Dynamic stability
3) Transient stability.

2.2 TRANSIENT STABILITY

Transient stability is concerned with sudden and large changes in network conditions brought on by faults, the most severe of which is the three-phase short-circuit. When fault occurs, the power output of the machine is greatly reduced as it is supplying a mainly inductive circuit. However, the input power to the generator from the turbine does not have time to change during the short period of the fault and the rotor will gain speed to store the excess energy. If the fault persists long enough, the rotor angle will increase continuously and synchronism will be lost [8]. Transient stability studies are best performed with the use of the digital computer program as shown in appendix D.

2.3 THE SWING EQUATION

In order to determine the angular displacement between the machines of a power system during transient conditions, it is necessary to solve the differential equations describing the motion of the machine's rotor [8]. The rotor motion is determined by Newton's second law, given by

$$J_{\alpha m}(t) = T_m(t) - T_e(t) = T_a(t) \tag{2.3.1}$$

The rotor angular acceleration is

$$\alpha_m(t) = \frac{dW_m(t)}{dt} = \frac{d^2\theta_m(t)}{dt^2} \tag{2.3.2}$$

The rotor velocity is given by

$$W_m(t) = \frac{d\theta_m(t)}{dt} \tag{2.3.3}$$

The mechanical torque (T_m) and the electrical torque (T_e) are positive for generator operation. In the steady-state condition, the mechanical torque equals the electrical torque, the acceleration torque (T_a) is zero, thus the rotor acceleration (α_m) is zero; this results in a constant rotor velocity called synchronous speed. When the mechanical torque is greater than the electrical torque, the acceleration torque is positive and thus the rotor acceleration is positive; this results in increasing rotor speed. Similarly, when the mechanical torque is less than the electrical torque, the rotor speed is decreasing [8].

It is convenient to measure the rotor angular position with respect to a synchronous rotating reference axis instead of a stationary axis. Therefore, the equation is given by

$$\theta_m(t) = W_{m_{syn}}(t) + \delta_m(t) \tag{2.3.4}$$

Substitute equations (2.3.2), (2.3.3) and (2.3.4) into equation (2.3.1) and obtain

$$J\frac{d^2\theta_m(t)}{dt^2} = J\frac{d^2\delta_m(t)}{dt^2} = T_m(t) - T_e(t) = T_a(t) \tag{2.3.5}$$

To work with power rather than torque and normalized inertia constant, multiply equation (2.3.5) by the rotor angular velocity and divide by the three-phase voltampere rating of the generator. The equation is given by

$$P_{a_{p.u}}(t)=P_{m_{p.u}}(t)-P_{e_{p.u}}(t)=\frac{2H}{W_{m_{syn}}}W_{p.u}(t)\times\frac{d^2\delta_m(t)}{dt^2} \quad (2.3.6)$$

This equation is called the **Swing Equation** [8]. This is the fundamental equation that determines the rotor dynamics in transient stability studies. For more than one machine stability problem, however, numerical integration techniques can be employed to solve the swing equation for each machine.

a) NUMERICAL METHOD FOR SWING EQUATION

Given a first-order differential equation

$$\frac{dx}{dt}=f(x) \quad (2.3.7)$$

To calculate the slope at the beginning of the integration interval, from equation (2.3.7)

$$\frac{dx_t}{dt}=f(x_t) \quad (2.3.8)$$

The new value of the integration interval ($x_{t+\Delta t}$) is calculated from the old value of integration interval (x_t) by adding the increment of integration step (Δt). The equation is given by

$$x_{(t+\Delta t)} = x_t + \Delta t = x_t \left(\frac{dx_t}{dt}\right) \times \Delta t \qquad (2.3.9)$$

Euler's method is a simple integration technique used to find the slope. First, the slope at the beginning of the interval is calculated from equation (2.3.7) and is used to calculate a preliminary value of integration interval given by

$$\overline{x} = x_t + \left(\frac{dx_t}{dt}\right) \times \Delta t \qquad (2.3.10)$$

Next the slope at preliminary value of integration interval is calculated by

$$\frac{d\overline{x}}{dt} = f(\overline{x}) \qquad (2.3.11)$$

Then the new value is calculated using the average slope; this is given by

$$x_{(t+\Delta t)} = x_t + \frac{\frac{dx_t}{dt} + \frac{d\overline{x}}{dt}}{2} \times \Delta t \qquad (2.3.12)$$

To calculate the machine frequency and power angle, Euler's method is applied.

Use equation (2.3.6) to determine the slopes at the beginning of the interval:

$$\frac{d\delta_t}{dt} = w_t - w_{syn} \tag{2.3.13}$$

and

$$\frac{dw_t}{dt} = \frac{P_{a_{p.u}} \times w_{syn}}{2H \times w_{p.u}} \tag{2.3.14}$$

Next calculate the per unit accelerating power at the new power angle; the per unit radiance frequency is equal to radiance frequency divided by synchronous angular velocity of the rotor. By using equation (2.3.10), the values are

$$\overline{\delta} = \delta_t + \left(\frac{d\delta_t}{dt}\right) \times \Delta t \tag{2.3.15}$$

and

$$\overline{w} = w_t + \left(\frac{dw_t}{dt}\right) \Delta t \tag{2.3.16}$$

The slopes at the new power angle and new radiance frequency are calculated by using equation (2.3.6):

$$\frac{d\overline{\delta}}{dt} = \overline{w} - w_{syn} \tag{2.3.17}$$

and

$$\frac{d\overline{w}}{dt}=\frac{\overline{P}_{a_{p.u}}\times w_{syn}}{2H\times\overline{w}_{p.u}} \tag{2.3.18}$$

Applying equation (2.3.12), the new values at the end of the interval are:

$$\delta_{(t+\Delta t)}=\delta_t+\frac{\frac{d\delta}{dt}+\frac{d\overline{\delta}}{dt}}{2}\times\Delta t \tag{2.3.19}$$

and

$$w_{(t+\Delta t)}=w_t+\frac{\frac{dw_t}{dt}+\frac{d\overline{w}}{dt}}{2}\times\Delta t \tag{2.3.20}$$

Begin the procedure at t=0 by specifying the initial values of power angle (δ_0) and radiance frequency (w_0); continue iteratively until the specified final time, t=T, is reached.

2.4 THE RUNGE-KUTTA METHOD

There are several ways to solve for the power angle of the generator from the swing equation. The power angle is the most important variable for transient stability; it is often called the critical clearance angle. In this paper, the Runge-Kutta method [6] has been used to determine the critical clearance angle. In the Runge-Kutta method the changes in the values of the dependent variables are calculated from a given set of formulas that are expressed in terms of the derivative evaluated at predetermined points; this approach does not require repeated approximations. The changes in the internal voltage angles and machine speeds are determined as follows. Consider the first order differential equations in two variables x and y:

$$\frac{dx}{dt}=f(x,y) \qquad (2.4.1)$$

and

$$\frac{dy}{dt}=g(x,y) \qquad (2.4.2)$$

Start with known initial conditions of x, y and the increment of step time and determine:

$$K^0{}_1=f(X^0,y^0)\Delta t \qquad (2.4.3)$$

$$L^0{}_1=g(X^0,y^0)\Delta t \qquad (2.4.4)$$

$$K^0{}_2=f(X^0+\frac{1}{2}K^0{}_1,y^0+\frac{1}{2}L^0{}_1)\Delta t \qquad (2.4.5)$$

$$L^0_2 = g(x^0 + \frac{1}{2}K^0_1, y^0 + \frac{1}{2}L^0_1)\Delta t \tag{2.4.6}$$

$$K^0_3 = f(x^0 + \frac{1}{2}K^0_2, y^0 + \frac{1}{2}L^0_2)\Delta t \tag{2.4.7}$$

$$L^0_3 = g(x^0 + \frac{1}{2}K^0_2, y^0 + \frac{1}{2}L^0_2)\Delta t \tag{2.4.8}$$

$$K^0_4 = f(x^0 + K^0_3, y^0 + L^0_3)\Delta t \tag{2.4.9}$$

$$L^0_4 = g(x^0 + K^0_3, y^0 + L^0_3)\Delta t \tag{2.4.10}$$

Use these eight constants to estimate the change in x and y:

$$\Delta x^0 = \frac{1}{6}(K^0_1 + 2K^0_2 + 2K^0_3 + K^0_4) \tag{2.4.11}$$

$$\Delta y^0 = \frac{1}{6}(L^0_1 + 2L^0_2 + 2L^0_3 + L^0_4) \tag{2.4.12}$$

Update the values of t,x and y:

$$t^1 = 0 + \Delta t \tag{2.4.13}$$

$$x^1 = x^\circ + \Delta x^\circ \tag{2.4.14}$$

$$y^1 = y^\circ + \Delta y^\circ \tag{2.4.15}$$

Replace the old values of x and y with the new values of x and y and then recalculate the new values of K,L and the increment's values of x and y:

$$t^{k+1}=K\Delta t \tag{2.4.16}$$

$$x^{k+1}=x^{k}+\Delta x^{k} \tag{2.4.17}$$

$$y^{k+1}=y^{k}+\Delta y^{k} \tag{2.4.18}$$

CHAPTER III
SHORT CIRCUIT

3.1 INTRODUCTION

Short circuits occur in a power system when equipment insulation fails, due to system over voltages caused by lighting or switching surge or other to other mechanical causes. The resulting short circuit or "fault" current is determined by the internal voltages of the synchronous machines and by the system impedances between the machine voltages and the fault. Short circuit currents may be several orders of magnitude larger than normal operating currents.

3.2 THREE PHASE SHORT CIRCUIT

The current which flows in different parts of a power system network immediately after a fault differs from that flowing a few cycles later, just before circuit breakers are called upon to open the line on both sides of the fault. Both these currents differ from the current that would flow under steady-state conditions if the fault were not isolated from the rest of the system by the operation of the circuit breakers. Protective relay must be capable of discriminating between healthy and faulty sections of the network, in order to keep the disruption of the power supplies to a minimum. The incidence of a fault within a protection zone should result in high-speed operation of local relay, which then initiates the tripping of circuit breaker.

3.3 TRANSIENT STABILITY CALCULATION

A power system network runs in a steady-state condition until a fault occurs, when the system goes out of steady-state. To study the network operation during a fault condition it is necessary to calculate the Thevenin equivalent circuit of the system for three stages based on the location of a fault. Thevenin equivalent is a powerful circuit analysis tool which is based on the fact that any active linear network can be represented by a single voltage source equal to the open-circuit voltage across any two terminals, in series with the equivalent impedance of the network viewed from the same two terminals with all sources in the network inactivated [8,11].

The three stages are listed as

1) Before the fault
2) During the fault
3) After the fault

a) THEVENIN EQUIVALENT CIRCUIT BEFORE FAULT

Determine the maximum power of the generator; calculate Thevenin equivalent circuit and use the steady-state current and voltage from the power flow program.

$$P_e = \frac{EV_{bus}}{Z_{th1}} \sin\delta \tag{3.3.1}$$

The electric power is a sinusoidal function of the generator's power angle, delta. The angle of the generator's internal voltage is the initial value. The maximum power is obtained at delta equals to 90 degrees. If delta becomes larger than 90 degrees power output decreases and the generator becomes unstable and loses synchronism. The generator's internal voltage can be calculated from the equation:

$$E = V_{th} = V_{bus} + Z_{th1} I_1 \tag{3.3.2}$$

b) THEVENIN EQUIVALENT CIRCUIT DURING FAULT

Use the Thevenin equivalent circuit to find the maximum fault current and maximum electric power during fault. The power generated can be used to find the maximum fault current:

$$I_2=\frac{P_G}{V_{bus}(p.f)}\angle -\cos^{-1}(p.f) \qquad (3.3.3)$$

Generator's internal voltage and maximum electric power are calculated from the equations:

$$E=V_{th}=V_{bus}+Z_{th2}I_2 \qquad (3.3.4)$$

and

$$P_e=\frac{EV_{bus}}{Z_{th2}}\sin\delta \qquad (3.3.5)$$

c) THEVENIN EQUIVALENT CIRCUIT AFTER FAULT

The Thevenin equivalent current can be used to find the maximum electric power after the fault:

$$P_e=\frac{EV_{bus}}{Z_{th3}}\sin\delta \qquad (3.3.6)$$

3.4 FAULT CLEARANCE

In order to keep the system in the steady-state condition, the fault should be cleared in a very short time period (less than one second). As the fault duration increases, the risk of instability also increases. The critical clearing time is the longest fault duration and the critical clearance angle is the largest angle allowable for stability.

The Runge-Kutta method is used to determine the critical clearance angle for the Swing Equation. The variation of the Swing Equation then uses the value of critical clearance angle to predict the critical clearing time. The circuit breakers should open before the critical clearing time to make generator isolated from the faulted bus. The breakers used for the system in this paper are able to open in two-and-a-half cycles, when there is fault at bus #12. The circuit breakers open and reclose every two-and-a-half cycles to make sure that the fault has been cleared. If the fault is not cleared with-in a certain time period, the breakers remain open.

CHAPTER IV

HARMONICS

4.1 INTRODUCTION

With the advancement of semiconductor technology, more and more power electronic devices, such as static power converters, static Var compensators, etc., are used in industry. Most of these devices produce harmonic currents; these result in voltage and current distortion in the power distribution system [1,5,4].

Harmonics have been reported to cause operational problems over fifty years. Some of the major effects are:

1) Capacitor bank failure from dielectric breakdown or reactive power overload.
2) Interference with ripple control and power line carrier systems, causing mis-operation of systems which accomplish remote switching, load control and metering.
3) Over voltages and excessive currents on the system from resonance to harmonic voltages or currents on the network.
4) Dielectric breakdown of insulated cables resulting from harmonic over-voltages on the system.

5) Inductive interference with telecommunication systems.

6) Error in induction Kwh meters.

7) Signal interference and relay malfunction, particularly in solid-state and microprocessor controlled systems.

8) Interference with large motor controllers and power plant excitation systems.

9) Mechanical oscillations of induction and synchronous machines.

These effects depend on the harmonic source, its location in the power system, and the network characteristics that promote propagation of harmonics.

4.2 HARMONIC CURRENT DEVICE

The ac/dc converters are the main sources of the harmonic current at the present time. There are two basic types of large capacity static power converters that are widely used in industry, i.e, self-commutated and line-commutated converters [2,3,8].

a) LINE COMMUTATED CONVERTER

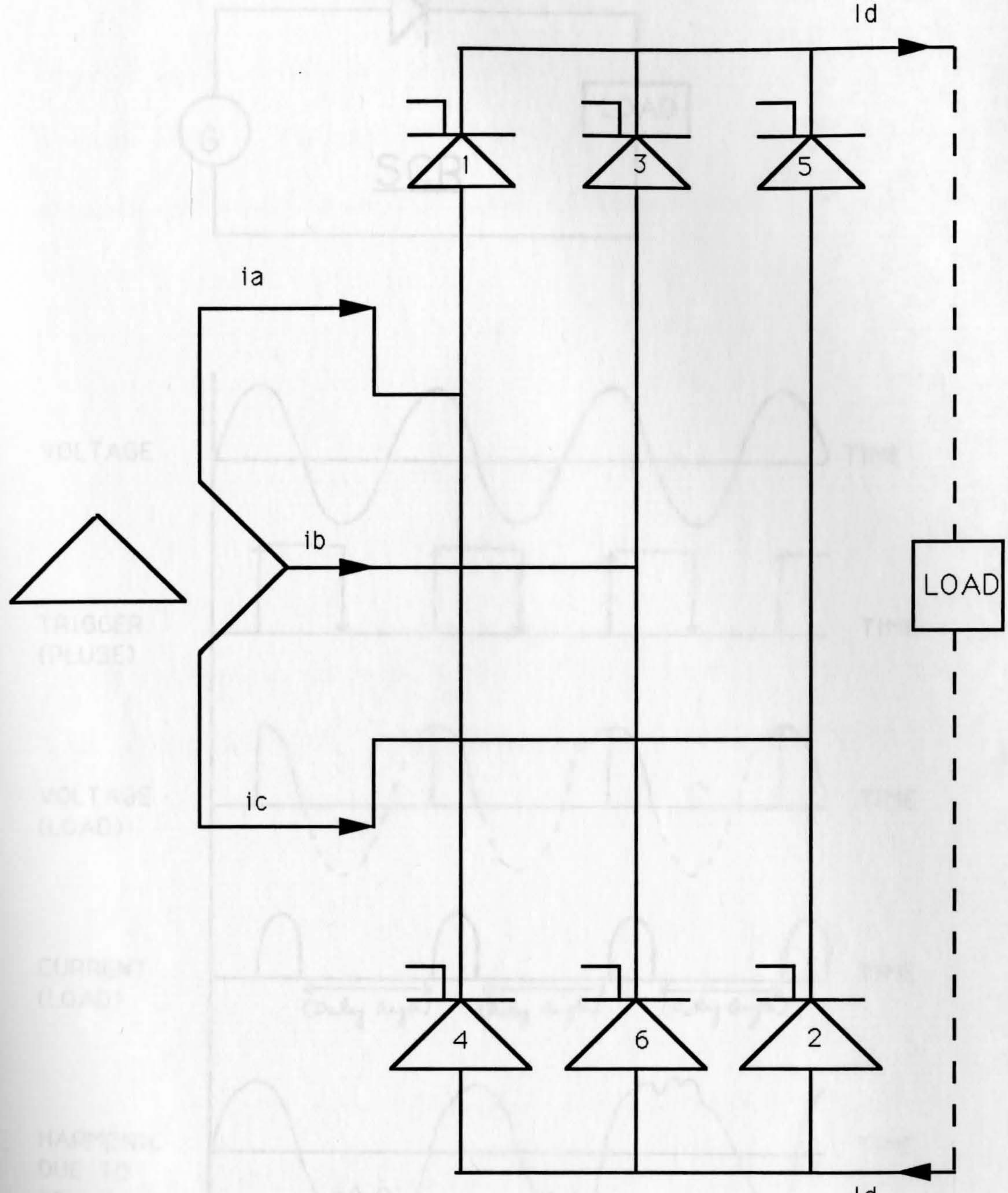
Line-commutated converters are simple, highly efficient and standard components of power electronic equipment. They are able to turn off SCRs by natural commutation when they are connected to an ac power system. They can be treated as ideal current sources of known harmonic contents. Through Fourier analysis, it can be shown that the ac power system has to furnish harmonic currents of the order and magnitude of

$$h=kq\pm 1 \qquad (4.2.1)$$

and

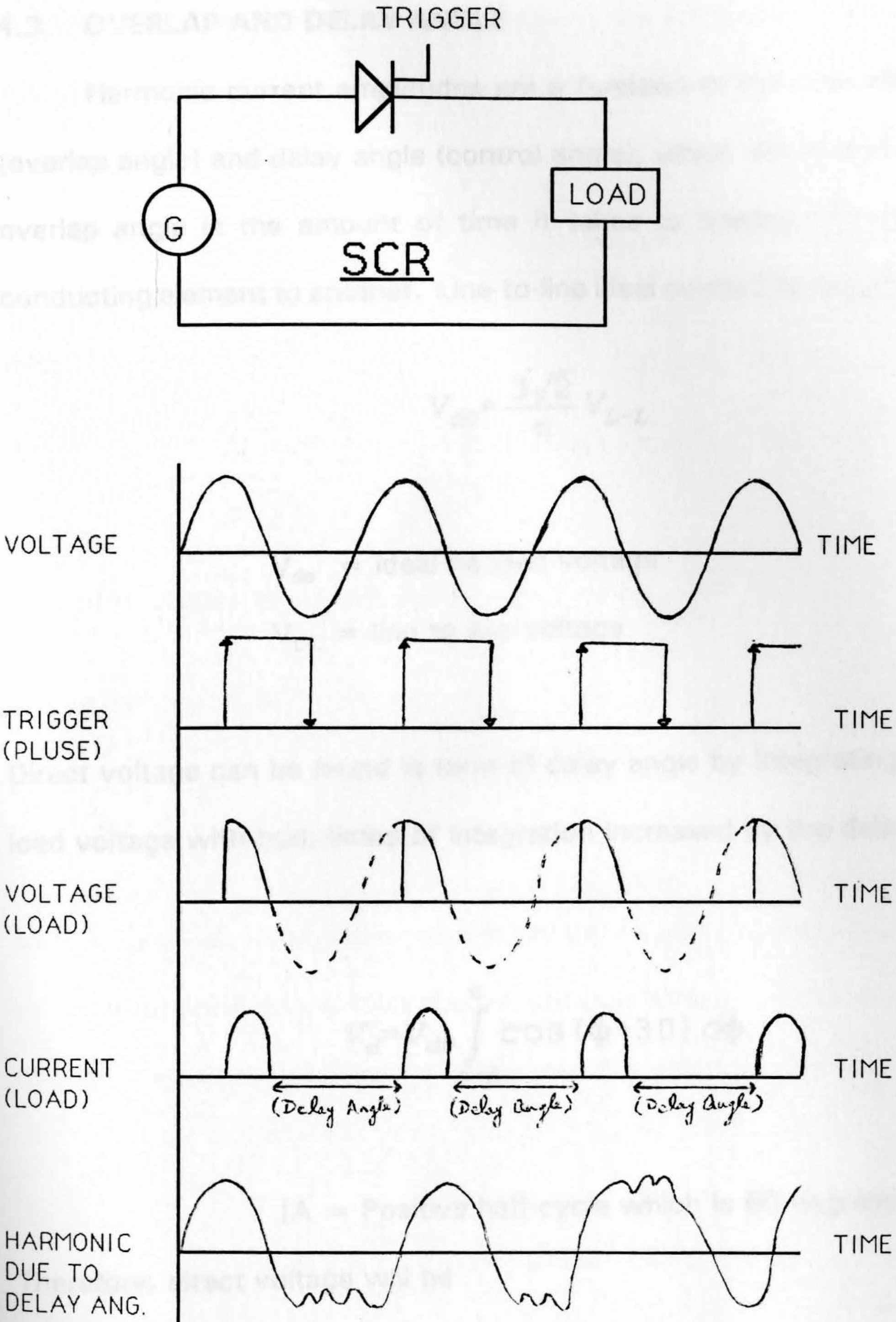
$$I_h=\frac{I_1}{h} \qquad (4.2.2)$$

The three phase, six pulse ac/dc commutated converter is shown in figure 4.2.1. These kinds of converters have six SCR firing pulses and six pulses per power frequency cycle in the output at the dc terminals. In a six pulse bridge circuit, the SCR 1, 3 and 5 commutate the outgoing direct current between themselves, while the SCR 2,4 and 6 commutate the incoming direct current; the two three pulse conversion processes from the six pulse bridge conversion. Harmonic produced by line commutated converters are related to the pulse number of the device. The SCR are numbered in order of sequences and each one conducts of 120 degrees. During the positive half-cycle (60 degree) of the input voltage, SCR #1 conducts and the input voltage appears across the load. During the negative half-cycle of the input voltage, the SCR is in a blocking condition and the output voltage is zero. Due to this discontinuity, it contains harmonics [2,3,8,12]. The function of SCR for one phase is shown graphically in figure 4.2.2.



A SIX LINE COMMUTATED CONVERTER

FIGURE 4.2.1



FUNCTION DIAGRAM OF SCR FOR ONE LINE

FIGURE 4.2.2

4.3 OVERLAP AND DELAY ANGLE

Harmonic current amplitudes are a function of the commutation angle (overlap angle) and delay angle (control angle), which are always given. The overlap angle is the amount of time it takes to transfer current from one conducting element to another. Line-to-line ideal no-load dc voltage is given by

$$V_{d0}=\frac{3\sqrt{2}}{\pi}V_{L-L} \tag{4.3.1}$$

V_{do} = ideal no load voltage

V_{L-L} = line to line voltage

Direct voltage can be found in term of delay angle by integrating the ideal no load voltage with both limits of integration increased by the delay angle.

$$V_d=V_{d0}\int_{\alpha-A}^{\alpha}\cos(\phi+30)\,d\phi \tag{4.3.2}$$

[A = Positive half-cycle which is 60 degrees]

Therefore, direct voltage will be

$$V_d=V_{d0}\cos(\alpha) \tag{4.2.3}$$

One effect of the delay ignition is to reduce the average direct voltage by the factor of cosine of delay angle. Therefore, without overlap the direct voltage is given by

$$V_d = \frac{V_{do}(\cos\alpha - \cos\delta)}{2} \tag{4.3.4}$$

Where

$$\delta = (\alpha + \mu) \tag{4.3.5}$$

And with overlap the direct voltage is given by

$$V_d = \frac{V_{do}[\cos\alpha + \cos(\alpha + \mu)]}{2} \tag{4.3.6}$$

Assume a purely inductive commutative circuit and the reactance per phase of the commutation circuit from the transformer leakage reactance at the end of the commutation; the commutating current is given by

$$I_d = [\frac{V_{L-L}}{\sqrt{2}wL}]\,[\cos(\alpha) - \cos(\alpha + \mu)] \tag{4.3.7}$$

The output dc power is maximum when the delay angle is equal to zero. The dc voltage from equation (4.3.6) is given by

$$V_d = \frac{V_{do}\,[1+\cos(\mu)]}{2} \qquad (4.3.8)$$

and dc current from equation (4.3.7) is given by

$$I_d = \left[\frac{V_{L-L}}{\sqrt{2}\,wL}\right]\,[1-\cos(\mu)] \qquad (4.3.9)$$

Since direct voltage and direct current are functions of the overlap angle, by computation of equations (4.3.8) and (4.3.9) the overlap angle could be determined.

CHAPTER V

SUPPRESSION OF HARMONICS BY FILTER

5.1 INTRODUCTION

The ac harmonic filters serve two purposes:

1) To reduce the harmonic voltages and currents in the ac power network to acceptable levels.

2) To provide all or part of the reactive power consumed by the ac/dc converter.

Filters are nearly always used on the ac side of the converters. The effects make the ac bus voltage sinusoidal. Higher harmonic frequencies are effectively short circuited by the filters and do not enter the ac network [5].

5.2 TYPES OF FILTERS

There are two types of filters:

1) TUNED FILTERS (low pass band filters)

   a) Single tuned

   b) Double tuned

These filters are sharply tuned to one or two of the lower harmonic frequencies (e.g., 3, 5, 7, 9). The lower characteristic harmonics have the largest current magnitudes and, therefore, require filters that have low impedances at and near the frequencies of these harmonics.

2) DAMPED FILTERS (for higher harmonics)

a) 1st order

b) 2nd order

c) 3rd order

5.3 FILTER DESIGN CRITERIA

The criteria for designing a filter are [1,2]:

a) Elimination of all detrimental effects caused by wave distortion, including telephone interference.

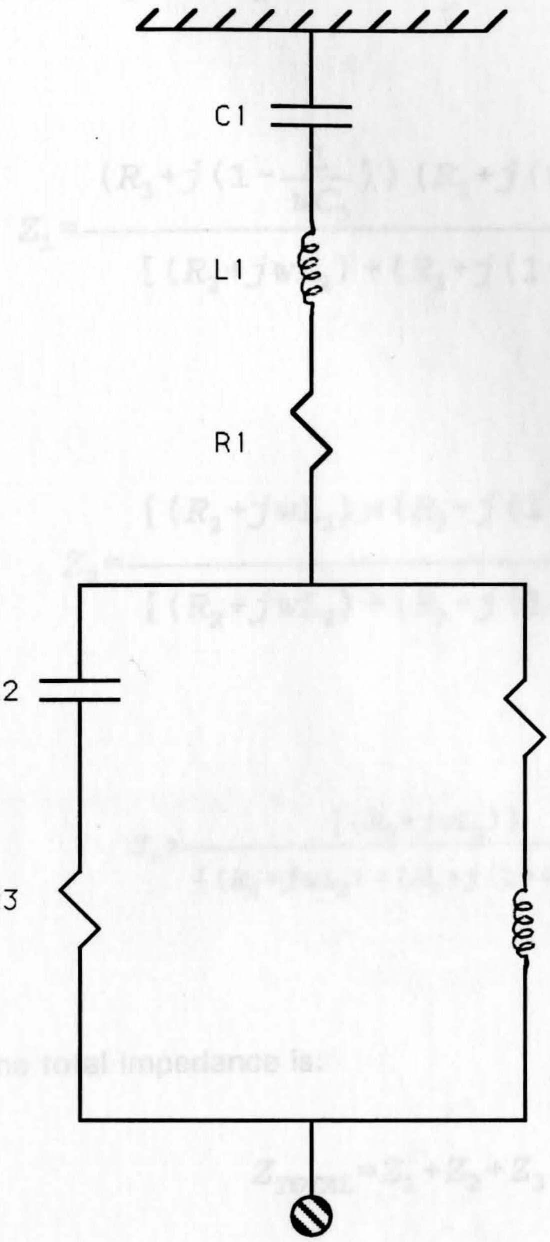
b) IEEE standard 519-1981 requirement, which is defined as

$$H_{fv}=[(V_3)^2+(V_5)^2+(V_7)^2+(V_9)^2+...]/V \quad (5.2.1)$$

$$I_{fI}=[(I_3)^2+(I_5)^2+(I_7)^2+(I_9)^2+...]/I \quad (5.2.2)$$

5.4 DOUBLE TUNED FILTER

A double tuned filter has the equivalent impedance of two single tuned filters near their resonance frequencies. It is the combination of RLC tuned to the frequency of one or two harmonic (generally a low harmonic). The main advantage of the double tuned filter is in high voltage applications, due to the reduction in the number of inductors to be subjected to full impulse voltages. A double tuned filter is shown in figure 5.4.1.



DOUBLE TUNED FILTER

FIGURE 5.4.1

The relationships among the double tuned filter's components are:

$$Z_1 = \frac{(R_3 + j(1 - \frac{1}{wC_3}))(R_1 + j(wL_1 - \frac{1}{wC_1})]}{[(R_2 + jwL_2) + (R_3 + j(1 - \frac{1}{wC_3}))]} \quad (5.4.1)$$

and

$$Z_2 = \frac{[(R_2 + jwL_2) \times (R_3 + j(1 - \frac{1}{wC_3}))]}{[(R_2 + jwL_2) + (R_3 + j(1 - \frac{1}{wC_3}))]} \quad (5.4.2)$$

and

$$Z_3 = \frac{[(R_2 + jwL_2)]}{[(R_2 + jwL_2) + (R_3 + j(1 - \frac{1}{wC_3}))]} \quad (5.4.3)$$

Therefore, the total impedance is:

$$Z_{TOTAL} = Z_1 + Z_2 + Z_3 \quad (5.4.4)$$

and the total admittance form is:

$$Y_{TOTAL} = \frac{1}{Z_{TOTAL}} \quad (5.4.5)$$

$$X_0 = w_n L = \sqrt{\frac{L}{C}} \tag{5.4.6}$$

and

$$X_1 = \sqrt{\frac{L_1}{C_1}} \tag{5.4.7}$$

and

$$X_2 = \frac{(wL_2)\times(wC_3)+1}{wL_2} \tag{5.4.8}$$

Therefore, the double tuned filter in impedance form is

$$Q = \frac{(X_1 + X_2)}{Z_{TOTAL}} \tag{5.4.9}$$

In order to express in admittance form

$$Q^{-1} = \frac{Z_{TOTAL}}{(X_1 + X_2)} \tag{5.4.10}$$

5.5 FILTER POSITION

The position of the filter in the network plays a very important role in the suppression of harmonics. If the filter is connected far away from the source of the harmonic, it will not reduce harmonics as effectively as if it is connected close to the source of the harmonic. In this paper, the filter has been used at different buses to show the effectiveness of the filter at each particular bus.

5.6 RESULTS FROM THE PROGRAMS

The results obtained from the power flow program and the swing equation are given in the following pages in the form of graphs and tables.

TABLE NO. 1

SYSTEM WITHOUT HARMONICS

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	-1.7891	-0.5275	0.000	0.000
2.	P-V	1.050	-17.632	1.3000	-1.5417	0.000	0.000
3.	P-V	1.040	-11.791	1.2000	-1.4391	0.000	0.000
4.	P-Q	0.996	-9.742	-	-	0.000	0.000
5.	P-Q	0.954	-14.639	-	-	-0.200	-0.100
6.	P-Q	0.982	-13.692	-	-	0.000	0.000
7.	P-Q	0.976	-11.980	-	-	0.000	0.000
8.	P-Q	0.998	-8.914	-	-	0.000	0.000
9.	P-Q	0.896	-15.895	-	-	-0.250	-0.150
10.	P-Q	0.965	-16.836	-	-	-0.200	-0.120
11.	P-Q	0.953	-14.731	-	-	-0.150	-0.080
12.	P-Q	0.962	-17.420	-	-	-0.400	-0.300
13.	P-Q	0.939	-7.134	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79 + j12.45	1.865	-1.7891	-0.5272
1--13	-2.36 + j19.70	1.908	-1.4291	1.3915
2--6	-3.67 + j24.45	1.832	-1.2234	-1.5415
3--8	-7.37 + j31.60	1.952	-1.6210	-1.2939
4--6	-4.25 + j24.26	1.589	-1.2639	0.8249
4--9	-1.02 + j 8.20	1.534	-1.3271	-1.9236
5--7	-0.81 + j14.24	1.036	-1.0121	0.3619
5--8	-3.66 + j24.45	1.123	-1.0291	-1.1982
6--7	-4.37 + j32.75	0.789	0.2745	0.2246
7--8	-5.40 + j32.43	0.821	-0.9750	0.5311
8--9	-1.74 + j 9.68	1.022	-0.7451	-0.1729
9--10	-5.40 + j32.40	1.213	-1.0827	-0.9362
10--12	-0.98 + j 8.98	0.501	-0.7392	-0.7832
11--12	-0.82 + j 8.25	0.721	-0.9283	-0.2894
11--13	-1.02 + j 8.30	1.213	-1.4291	-0.9562

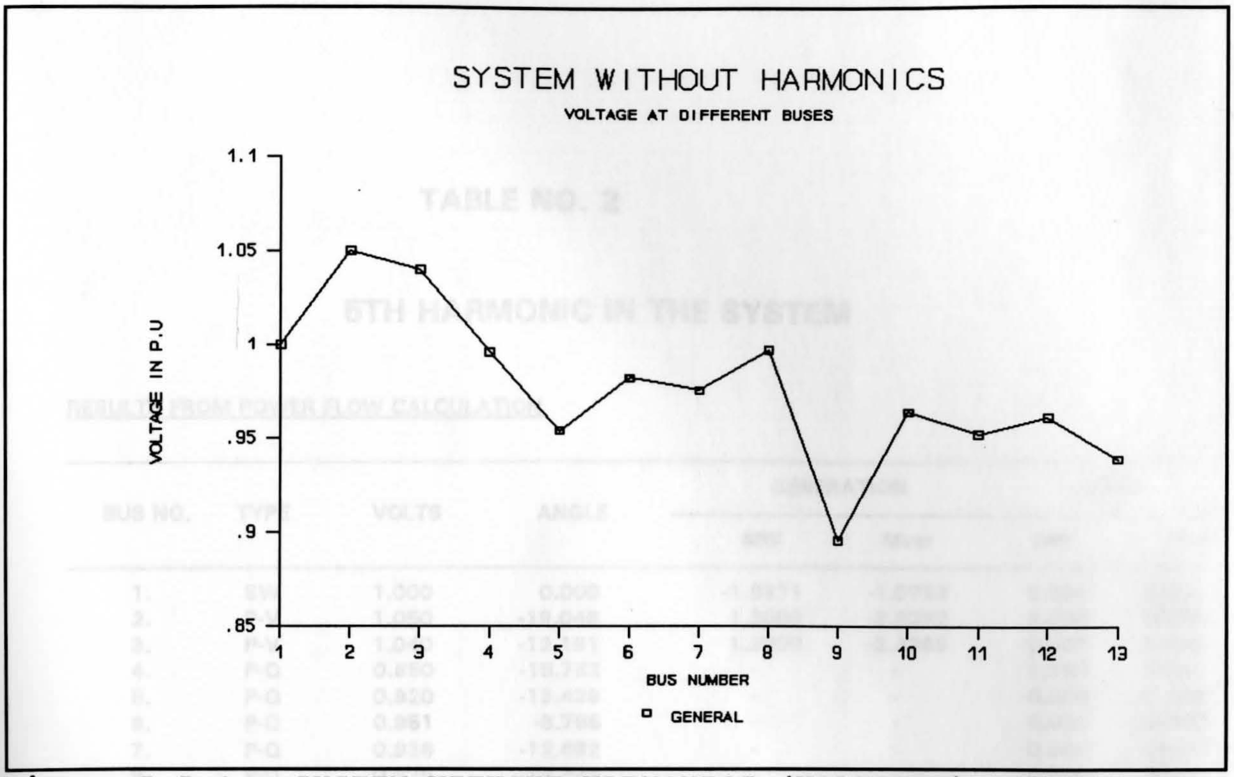


Figure 5.5.1 SYSTEM WITHOUT HARMONICS (VOLTAGES)

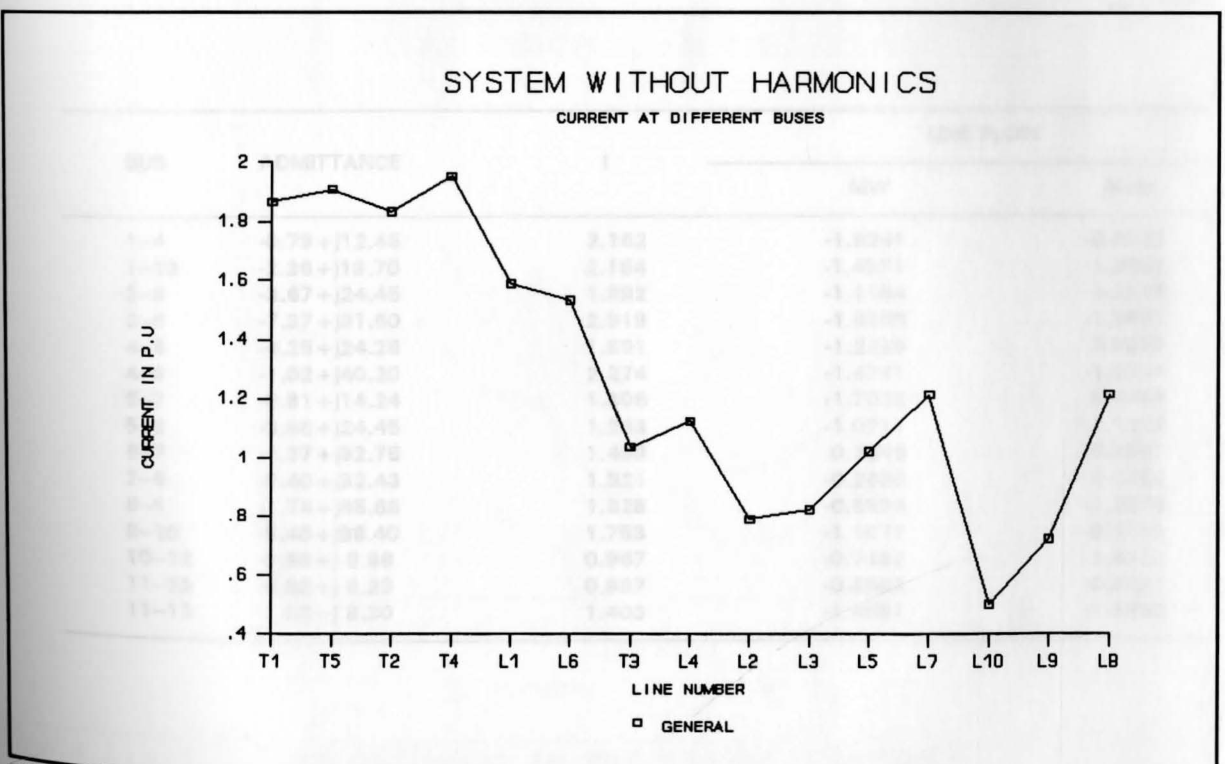


Figure 5.5.2 SYSTEM WITHOUT HARMONICS (CURRENTS)

TABLE NO. 2

5TH HARMONIC IN THE SYSTEM

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	-1.8371	-1.0753	0.000	0.000
2.	P-V	1.050	-19.048	1.3000	-2.2382	0.000	0.000
3.	P-V	1.040	-12.181	1.2000	-2.3965	0.000	0.000
4.	P-Q	0.850	-15.782	-	-	0.000	0.000
5.	P-Q	0.920	-13.439	-	-	-0.200	-0.100
6.	P-Q	0.951	-8.795	-	-	0.000	0.000
7.	P-Q	0.936	-12.682	-	-	0.000	0.000
8.	P-Q	0.835	-16.946	-	-	0.000	0.000
9.	P-Q	0.707	-13.596	-	-	-0.250	-0.150
10.	P-Q	0.820	-16.836	-	-	-0.200	-0.120
11.	P-Q	0.910	-9.731	-	-	-0.150	-0.080
12.	P-Q	0.891	-14.440	-	-	-0.400	-0.300
13.	P-Q	0.900	-7.934	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79+j12.45	2.162	-1.8241	-0.6572
1--13	-2.36+j19.70	2.164	-1.4571	1.3955
2--6	-3.67+j24.45	1.892	-1.1194	-1.2515
3--8	-7.37+j31.60	2.919	-1.6765	-1.3653
4--6	-4.25+j24.26	1.891	-1.2229	0.9310
4--9	-1.02+j40.20	2.274	-1.4741	-1.6346
5--7	-0.81+j14.24	1.306	-1.7028	0.6459
5--8	-3.66+j24.45	1.263	-1.0711	-1.1232
6--7	-4.37+j32.75	1.489	0.7645	0.4547
7--8	-5.40+j32.43	1.521	-0.2650	0.5654
8--9	-1.74+j45.68	1.828	-0.6574	-1.2579
9--10	-5.40+j98.40	1.753	-1.1077	-0.9362
10--12	-0.98+j 8.98	0.967	-0.7432	-1.3233
11--12	-0.82+j 8.25	0.987	-0.3583	-0.2567
11--13	-1.02+j 8.30	1.403	-1.4531	-1.3462

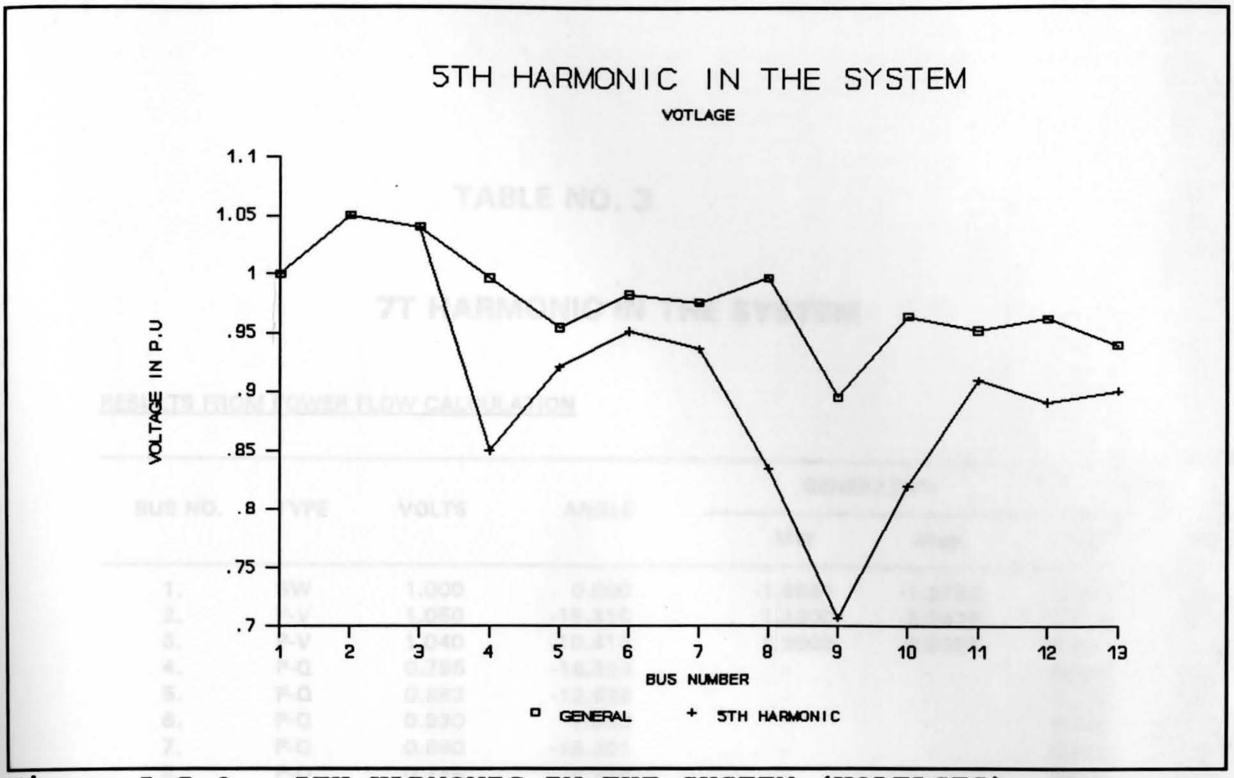


Figure 5.5.3 5TH HARMONIC IN THE SYSTEM (VOLTAGES)

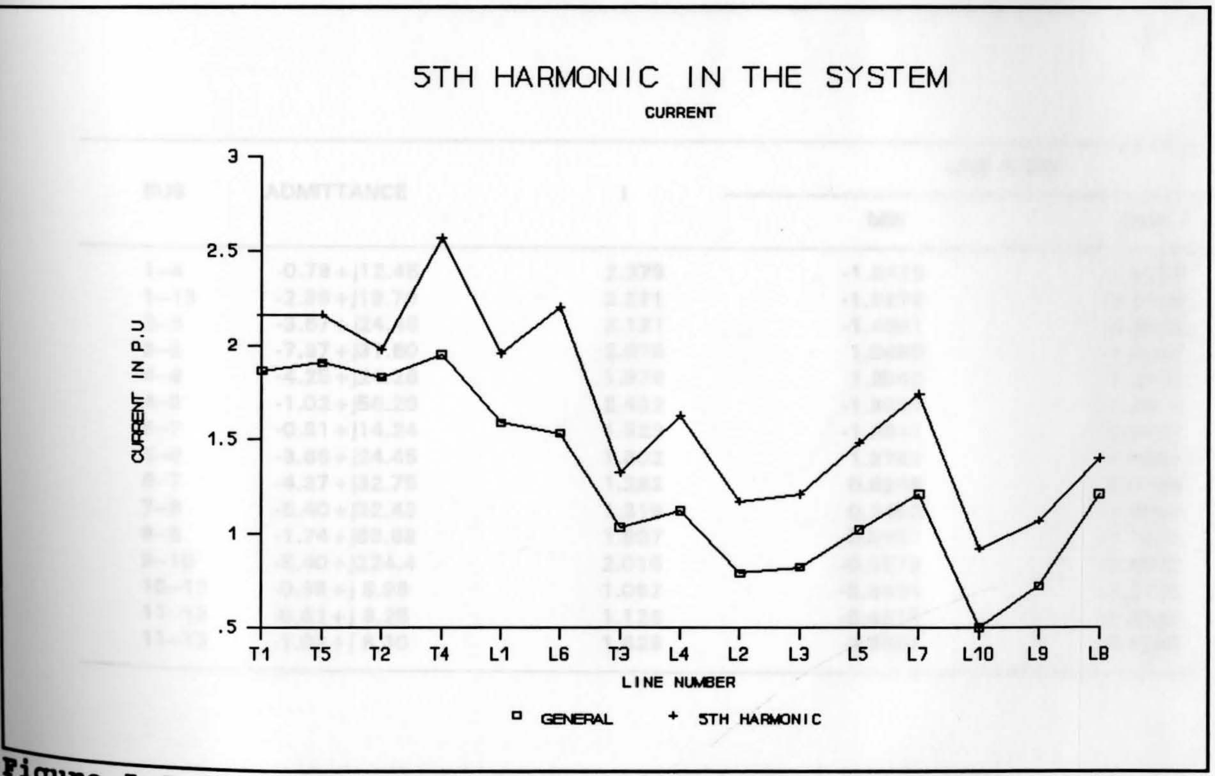


Figure 5.5.4 5TH HARMONIC IN THE SYSTEM (CURRENTS)

TABLE NO. 3

7T HARMONIC IN THE SYSTEM

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	-1.8661	-1.2752	0.000	0.000
2.	P-V	1.050	-19.315	1.3000	-2.5426	0.000	0.000
3.	P-V	1.040	-10.412	1.2000	-2.9354	0.000	0.000
4.	P-Q	0.795	-16.823	-	-	0.000	0.000
5.	P-Q	0.883	-12.629	-	-	0.000	0.000
6.	P-Q	0.930	-9.352	-	-	0.000	0.000
7.	P-Q	0.890	-18.201	-	-	0.000	0.000
8.	P-Q	0.785	6.934	-	-	0.000	0.000
9.	P-Q	0.654	-10.313	-	-	-0.250	-0.150
10.	P-Q	0.792	-9.231	-	-	-0.200	-0.120
11.	P-Q	0.891	-5.234	-	-	-0.150	-0.080
12.	P-Q	0.853	10.376	-	-	-0.400	-0.300
13.	P-Q	0.880	-7.493	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79+j12.45	2.279	-1.3415	-1.6132
1--13	-2.36+j19.70	2.271	-1.5272	2.2316
2--6	-3.67+j24.45	2.121	-1.4691	-2.2415
3--8	-7.37+j31.60	2.678	1.0490	-1.2962
4--6	-4.25+j24.26	1.976	1.2042	1.3724
4--9	-1.02+j56.20	2.432	-1.3051	-1.4212
5--7	-0.81+j14.24	1.523	-1.2941	0.9625
5--8	-3.66+j24.45	1.802	1.2781	-1.4262
6--7	-4.37+j32.75	1.282	0.8245	0.9125
7--8	-5.40+j32.43	1.319	0.2452	-1.9547
8--9	-1.74+j63.68	1.907	-0.8557	-1.1321
9--10	-5.40+j224.4	2.015	-0.9578	-1.3922
10--12	-0.98+j 8.98	1.062	-0.6464	-1.4128
11--12	-0.82+j 8.25	1.126	-0.4315	-0.2535
11--13	-1.02+j 8.30	1.626	-0.3561	-0.4245

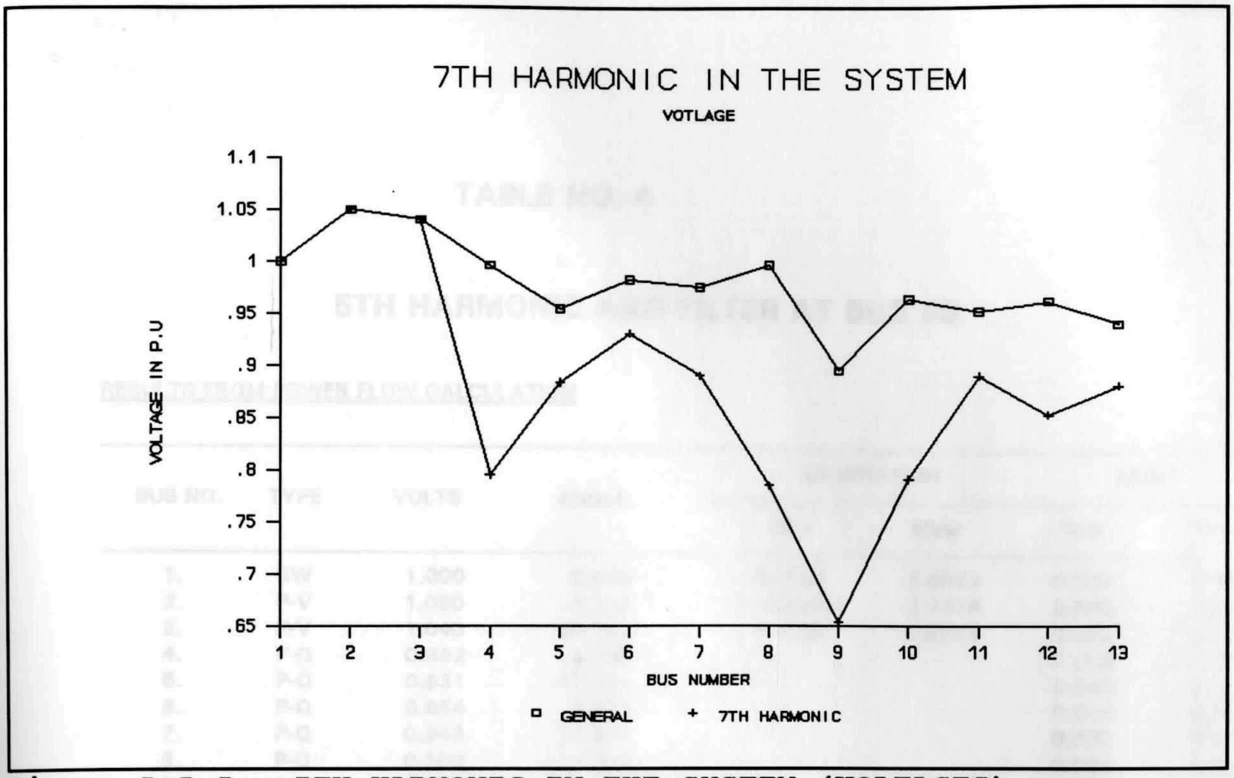


Figure 5.5.5 7TH HARMONIC IN THE SYSTEM (VOLTAGES)

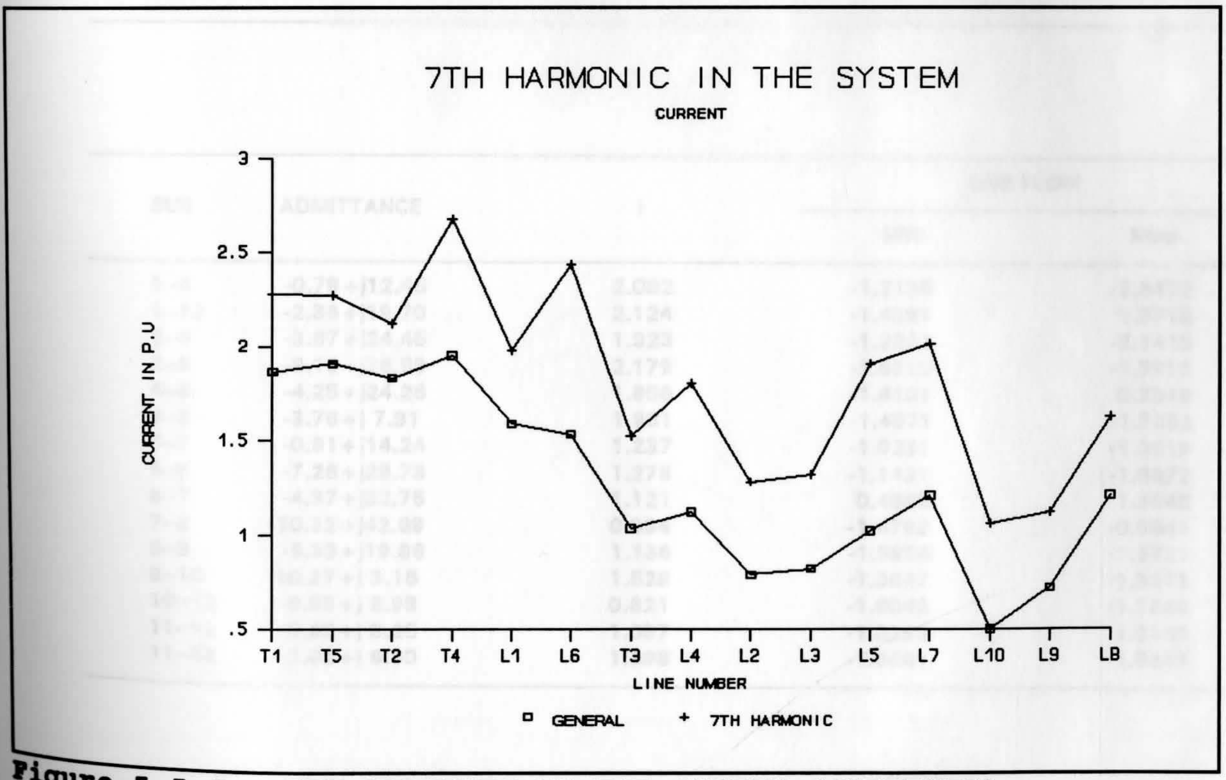


Figure 5.5.6 7TH HARMONIC IN THE SYSTEM (CURRENTS)

TABLE NO. 4

5TH HARMONIC AND FILTER AT BUS #8

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	0.7981	-2.0823	0.000	0.000
2.	P-V	1.050	-2.118	1.3000	-3.4476	0.000	0.000
3.	P-V	1.040	55.142	1.2000	-2.9665	0.000	0.000
4.	P-Q	0.892	5.786	-	-	0.000	0.000
5.	P-Q	0.931	-17.339	-	-	0.000	0.000
6.	P-Q	0.954	8.772	-	-	0.000	0.000
7.	P-Q	0.943	10.382	-	-	0.000	0.000
8.	P-Q	0.902	-15.894	-	-	0.000	0.000
9.	P-Q	0.756	13.553	-	-	-0.250	-0.150
10.	P-Q	0.860	16.836	-	-	-0.200	-0.120
11.	P-Q	0.920	8.461	-	-	-0.150	-0.080
12.	P-Q	0.910	7.829	-	-	-0.400	-0.300
13.	P-Q	0.908	3.149	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79+j12.45	2.092	-1.2135	-2.8472
1--13	-2.36+j19.70	2.124	-1.4391	1.9716
2--6	-3.67+j24.45	1.923	-1.2231	-2.1415
3--8	-8.18+j26.59	2.179	-1.6310	-1.7912
4--6	-4.25+j24.26	1.856	-1.4101	0.7849
4--9	-3.76+j 7.91	1.981	-1.4871	-1.7232
5--7	-0.81+j14.24	1.237	-1.0231	-1.3619
5--8	-7.26+j29.73	1.278	-1.1421	-1.0872
6--7	-4.37+j32.75	1.121	0.4965	1.3545
7--8	-10.32+j42.69	0.934	-1.4762	-0.9541
8--9	-6.39+j19.86	1.136	-1.9856	-1.3721
9--10	-10.27+j 3.16	1.528	-1.3627	-1.3672
10--12	-0.98+j 8.98	0.821	-1.8042	-1.1242
11--12	-0.82+j 8.25	1.057	-1.3285	1.3145
11--13	-1.02+j 8.30	1.398	-1.5041	-1.5643

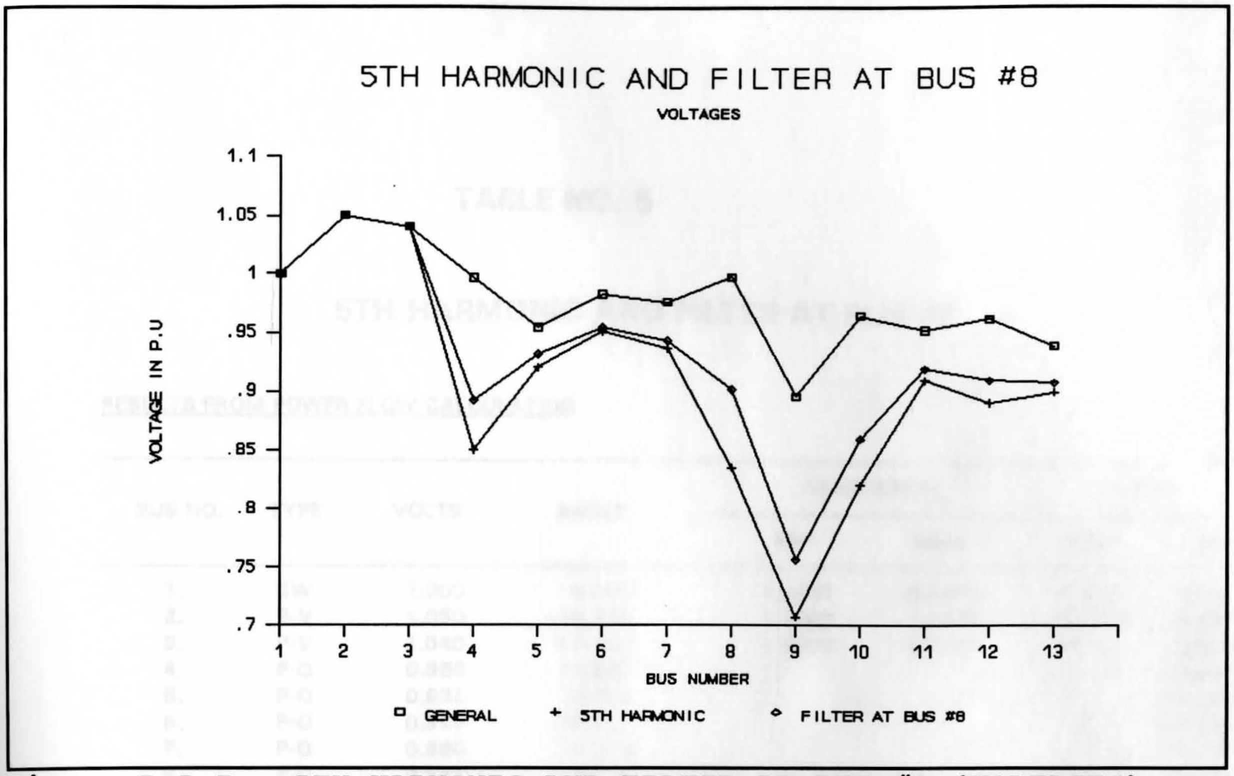


Figure 5.5.7 5TH HARMONIC AND FILTER AT BUS #8 (VOLTAGES)

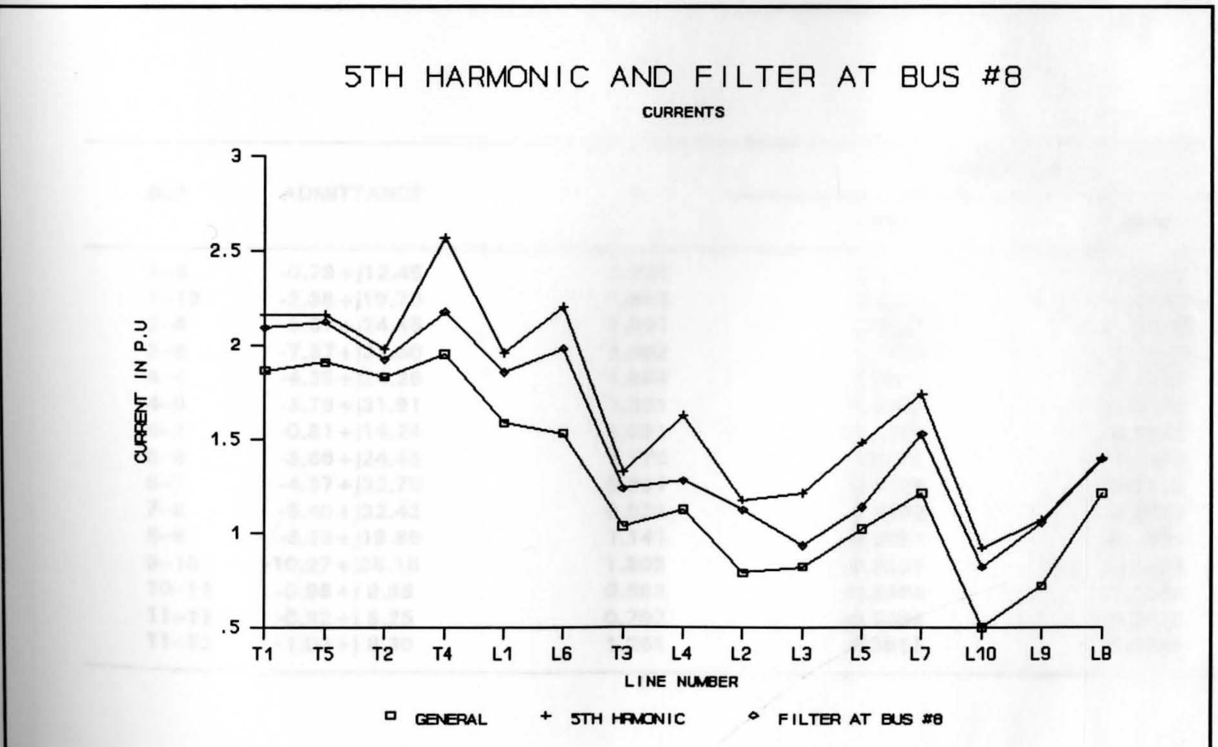


Figure 5.5.8 5TH HARMONIC AND FILTER AT BUS #8 (CURRENTS)

TABLE NO. 5

5TH HARMONIC AND FILTER AT BUS #9

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	-1.6381	-0.6462	0.000	0.000
2.	P-V	1.050	-18.218	1.3000	-1.8476	0.000	0.000
3.	P-V	1.040	-14.112	1.2000	-1.3165	0.000	0.000
4.	P-Q	0.958	-11.320	-	-	0.000	0.000
5.	P-Q	0.938	-7.244	-	-	0.000	0.000
6.	P-Q	0.965	-10.172	-	-	0.000	0.000
7.	P-Q	0.960	-8.752	-	-	0.000	0.000
8.	P-Q	0.941	-5.234	-	-	0.000	0.000
9.	P-Q	0.853	-12.013	-	-	-0.250	-0.150
10.	P-Q	0.932	-3.736	-	-	-0.200	-0.120
11.	P-Q	0.943	-12.359	-	-	-0.150	-0.080
12.	P-Q	0.951	8.916	-	-	-0.400	-0.300
13.	P-Q	0.923	-11.333	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79+j12.45	1.932	-1.2475	-1.8632
1--13	-2.36+j19.70	1.942	-1.3572	1.2716
2--6	-3.67+j24.45	1.891	1.5601	-1.5415
3--8	-7.37+j31.60	2.052	1.1460	-1.1942
4--6	-4.25+j24.26	1.684	1.0977	0.7249
4--9	-3.76+j31.91	1.621	-1.2851	-1.9262
5--7	-0.81+j14.24	1.091	-1.1031	0.2615
5--8	-3.66+j24.45	1.179	-1.0191	-1.1962
6--7	-4.37+j32.75	0.927	0.3325	0.5145
7--8	-5.40+j32.43	0.921	0.6762	-0.9567
8--9	-6.39+j19.86	1.141	-0.2857	-0.1521
9--10	-10.27+j35.16	1.302	-0.2527	-0.7322
10--12	-0.98+j 8.98	0.592	-0.8464	-1.0198
11--12	-0.82+j 8.25	0.797	-0.7365	-0.2515
11--13	-1.02+j 8.30	1.261	-1.3511	-0.8245

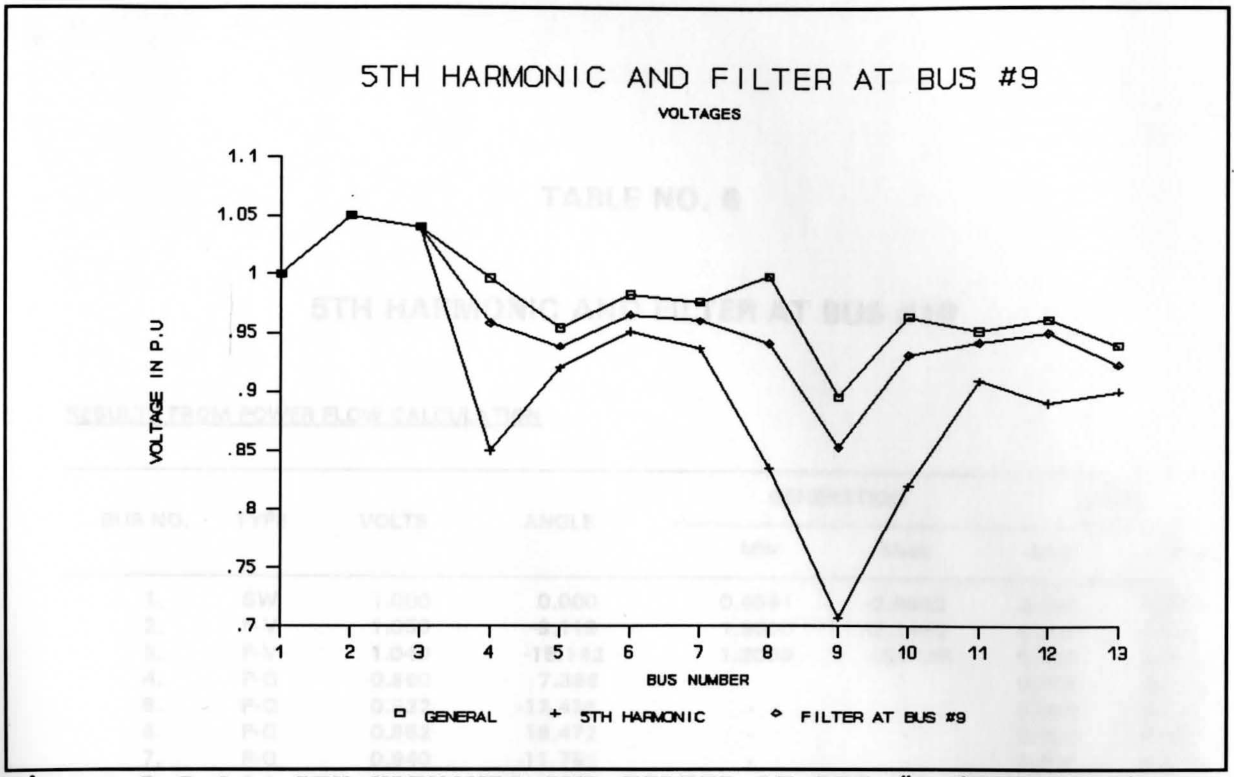


Figure 5.5.9 5TH HARMONIC AND FILTER AT BUS #9 (VOLTAGES)

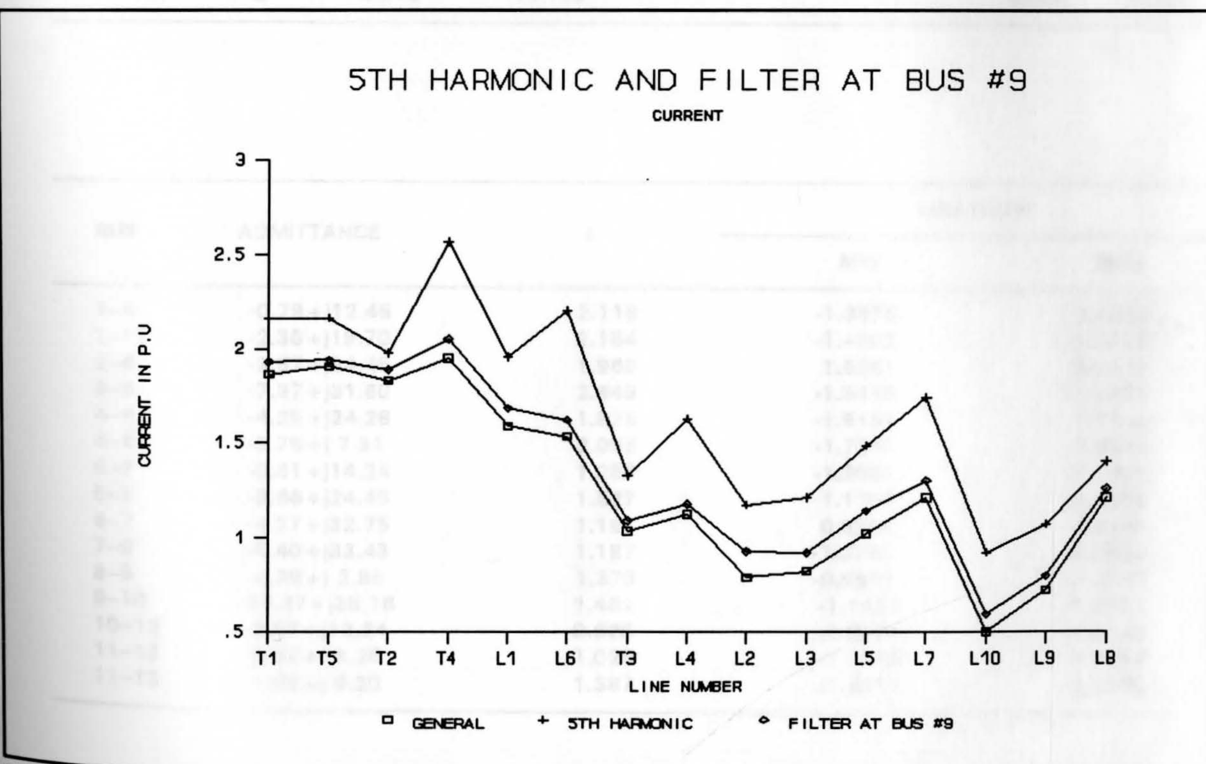


Figure 5.5.10 5TH HARMONIC AND FILTER AT BUS #9 (CURRENTS)

TABLE NO. 6

5TH HARMONIC AND FILTER AT BUS #10

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	0.6581	-0.9862	0.000	0.000
2.	P-V	1.050	-8.118	1.3000	-2.1446	0.000	0.000
3.	P-V	1.040	-15.142	1.2000	-2.0165	0.000	0.000
4.	P-Q	0.860	7.386	-	-	0.000	0.000
5.	P-Q	0.922	-12.439	-	-	0.000	0.000
6.	P-Q	0.952	18.472	-	-	0.000	0.000
7.	P-Q	0.940	-11.752	-	-	0.000	0.000
8.	P-Q	0.871	-15.894	-	-	0.000	0.000
9.	P-Q	0.784	-16.153	-	-	-0.250	-0.150
10.	P-Q	0.895	-10.836	-	-	-0.200	-0.120
11.	P-Q	0.925	12.401	-	-	-0.150	-0.080
12.	P-Q	0.938	2.826	-	-	-0.400	-0.300
13.	P-Q	0.912	-13.139	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79+j12.45	2.118	-1.3575	2.8222
1--13	-2.36+j19.70	2.154	-1.4392	-1.5716
2--6	-3.67+j24.45	1.969	1.6261	3.3415
3--8	-7.37+j31.60	2.449	-1.5410	-1.4952
4--6	-4.25+j24.26	1.926	-1.5161	1.7249
4--9	-3.76+j 7.91	2.058	-1.7551	-1.9262
5--7	-0.81+j14.24	1.287	-1.2031	-1.1615
5--8	-3.66+j24.45	1.527	1.1101	-1.1272
6--7	-4.37+j32.75	1.161	0.3965	1.5145
7--8	-5.40+j32.43	1.187	-1.2762	-0.9567
8--9	-4.39+j 2.86	1.379	-0.9857	-1.2521
9--10	-10.27+j35.16	1.482	-1.1427	-1.0322
10--12	-2.57+j12.24	0.625	-0.8074	-1.0142
11--12	-0.82+j 8.25	1.029	-1.2365	0.5315
11--13	-1.02+j 8.30	1.387	-1.4511	-1.2645

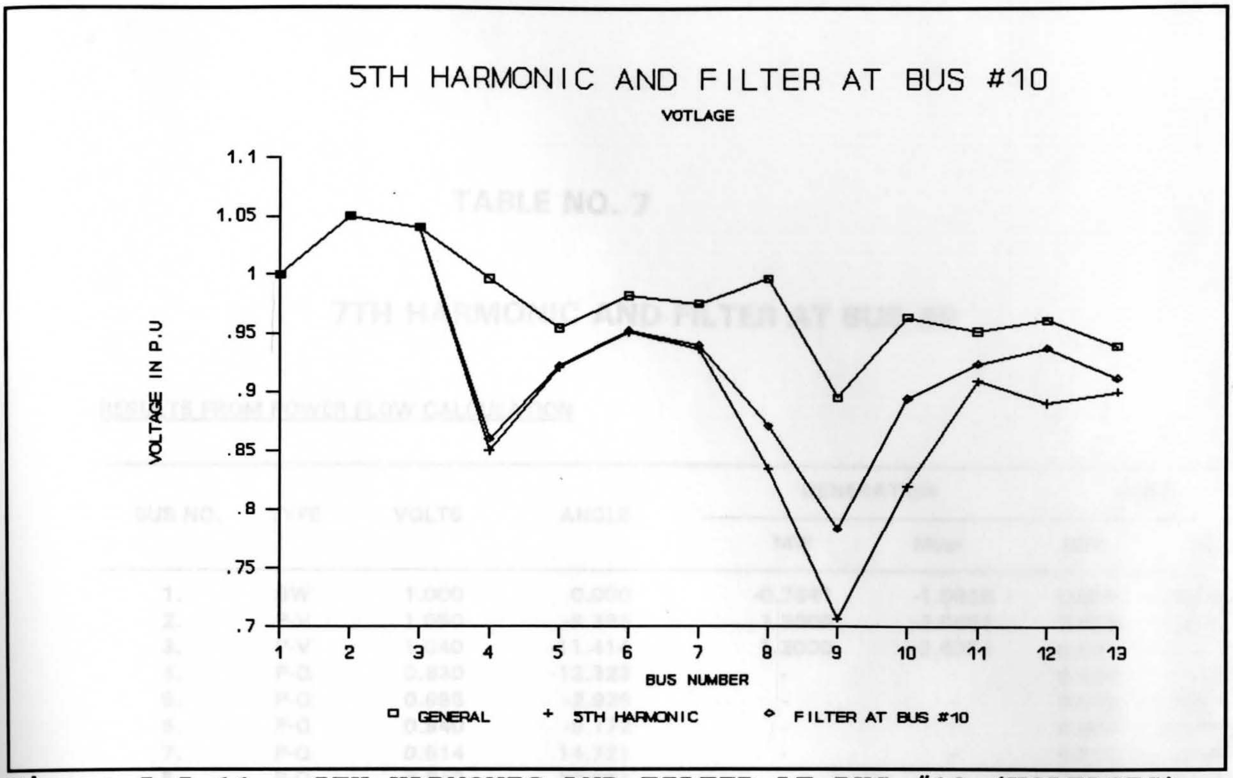


Figure 5.5.11 5TH HARMONIC AND FILTER AT BUS #10 (VOLTAGES)

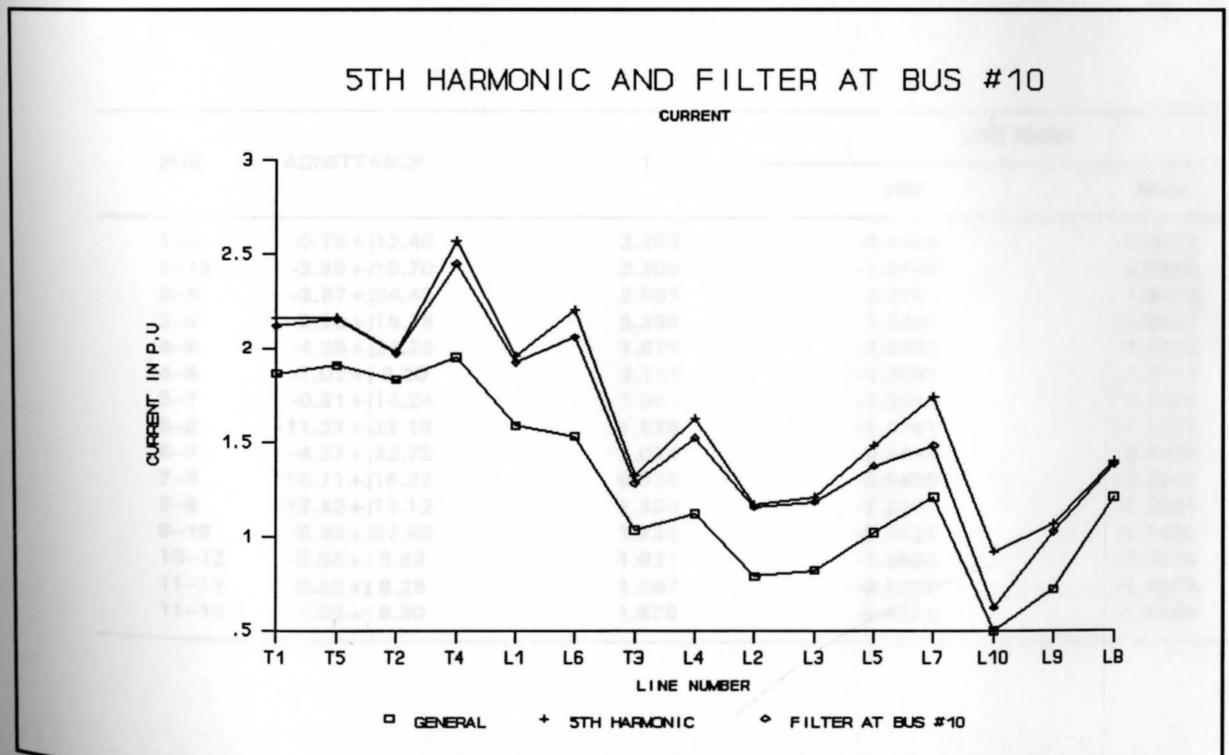


Figure 5.5.12 5TH HARMONIC AND FILTER AT BUS #10 (CURRENTS)

TABLE NO. 7

7TH HARMONIC AND FILTER AT BUS #8

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	-0.7641	-1.0835	0.000	0.000
2.	P-V	1.050	-9.395	1.3000	-2.0651	0.000	0.000
3.	P-V	1.040	-11.414	1.2000	-2.4054	0.000	0.000
4.	P-Q	0.830	-12.323	-	-	0.000	0.000
5.	P-Q	0.895	-2.929	-	-	0.000	0.000
6.	P-Q	0.940	-9.172	-	-	0.000	0.000
7.	P-Q	0.914	14.721	-	-	0.000	0.000
8.	P-Q	0.840	10.304	-	-	0.000	0.000
9.	P-Q	0.702	-15.823	-	-	-0.250	-0.150
10.	P-Q	0.820	-11.691	-	-	-0.200	-0.120
11.	P-Q	0.903	-3.634	-	-	-0.150	-0.080
12.	P-Q	0.872	-2.976	-	-	-0.400	-0.300
13.	P-Q	0.895	-3.593	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79+j12.45	2.203	-1.6433	-1.0312
1--13	-2.36+j19.70	2.209	-1.3160	2.0316
2--6	-3.67+j24.45	2.037	-1.3781	1.9415
3--8	-9.20+j18.16	2.358	1.2460	-1.0202
4--6	-4.25+j24.26	1.879	-1.0452	1.4624
4--9	-1.02+j 8.20	2.132	-1.2081	-1.2712
5--7	-0.81+j14.24	1.367	-1.3041	1.3605
5--8	-11.27+j33.19	1.229	-1.2781	-1.1252
6--7	-4.37+j32.75	1.074	0.8641	0.4925
7--8	-15.71+j19.27	0.978	0.6455	-2.3047
8--9	-12.42+j13.12	1.325	-1.2357	-1.3621
9--10	-5.40+j32.40	1.732	-0.5529	-1.1602
10--12	-0.98+j 8.98	1.021	-1.4586	-1.7018
11--12	-0.82+j 8.25	1.067	-0.8215	-1.4015
11--13	-1.02+j 8.30	1.579	-0.4562	-1.3245

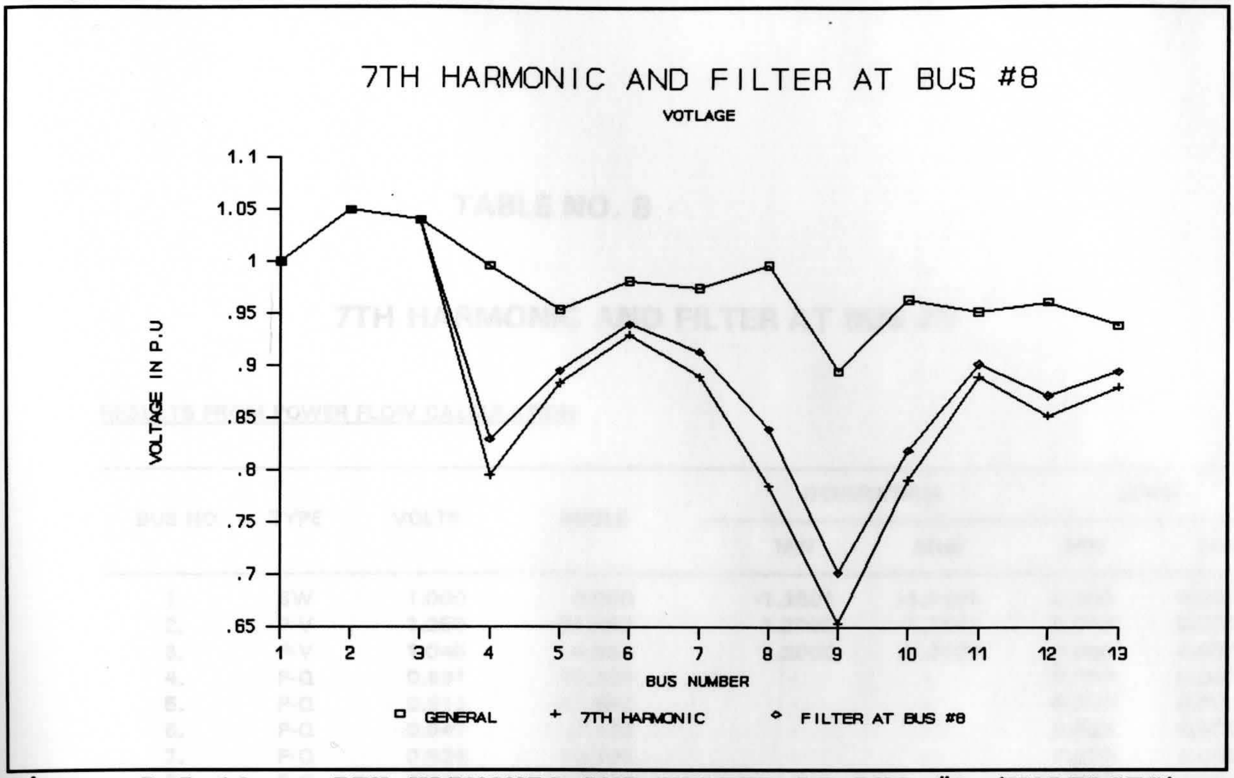


Figure 5.5.13 7TH HARMONIC AND FILTER AT BUS #8 (VOLTAGES)

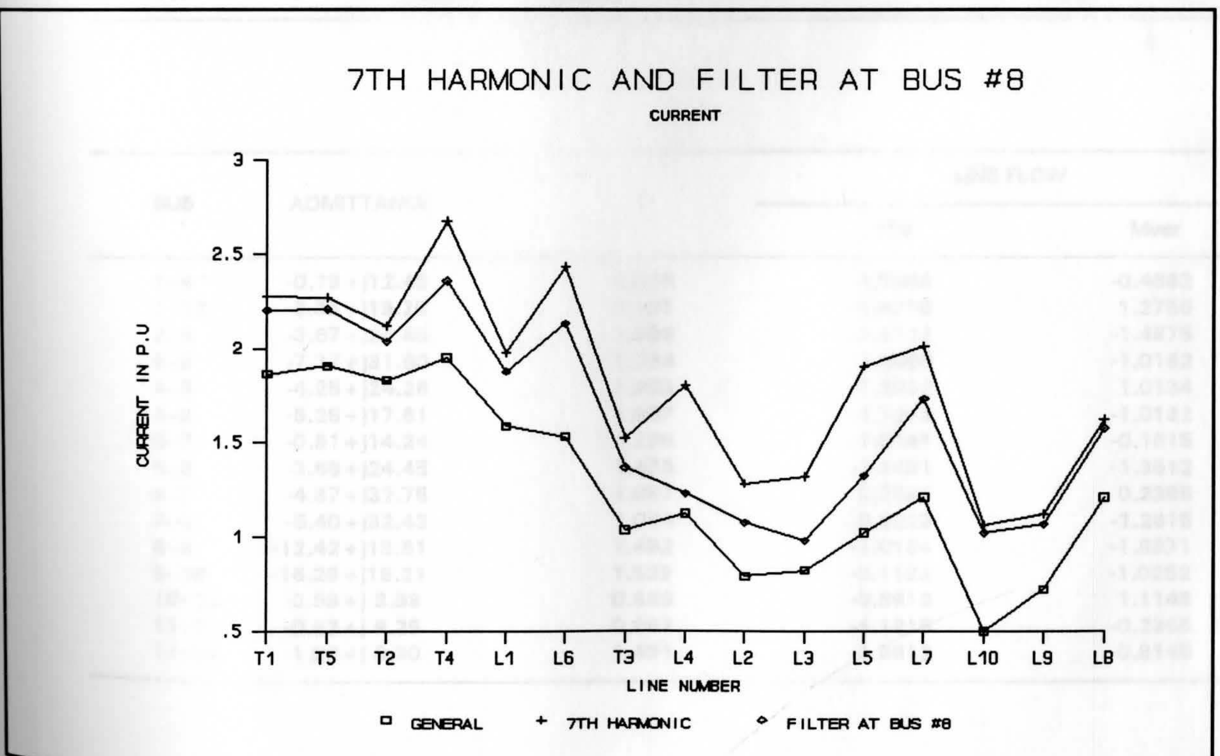


Figure 5.5.14 7TH HARMONIC AND FILTER AT BUS #8 (CURRENTS)

TABLE NO. 8

7TH HARMONIC AND FILTER AT BUS #9

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	-1.3801	-1.1265	0.000	0.000
2.	P-V	1.050	-11.467	1.3000	-1.7341	0.000	0.000
3.	P-V	1.040	6.564	1.2000	-1.3604	0.000	0.000
4.	P-Q	0.891	10.238	-	-	0.000	0.000
5.	P-Q	0.912	-17.642	-	-	0.000	0.000
6.	P-Q	0.947	-9.162	-	-	0.000	0.000
7.	P-Q	0.926	-10.461	-	-	0.000	0.000
8.	P-Q	0.916	3.834	-	-	0.000	0.000
9.	P-Q	0.795	-12.471	-	-	-0.250	-0.150
10.	P-Q	0.889	-5.183	-	-	-0.200	-0.120
11.	P-Q	0.915	-12.924	-	-	-0.150	-0.080
12.	P-Q	0.923	-6.126	-	-	-0.400	-0.300
13.	P-Q	0.895	-11.593	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79+j12.45	2.078	-1.6986	-0.4862
1--13	-2.36+j19.70	2.101	-1.4236	1.2756
2--6	-3.67+j24.45	1.998	-1.3111	-1.4875
3--8	-7.37+j31.60	2.289	-1.5660	-1.0182
4--6	-4.25+j24.26	1.823	-1.2032	1.0134
4--9	-5.28+j17.61	1.967	-1.3213	-1.0132
5--7	-0.81+j14.24	1.296	-1.0141	-0.1615
5--8	-3.66+j24.45	1.473	-1.1491	-1.3512
6--7	-4.37+j32.75	1.087	0.2581	0.2395
7--8	-5.40+j32.43	1.054	-0.9223	-1.2615
8--9	-12.42+j13.61	1.492	-1.0134	-1.6371
9--10	-16.29+j19.21	1.539	-0.1122	-1.0252
10--12	-0.98+j 8.98	0.839	-0.5616	1.1148
11--12	-0.82+j 8.25	0.987	-1.1215	-0.2365
11--13	-1.02+j 8.30	1.491	-1.3612	-0.8145

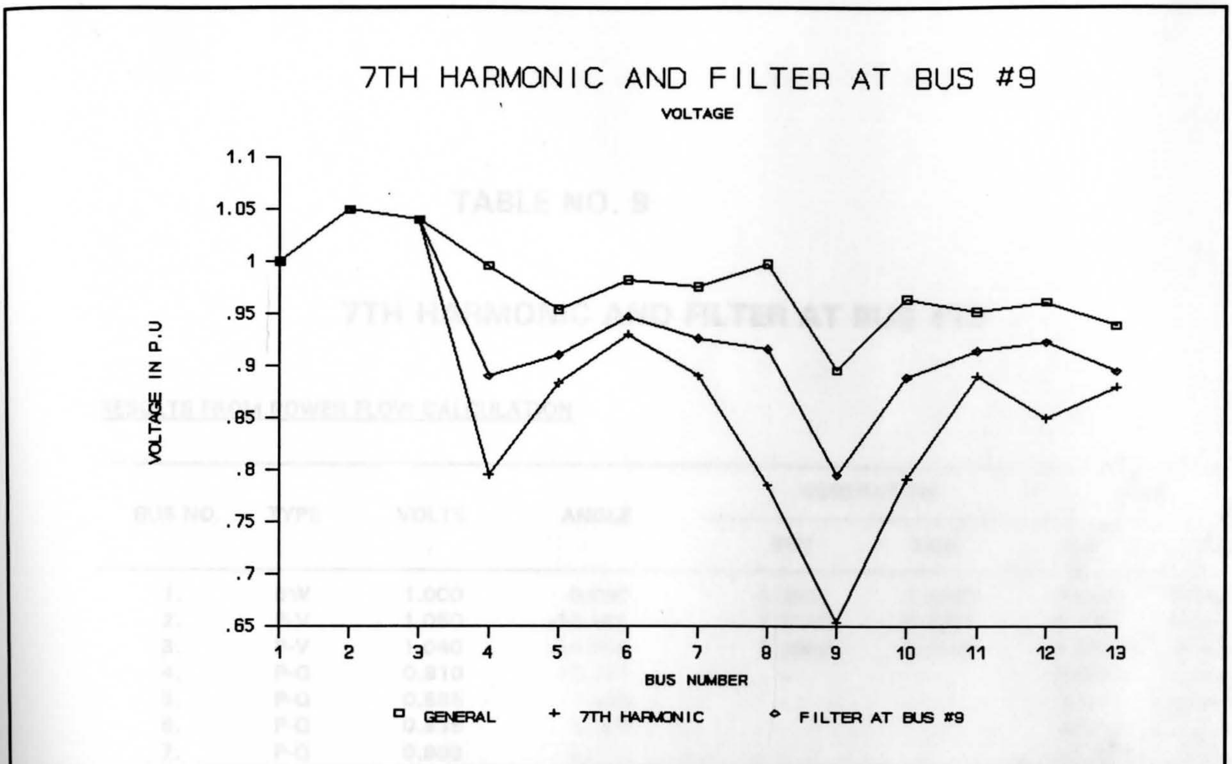


Figure 5.5.15 7TH HARMONIC AND FILTER AT BUS #9 (VOLTAGES)

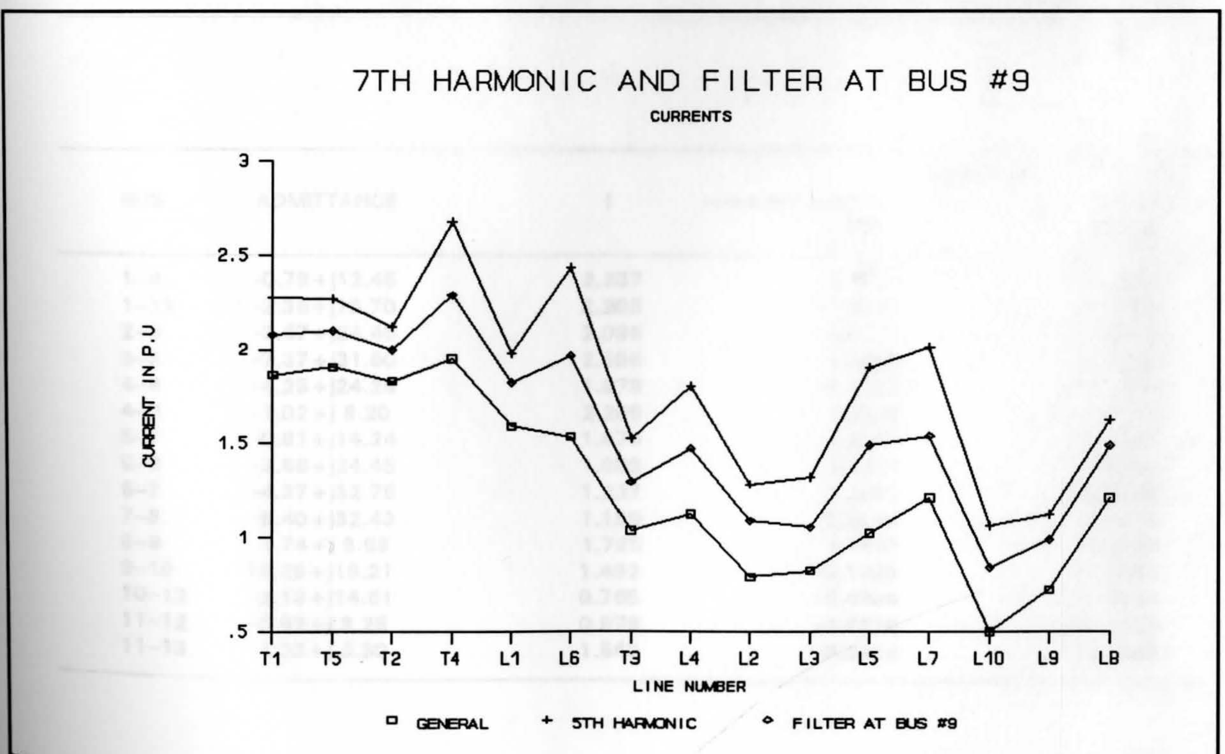


Figure 5.5.16 7TH HARMONIC AND FILTER AT BUS #9 (CURRENTS)

TABLE NO. 9

7TH HARMONIC AND FILTER AT BUS #10

RESULTS FROM POWER FLOW CALCULATION

BUS NO.	TYPE	VOLTS	ANGLE	GENERATION		LOAD	
				MW	Mvar	MW	Mvar
1.	SW	1.000	0.000	-1.2801	-1.0965	0.000	0.000
2.	P-V	1.050	-12.165	1.3000	-2.3791	0.000	0.000
3.	P-V	1.040	-16.954	1.2000	-2.1704	0.000	0.000
4.	P-Q	0.810	12.378	-	-	0.000	0.000
5.	P-Q	0.885	-7.162	-	-	0.000	0.000
6.	P-Q	0.935	-3.132	-	-	0.000	0.000
7.	P-Q	0.903	10.111	-	-	0.000	0.000
8.	P-Q	0.801	13.634	-	-	0.000	0.000
9.	P-Q	0.715	-15.111	-	-	-0.250	-0.150
10.	P-Q	0.830	-9.293	-	-	-0.200	-0.120
11.	P-Q	0.910	-6.924	-	-	-0.150	-0.080
12.	P-Q	0.911	-8.126	-	-	-0.400	-0.300
13.	P-Q	0.898	-8.593	-	-	0.000	0.000

BUS	ADMITTANCE	I	LINE FLOW	
			MW	Mvar
1--4	-0.79+j12.45	2.237	1.2756	-0.3812
1--13	-2.36+j19.70	2.208	-1.5230	-1.0256
2--6	-3.67+j24.45	2.098	-1.5211	1.3815
3--8	-7.37+j31.60	2.598	1.2560	-1.2782
4--6	-4.25+j24.26	1.878	-1.1332	1.1564
4--9	-1.02+j 8.20	2.209	1.0333	-1.3512
5--7	-0.81+j14.24	1.479	-1.2141	-0.3325
5--8	-3.66+j24.45	1.689	-1.2451	-1.5432
6--7	-4.37+j32.75	1.227	1.2501	0.5395
7--8	-5.40+j32.43	1.195	0.9223	-1.3617
8--9	-1.74+j 9.68	1.725	1.1437	-1.5321
9--10	-16.29+j19.21	1.492	-0.1329	-1.7252
10--12	-2.13+j14.61	0.765	-1.4606	-1.4148
11--12	-0.82+j 8.25	0.979	-1.4215	-1.2305
11--13	-1.02+j 8.30	1.543	-0.8292	-1.2845

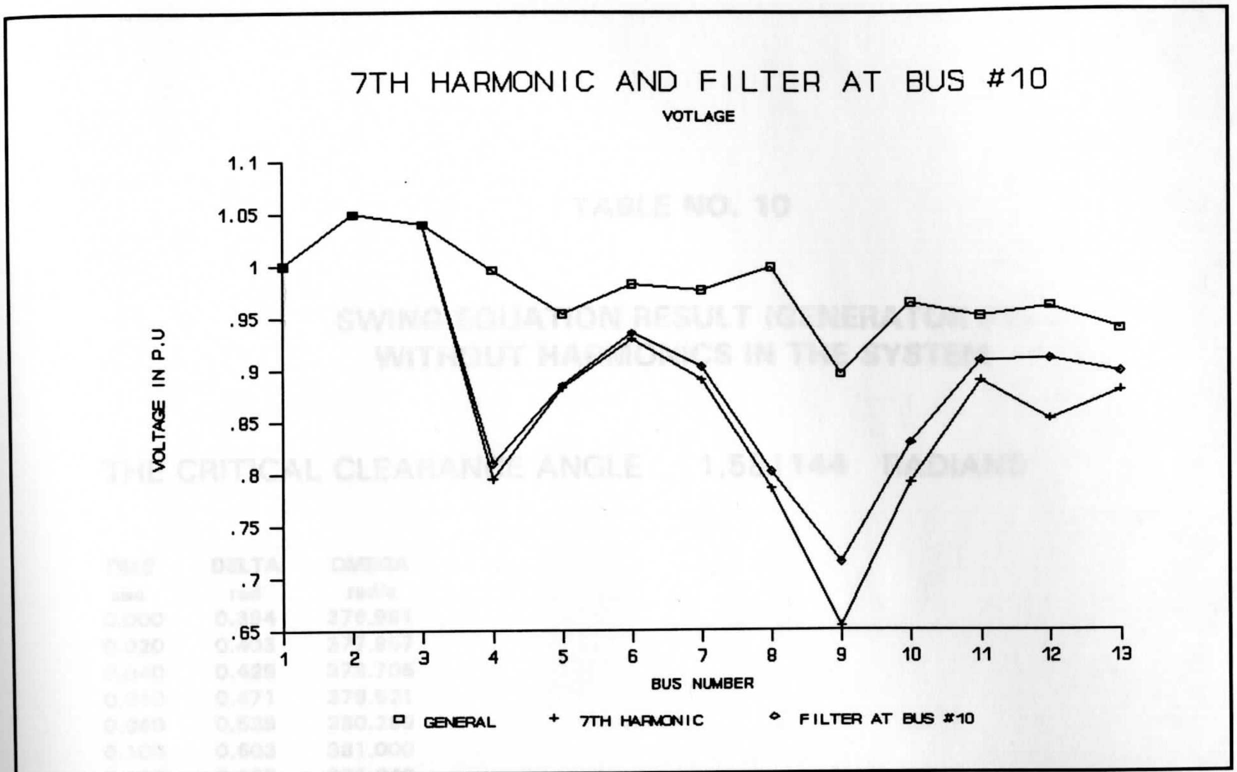


Figure 5.5.17 7TH HARMONIC AND FILTER AT BUS #10 (VOLTAGES)

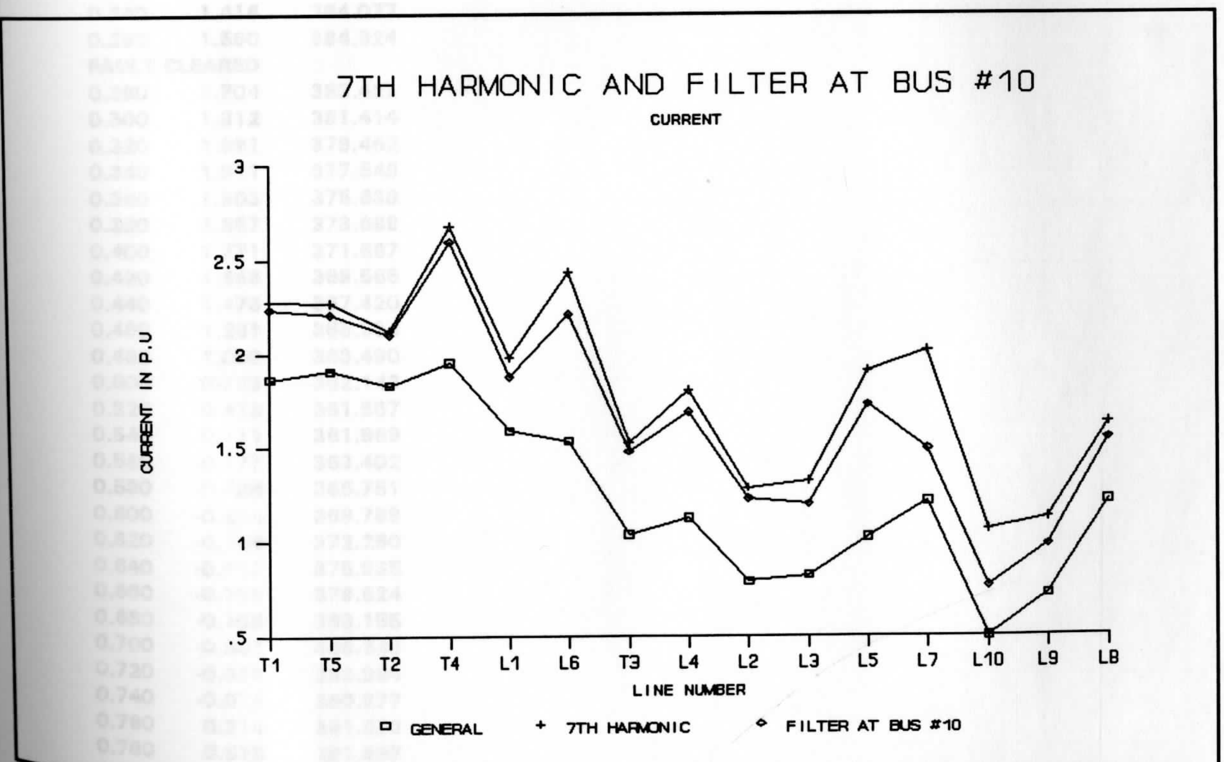


Figure 5.5.18 7TH HARMONIC AND FILTER AT BUS #10 (CURRENTS)

TABLE NO. 10

SWING EQUATION RESULT (GENERATOR #1) WITHOUT HARMONICS IN THE SYSTEM

THE CRITICAL CLEARANCE ANGLE 1.581144 RADIANS

TIME sec	DELTA rad	OMEGA rad/s
0.000	0.394	376.991
0.020	0.403	377.857
0.040	0.429	378.706
0.060	0.471	379.521
0.080	0.529	380.289
0.100	0.603	381.000
0.120	0.689	381.643
0.140	0.788	382.214
0.160	0.898	382.711
0.180	1.017	383.137
0.200	1.144	383.499
0.220	1.277	383.807
0.240	1.416	384.077
0.260	1.560	384.324
FAULT CLEARED		
0.280	1.704	383.423
0.300	1.812	381.414
0.320	1.881	379.462
0.340	1.911	377.549
0.360	1.903	375.638
0.380	1.857	373.688
0.400	1.771	371.667
0.420	1.643	369.565
0.440	1.473	367.420
0.460	1.261	365.334
0.480	1.008	363.490
0.500	0.723	362.143
0.520	0.418	361.567
0.540	0.111	361.969
0.560	-0.177	363.402
0.580	-0.428	365.751
0.600	-0.624	368.789
0.620	-0.754	372.260
0.640	-0.812	375.935
0.660	-0.796	379.624
0.680	-0.708	383.155
0.700	-0.551	386.343
0.720	-0.336	388.984
0.740	-0.076	390.877
0.760	0.214	391.873
0.780	0.515	391.937
0.800	0.808	391.167
0.820	1.079	389.761
0.840	1.317	387.952
0.860	1.516	385.949

TABLE NO. 11

SWING EQUATION RESULT (GENERATOR #3) WITHOUT HARMONICS IN THE SYSTEM

THE CRITICAL CLEARANCE ANGLE 1.459474 RADIANS

TIME sec	DELTA rad	OMEGA rad/s
0.000	0.423	376.991
0.020	0.431	377.819
0.040	0.456	378.630
0.060	0.497	379.409
0.080	0.553	380.143
0.100	0.622	380.820
0.120	0.705	381.433
0.140	0.800	381.975
0.160	0.904	382.447
0.180	1.018	382.849
0.200	1.138	383.188
0.220	1.265	383.474
0.240	1.397	383.720
FAULT CLEARED		
0.260	1.528	382.770
0.280	1.623	380.625
0.300	1.674	378.478
0.320	1.682	376.328
0.340	1.647	374.161
0.360	1.569	371.969
0.380	1.446	369.767
0.400	1.280	367.622
0.420	1.072	365.659
0.440	0.829	364.075
0.460	0.559	363.106
0.480	0.278	362.970
0.500	0.003	363.785
0.520	-0.246	365.527
0.540	-0.452	368.041
0.560	-0.601	371.102
0.580	-0.686	374.477
0.600	-0.702	377.958
0.620	-0.648	381.356
0.640	-0.528	384.488
0.660	-0.350	387.160
0.680	-0.125	389.180
0.700	0.133	390.393
0.720	0.407	390.732
0.740	0.678	390.240
0.760	0.933	389.065
0.780	1.159	387.405
0.800	1.348	385.454
0.820	1.497	383.361
0.840	1.603	381.220
0.860	1.666	379.074

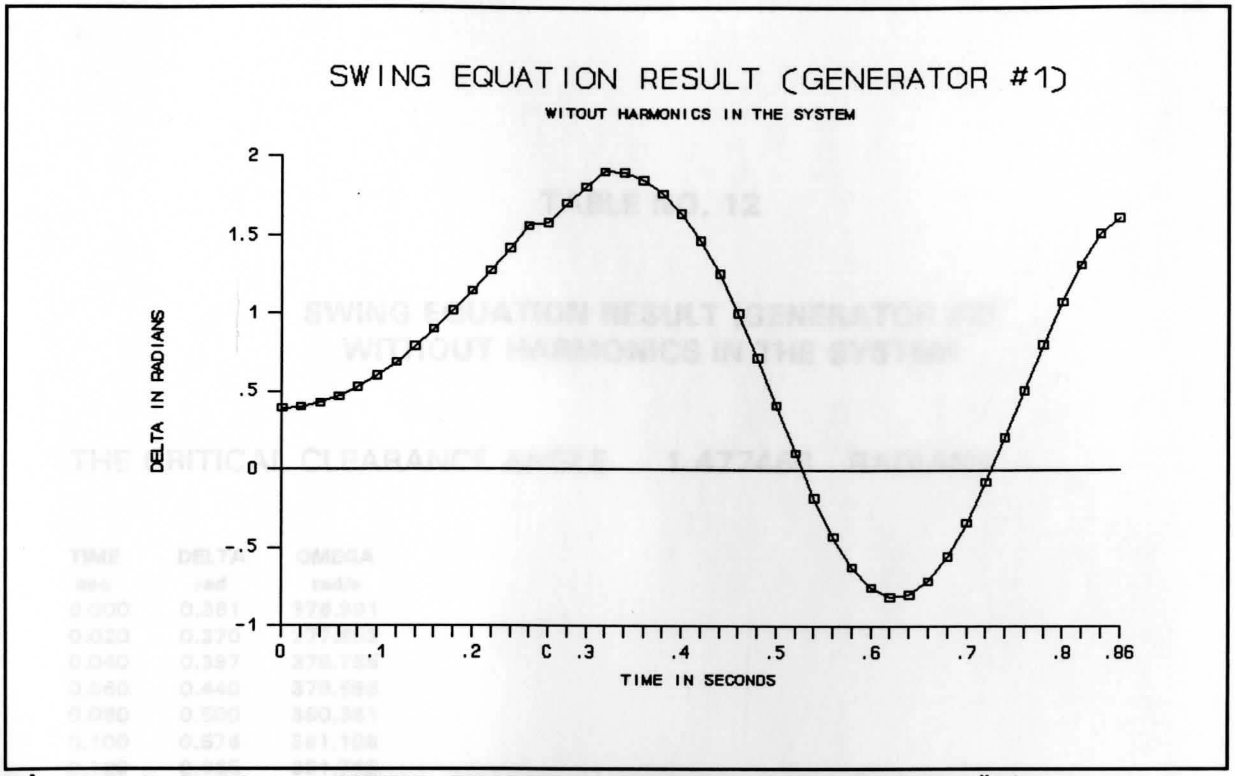


Figure 5.5.19 SWING EUQATION RESULT (GENERATOR #1) WITHOUT HARMONICS IN THE SYSTEM

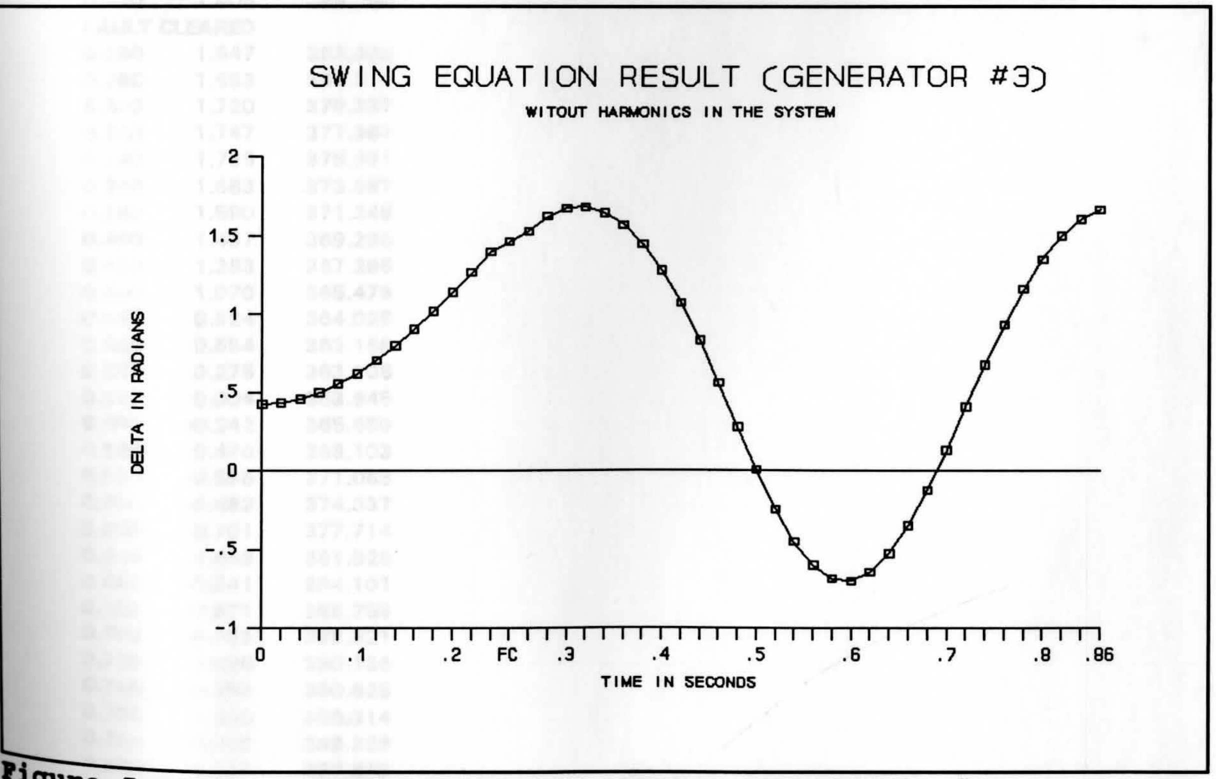


Figure 5.5.20 SWING EQUATION RESULT (GENERATOR #3) WITHOUT HARMONIC IN THE SYSTEM

TABLE NO. 12

SWING EQUATION RESULT (GENERATOR #2) WITHOUT HARMONICS IN THE SYSTEM

THE CRITICAL CLEARANCE ANGLE 1.477468 RADIANS

TIME sec	DELTA rad	OMEGA rad/s
0.000	0.361	376.991
0.020	0.370	377.883
0.040	0.397	378.755
0.060	0.440	379.593
0.080	0.500	380.381
0.100	0.576	381.108
0.120	0.665	381.763
0.140	0.766	382.342
0.160	0.878	382.842
0.180	1.000	383.267
0.200	1.129	383.623
0.220	1.265	383.922
0.240	1.406	384.180
FAULT CLEARED		
0.260	1.547	383.308
0.280	1.653	381.317
0.300	1.720	379.337
0.320	1.747	377.367
0.340	1.735	375.391
0.360	1.683	373.387
0.380	1.590	371.349
0.400	1.457	369.296
0.420	1.283	367.295
0.440	1.070	365.475
0.460	0.824	364.025
0.480	0.554	363.168
0.500	0.275	363.106
0.520	0.004	363.945
0.540	-0.242	365.659
0.560	-0.446	368.103
0.580	-0.595	371.068
0.600	-0.682	374.337
0.620	-0.701	377.714
0.640	-0.653	381.026
0.660	-0.541	384.101
0.680	-0.371	386.759
0.700	-0.153	388.821
0.720	0.098	390.136
0.740	0.368	390.625
0.760	0.640	390.314
0.780	0.898	389.328
0.800	1.131	387.849
0.820	1.331	386.064
0.840	1.493	384.127
0.860	1.616	382.140

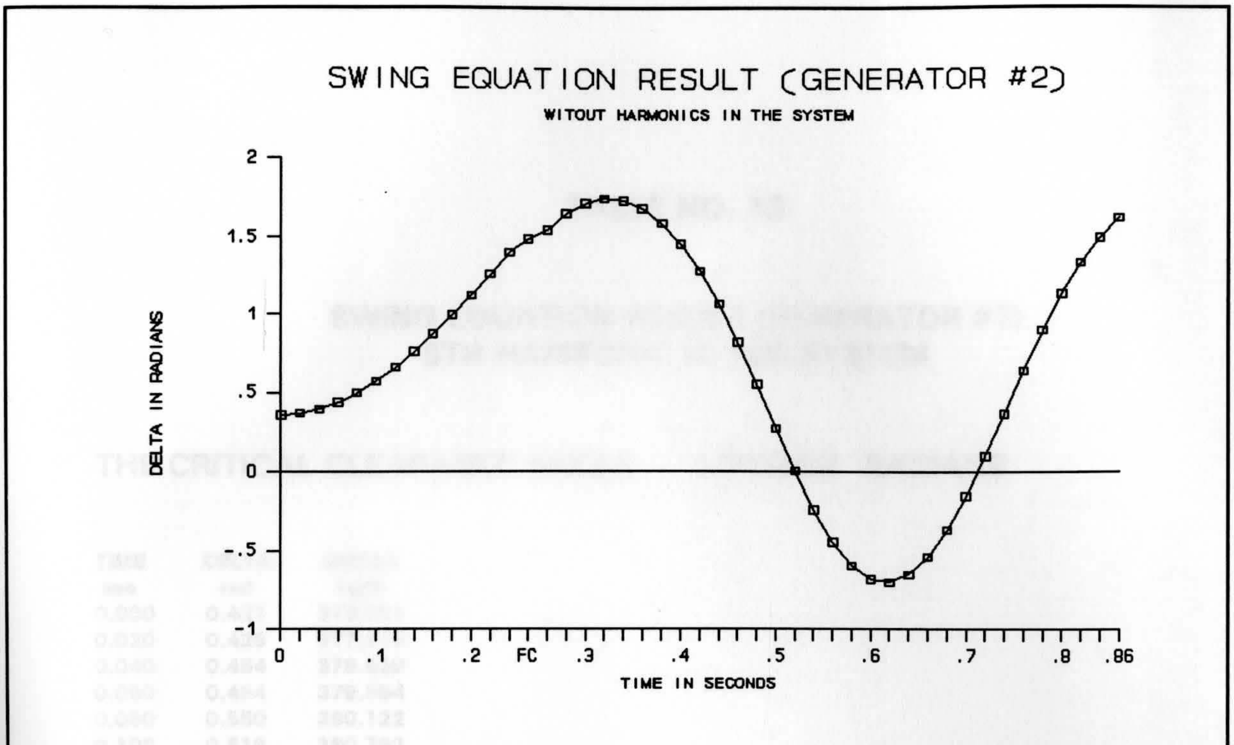


Figure 5.5.21 SWING EQUATION RESULT (GENERATOR #2) WITHOUT HARMONICS IN THE SYSTEM

TABLE NO. 13

SWING EQUATION RESULT (GENERATOR #1)
5TH HARMONIC IN THE SYSTEM

THE CRITICAL CLEARANCE ANGLE 1.287403 RADIANS

TIME sec	DELTA rad	OMEGA rad/s
0.000	0.421	376.991
0.020	0.429	377.815
0.040	0.454	378.620
0.060	0.494	379.394
0.080	0.550	380.122
0.100	0.619	380.793
0.120	0.701	381.399
0.140	0.795	381.934
0.160	0.899	382.396
0.180	1.011	382.789
0.200	1.130	383.117
0.220	1.256	383.392
FAULT CLEARED		
0.240	1.380	382.343
0.260	1.463	379.944
0.280	1.498	377.504
0.300	1.483	375.044
0.320	1.420	372.582
0.340	1.307	370.158
0.360	1.147	367.859
0.380	0.943	365.840
0.400	0.704	364.317
0.420	0.440	363.534
0.440	0.170	363.682
0.460	-0.087	364.834
0.480	-0.312	366.904
0.500	-0.487	369.692
0.520	-0.601	372.948
0.540	-0.648	376.428
0.560	-0.624	379.911
0.580	-0.532	383.186
0.600	-0.378	386.044
0.620	-0.173	388.272
0.640	0.069	389.692
0.660	0.330	390.203
0.680	0.593	389.820
0.700	0.839	388.673
0.720	1.057	386.956
0.740	1.236	384.869
0.760	1.371	382.575
0.780	1.459	380.181
0.800	1.499	377.742
0.820	1.489	375.283
0.840	1.430	372.819
0.860	1.322	370.387

TABLE NO. 14

SWING EQUATION RESULT (GENERATOR #3)
5TH HARMONIC IN THE SYSTEM

THE CRITICAL CLEARANCE ANGLE 1.185265 RADIANS

TIME sec	DELTA rad	OMEGA rad/s
0.000	0.532	376.991
0.020	0.539	377.706
0.040	0.561	378.407
0.060	0.596	379.081
0.080	0.644	379.718
0.100	0.704	380.307
0.120	0.776	380.843
0.140	0.858	381.320
0.160	0.949	381.738
0.180	1.048	382.097
0.200	1.153	382.403
FAULT CLEARED		
0.220	1.258	381.393
0.240	1.322	379.024
0.260	1.339	376.601
0.280	1.307	374.169
0.300	1.226	371.780
0.320	1.099	369.516
0.340	0.929	367.507
0.360	0.722	365.934
0.380	0.490	365.004
0.400	0.246	364.898
0.420	0.010	365.702
0.440	-0.201	367.379
0.460	-0.371	369.776
0.480	-0.487	372.675
0.500	-0.542	375.844
0.520	-0.533	379.062
0.540	-0.460	382.119
0.560	-0.330	384.810
0.580	-0.150	386.935
0.600	0.064	388.329
0.620	0.299	388.892
0.640	0.536	388.624
0.660	0.761	387.622
0.680	0.959	386.048
0.700	1.121	384.076
0.720	1.241	381.859
0.740	1.315	379.506
0.760	1.341	377.088
0.780	1.319	374.653
0.800	1.248	372.248
0.820	1.130	369.948
0.840	0.967	367.872
0.860	0.767	366.191

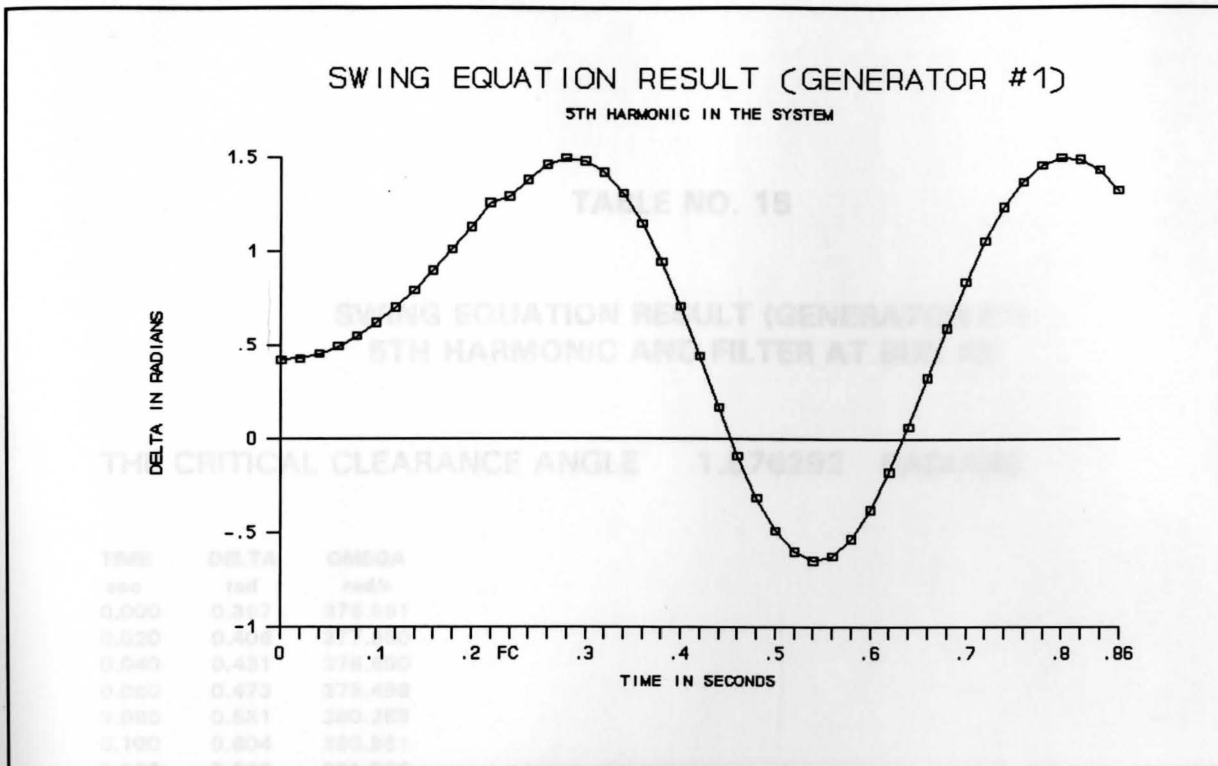


Figure 5.5.22 SWING EQUATION RESULT (GENERATOR #1)
5TH HARMONIC IN THE SYSTEM

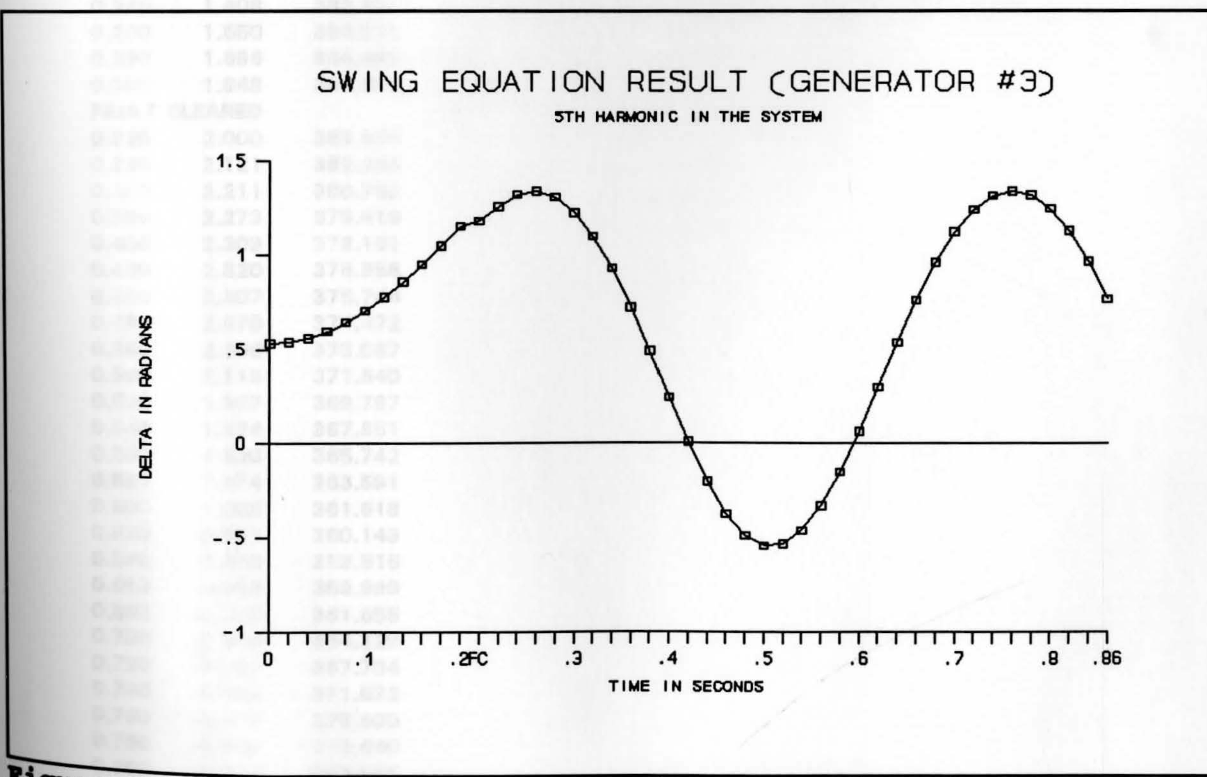


Figure 5.5.23 SWING EQUATION RESULT (GENERATOR #3)
5TH HARMONIC IN THE SYSTEM

TABLE NO. 15

SWING EQUATION RESULT (GENERATOR #1)
5TH HARMONIC AND FILTER AT BUS #9

THE CRITICAL CLEARANCE ANGLE 1.876292 RADIANS

TIME sec	DELTA rad	OMEGA rad/s
0.000	0.397	376.991
0.020	0.406	377.850
0.040	0.431	378.690
0.060	0.473	379.498
0.080	0.531	380.259
0.100	0.604	380.961
0.120	0.690	381.596
0.140	0.788	382.159
0.160	0.896	382.648
0.180	1.014	383.066
0.200	1.139	383.419
0.220	1.270	383.718
0.240	1.408	383.977
0.260	1.550	384.213
0.280	1.696	384.446
0.300	1.848	384.698
FAULT CLEARED		
0.320	2.000	383.935
0.340	2.121	382.265
0.360	2.211	380.769
0.380	2.273	379.416
0.400	2.309	378.161
0.420	2.320	376.956
0.440	2.307	375.744
0.460	2.270	374.472
0.480	2.206	373.087
0.500	2.113	371.540
0.520	1.987	369.797
0.540	1.824	367.851
0.560	1.620	365.742
0.580	1.374	363.591
0.600	1.085	361.618
0.620	0.761	360.143
0.640	0.416	359.515
0.660	0.068	359.999
0.680	-0.258	361.655
0.700	-0.540	364.329
0.720	-0.761	367.734
0.740	-0.909	371.572
0.760	-0.977	375.600
0.780	-0.964	379.640
0.800	-0.872	383.535
0.820	-0.704	387.111
0.840	-0.470	390.149
0.860	-0.182	392.409

TABLE NO. 16

SWING EQUATION RESULT (GENERATOR #3)
5TH HARMONIC AND FILTER AT BUS #9

THE CRITICAL CLEARANCE ANGLE 1.779527 RADIANS

TIME sec	DELTA rad	OMEGA rad/s
0.000	0.362	376.991
0.020	0.371	377.896
0.040	0.398	378.782
0.060	0.443	379.633
0.080	0.504	380.436
0.100	0.580	381.179
0.120	0.671	381.853
0.140	0.774	382.451
0.160	0.889	382.974
0.180	1.013	383.422
0.200	1.146	383.805
0.220	1.285	384.133
0.240	1.431	384.423
0.260	1.582	384.692
0.280	1.739	384.963
FAULT CLEARED		
0.300	1.896	384.147
0.320	2.020	382.332
0.340	2.110	380.661
0.360	2.168	379.106
0.380	2.195	377.623
0.400	2.193	376.159
0.420	2.162	374.657
0.440	2.099	373.062
0.460	2.004	371.326
0.480	1.872	369.423
0.500	1.700	367.360
0.520	1.486	365.207
0.540	1.229	363.119
0.560	0.933	361.351
0.580	0.607	360.230
0.600	0.267	360.066
0.620	-0.065	361.034
0.640	-0.366	363.034
0.660	-0.616	366.052
0.680	-0.800	369.597
0.700	-0.910	373.463
0.720	-0.941	377.439
0.740	-0.893	381.356
0.760	-0.768	385.050
0.780	-0.572	388.325
0.800	-0.318	390.955
0.820	-0.018	392.716
0.840	0.306	393.469
0.860	0.636	393.221

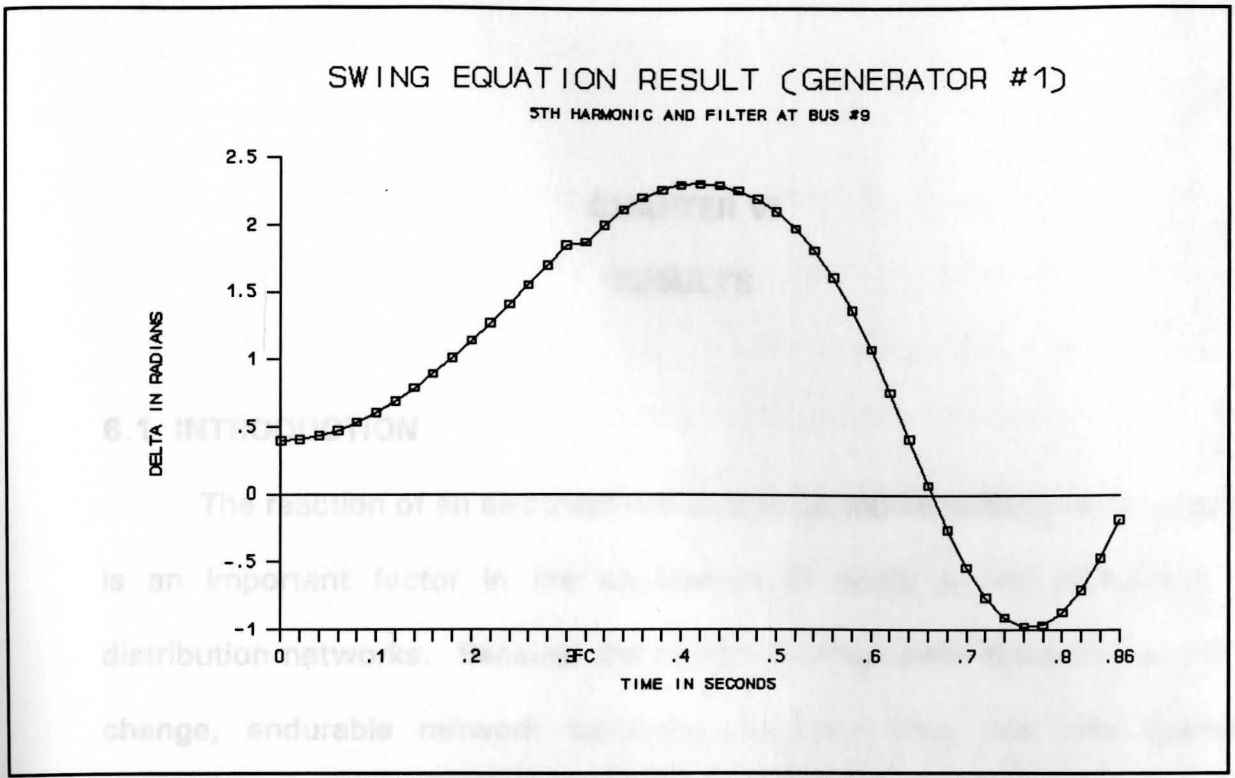


Figure 5.5.24 SWING EQUATION RESULT (GENERATOR #1) 5TH HARMONIC AND FILTER AT BUS #9

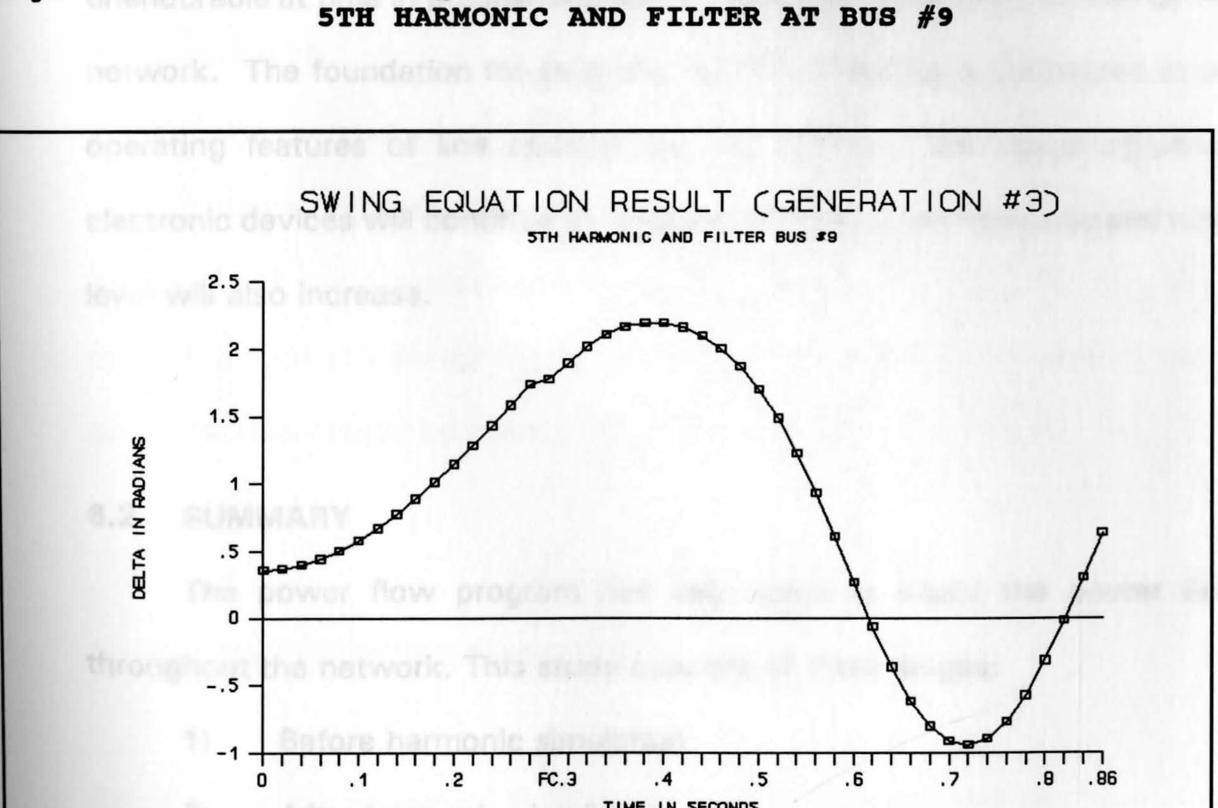


Figure 5.5.25 SWING EQUATION RESULT (GENERATOR #3) 5TH HARMONIC AND FILTER AT BUS #9

CHAPTER VI

RESULTS

6.1 INTRODUCTION

The reaction of an electrical network to harmonic voltages and currents is an important factor in the application of ac/dc power converters to distribution networks. Because the system configuration follows a series of change, endurable network harmonic response may not only become unendurable at time in precise location but also over wide areas served by this network. The foundation for selecting harmonic filtering is connected to the operating features of line commutated converters. The usage of power electronic devices will continue to increase; therefore, the harmonic and noise level will also increase.

6.2 SUMMARY

The power flow program has been used to study the power flow throughout the network. This study consists of three stages:

1) Before harmonic simulation

2) After harmonic simulation

3) Addition of the filter at bus #9

These calculated values have been used for the transient stability to find the critical clearance angle by the Runge-Kutta method. The critical clearance angle is then used in the swing equation to find the critical clearing time. For the transient stability, it is necessary to find the Thevenin equivalents circuit of the system by considering only one generating unit in the system at a time. In this paper, the three phase fault occurred at bus #12 and the power factor of the generators are 0.95 lagging.

6.3 RESULTS

To study the transient stability in the modeled distribution network, the three Thevenin equivalent circuits were solved for three different generators, before and after the harmonic and the design filter were introduced. The values needed to run the Runge-Kutta method program and the Swing equation programs were found by solving the Thevenin equivalent circuits.

1) BEFORE HARMONIC SIMULATION

A) When the generator #1 is in the system network and the rest of the generators are out of the system network,

Power before the fault = 2.867 per unit

Power during the fault = 0.803 per unit

Power after the fault = 2.673 per unit

Delta before the fault = 0.394 radian

Delta after the fault = 0.649 radian

Delta maximum = 2.747 radian

Delta critical = 1.581 radian (by Runge-Kutta method)

Critical clearing time is around 0.270 seconds (by Swing Eq.)

B) When the generator #2 is in the system network and the rest of the generators are out of the system network,

Power before the fault = 2.803 per unit

Power during the fault = 0.815 per unit

Power after the fault = 2.612 per unit

Delta before the fault = 0.361 radian

Delta after the fault = 0.665 radian

Delta maximum = 2.780 radian

Delta critical = 1.477 radian (by Runge-kutta method)

Critical clearing time is around 0.250 seconds (by Swing Eq.)

C) When the generator #3 is in the system network and the rest of the generators are out of the system network,

Power before the fault = 2.931 per unit

Power during the fault = 0.825 per unit

Power after the fault = 2.730 per unit

Delta before the fault = 0.423 radian

Delta after the fault = 0.656 radian

Delta maximum = 2.718 radian

Delta critical = 1.459 radian (by Runge-Kutta method)

Critical clearing time is around 0.250 seconds (by Swing Eq.)

2) AFTER HARMONIC SIMULATION

A) When the generator #1 is in the system network and the generator #3 is out of the system network,

Power before the fault = 3.132 per unit

Power during the fault = 0.838 per unit

Power after the fault = 2.962 per unit

Delta before the fault = 0.421 radian

Delta after the fault = 0.741 radian

Delta maximum = 2.719 radian

Delta critical = 1.287 radian (by Runge-Kutta method)

Critical clearing time is around 0.230 seconds (by Swing Eq.)

B) When the generator #3 is in the system network and the generator #1 is out of the system network,

Power before the fault = 3.261 per unit

Power during the fault = 0.846 per unit

Power after the fault = 3.015 per unit

Delta before the fault = 0.532 radian

Delta after the fault = 0.695 radian

Delta maximum = 2.610 radian

Delta critical = 1.185 radian (by Runge-Kutta method)

Critical clearing time is around 0.210 seconds (by Swing Eq.)

3) ADDITION OF THE FILTER AT BUS #9.

A) When the generator #1 is in the system network and the generator #3 is out of the system network,

Power before the fault = 2.897 per unit

Power during the fault = 0.813 per unit

Power after the fault = 2.672 per unit

Delta before the fault = 0.397 radian

Delta after the fault = 0.629 radian

Delta maximum = 2.739 radian

Delta critical = 1.876 radian (by Runge-Kutta method)

Critical clearing time is around 0.310 seconds (by Swing Eq.)

B) When the generator #3 is in the system network and the generator #1 is out of the system network,

Power before the fault = 2.835 per unit

Power during the fault = 0.784 per unit

Power after the fault = 2.673 per unit

Delta before the fault = 0.362 radian

Delta after the fault = 0.654 radian

Delta maximum = 2.779 radian

Delta critical = 1.779 radian (by Runge-Kutta method)

Critical clearing time is around 0.290 seconds (by Swing Eq.)

6.4 CONCLUSION

The filter is used at different buses to suppress the harmonics in the system network; the filter is used at bus #8, bus #9 and bus #10. It is obvious from the power flow program's results that the best position of the filter is at bus #9. The filter is more effective for the 5th harmonic than the 7th harmonic; the filter did suppress the 7th harmonic to some extent. To study the transient stability in the modeled distribution network, we considered only bus #9 with the filter, because having a filter on this bus suppresses the most harmonics.

When there are no harmonics in the system, generator #1 has the largest critical clearance angle and the longest critical time as compared to other generators; it has the biggest inertia constant (50 H). Increasing the per unit inertia constant of a synchronous machine reduces angular acceleration, thereby slowing down angular swings and increasing critical clearing time. Generator #2 is far away from the harmonics source; therefore, the harmonic source has very minor effects on it.

Comparing the results of generator #1 before and after the harmonics are introduced we found that: the critical clearance angle decreases by 0.294 radian and critical clearing time decreases by 0.04 seconds. For the generator #3, the critical clearance angle decreases by 0.274 radian and critical clearing time decreases by 0.04 seconds. But after introducing the filter into the network, the critical clearance angle and critical clearing time increases.

6.5 RECOMMENDATION FOR FUTURE EFFORTS

In this paper, assuming a balanced symmetrical three phase system, the following suggestions are made:

1) To examine the harmonic effects on the transient stability of an unbalanced, unsymmetrical system, which is the usual case on a power transmission and distribution system.

2) To develop a voltage control system around the testing bus to keep to a minimum the voltage change caused by the addition of the filter.

3) To examine every single bus node in the network system for different harmonics.

4) To develop fast responding, high gain amplifiers.

APPENDIX A

NEWTON-RAPHSON METHOD

The Newton-Raphson method has a better convergence property and for many systems is faster than Gauss-Seidal. It has a much larger time per iteration but requires very few iterations. The basic iteration procedure is as follows:

$$x^{(p+1)} = x^{(p)} - \frac{f(x^p)}{f'(x^p)} \qquad \text{(A-1)}$$

Extending this to a multi-equation system

$$x^{(p+1)} = x^{(p)} - J^{-1}(x^p)\, f(x^p) \qquad \text{(A-2)}$$

Now consider the application to an n-node power system, for a link connecting nodes k and j of admittance Y_{kj}:

$$P_k + jQ_k = V_k I_k^* = V_k \sum_{j=1}^{n-1} (Y_{kj} V_j)^* \qquad \text{(A-3)}$$

Let

$$V_k = a_k + jb_k \qquad \text{(A-4)}$$

and

$$Y_{kj}=G_{kj}-jB_{kj} \tag{A-5}$$

then

$$P_k+jQ_k=(a_k+jb_k)\sum_{1}^{n-1}[(G_{kj}-jB_{kj})(a_j+jb_j)]^* \tag{A-6}$$

from which

$$P_k=\sum_{j=1}^{n-1}[a_k(a_jG_{kj}+b_jB_{kj})+b_k(b_jG_{kj}-a_jB_{kj})] \tag{A-7}$$

and

$$Q_k=\sum_{j=1}^{n-1}[b_k(a_jG_{kj}+b_jB_{kj})-a_k(b_jG_{kj}-a_jB_{kj})] \tag{A-8}$$

There are two non-linear equations for each node. Changes in P and Q are related to changes in **a** and **b** by equations (A-7) and (A-8). For example,

$$\Delta P_1+\frac{\partial P_1}{\partial a_1}\Delta a_1+\frac{\partial P_1}{\partial a_2}\Delta a_2+\ldots+\frac{\partial P_1}{\partial a_{n-1}}\Delta a_{n-1} \tag{A-9}$$

Similar equations hold in terms of ΔP and Δb, and ΔQ in terms of Δa and Δb.

The Jacobin matrix can be denoted as

J_A	J_B
J_C	J_D

The elements of the matrix are evaluated for the values of P,Q and V at each iteration as follows:

For the Submatrix $\mathbf{J_A}$ and from the equation (A-7),

$$\frac{\partial P_k}{\partial a_j}=a_k G_{kj}-b_j B_{kj} \qquad \text{(A-10)}$$

(where k is not equal to j, i.e.,there are off-diagonal elements)

For diagonal elements,

$$\frac{\partial P_k}{\partial a_k}=2a_k G_{kk}+b_k B_{kk}-b_k B_{kk}+\sum_{j=1\setminus j\neq k}^{n-1}(a_j G_{kj}+b_j B_{kj}) \qquad \text{(A-11)}$$

This element can be obtained by expressing some of the quantities in terms of the current at node k, $\mathbf{I}_k$ which can be found separately at each iteration.

$$I_k=(G_{kk}-jB_{kk})(a_k+jb_k)+\sum_{j=1\setminus j\neq k}^{n-1}(G_{kj}-jB_{jk})(a_j+jb_j) \quad \text{(A-12)}$$

from which

$$c_k=a_kG_{kk}+b_kB_{kk}+\sum_{j=1\setminus j\neq k}^{n-1}(a_jG_{kj}+b_jB_{kj}) \quad \text{(A-13)}$$

and

$$d_k=b_kG_{kk}-a_kB_{kk}+\sum_{j=1\setminus j\neq k}^{n-1}(b_jG_{kj}-a_jB_{jk}) \quad \text{(A-14)}$$

therefore,

$$\frac{\partial P_k}{\partial a_k}=a_kG_{kk}-b_kB_{kk}+c_K \quad \text{(A-15)}$$

For the submatrix $\mathbf{J}_B$:

$$\frac{\partial P_k}{\partial b_k}=a_kB_{kk}+b_kG_{kk}+d_k \quad \text{(A-16)}$$

and

$$\frac{\partial P_k}{\partial b_j}=a_kB_{kj}+b_kG_{kj} \quad \text{(A-17)}$$

For the submatrix $\mathbf{J}_C$:

$$\frac{\partial Q_k}{\partial a_k} = a_k B_{kk} + b_k G_{kk} - d_k \tag{A-18}$$

and

$$\frac{\partial Q_k}{\partial a_j} = a_k B_{kj} + b_k G_{kj} \tag{A-19}$$

For the submatrix $\mathbf{J}_D$:

$$\frac{\partial Q_k}{\partial b_j} = -a_k G_{kj} + b_k B_{kj} \tag{A-20}$$

and

$$\frac{\partial Q_k}{\partial b_k} = -a_k G_{kk} + b_k B_{kk} + c_k \tag{A-21}$$

P and Q are calculated from equations (A-7) and (A-8) and the changes are then calculated from

$$\Delta P_k{}^p = P_k(specified) - P_k{}^p \tag{A-22}$$

and

$$\Delta Q_k{}^p = Q_k(specified) - Q_k{}^p \tag{A-23}$$

The node currents are calculated from

$$I_k{}^p = \left[\frac{P_k{}^p + jQ_k{}^p}{V^p}\right]^* = c_k{}^p + jd_k{}^p \qquad \text{(A-24)}$$

The elements of the Jacobin matrix are found and from here the values of **a** and **b** are determined and the new values are obtained:

$$a_k{}^{p+1} = a_k{}^p + \Delta a_k{}^p \qquad \text{(A-25)}$$

$$b_k{}^{p+1} = b_k{}^p + \Delta b_k{}^p \qquad \text{(A-26)}$$

This process is repeated ($p = p + 1$) until ΔP and ΔQ are less than a prescribed tolerance.

APPENDIX B

TABLE NO. 17

SYSTEM DATA FOR 13-BUS TEST SYSTEM

1) BUS DATA INPUT

BUS #	TYPE	VOL.	DELTA	Pg	Qg	Pl	Ql
		P.U	DEG.	P.U	P.U	P.U	P.U
1)	0	1.00	0.00	--	--	0.00	0.00
2)	2	1.05	--	1.30	--	0.00	0.00
3)	2	1.04	--	1.20	--	0.00	0.00
4)	1	--	--	--	--	0.00	0.00
5)	1	--	--	--	--	-0.20	-0.10
6)	1	--	--	--	--	0.00	0.00
7)	1	--	--	--	--	0.00	0.00
8)	1	--	--	--	--	0.00	0.00
9)	1	--	--	--	--	-0.25	-0.15
10)	1	--	--	--	--	-0.20	-0.12
11)	1	--	--	--	--	-0.15	-0.08
12)	1	--	--	--	--	-0.40	-0.30
13)	1	--	--	--	--	0.00	0.00

2) LINE INPUT DATA

LINE #	BUS-TO-BUS	R'	X'	G'	B'	MVA
		P.U	P.U	P.U	P.U	P.U
1)	4--6	0.007	0.04	0.00	0.07	3.00
2)	6--7	0.004	0.03	0.00	0.07	3.00
3)	7--8	0.005	0.03	0.00	0.06	3.00
4)	5--8	0.006	0.04	0.00	0.06	3.00
5)	8--9	0.018	0.10	0.00	0.11	3.00
6)	4--9	0.015	0.12	0.00	0.15	3.00
7)	9--10	0.005	0.03	0.00	0.07	3.00
8)	13--11	0.015	0.12	0.00	0.02	3.00
9)	11--12	0.012	0.12	0.00	0.03	3.00
10)	10--12	0.012	0.11	0.00	0.02	3.00

3) GENERATOR INPUT DATA

GENERATOR #	BUS #	X'	H
		P.U	P.U
1)	1	0.20	50.00
2)	2	0.15	10.00
3)	3	0.10	25.00

4) TRANSFORMER INPUT DATA

TRAN. #	BUS-TO-BUS	R	X	G	B	MVA
		P.U	P.U	P.U	P.U	P.U
1)	1--4	0.005	0.08	0.00	0.00	1.50
2)	2--6	0.006	0.04	0.00	0.00	2.50
3)	5--7	0.004	0.07	0.00	0.00	1.25
4)	3--8	0.007	0.03	0.00	0.00	2.25
5)	1--13	0.006	0.05	0.00	0.00	2.25

APPENDIX C

BASIC PROGRAM FOR NEWTON-RAPHSON METHOD

```
10 CLEAR
20 SCREEN 0
30 PRINT "       POWER FLOW PROGRAM              "
40 PRINT " "
50 PRINT "  (1) Inputing bus matrix by line admitance "
60 PRINT " "
70 PRINT "  (2) Calculating loadflow by N-R method    "
80 PRINT " "
90 PRINT "  (3) Quit                    "
100 PRINT " "
110 PRINT TAB(15);"Make a choice between 1, 2 and 3 ......<? >";
120 A$ = INPUT$(1)
130 AI = VAL(A$)
140 IF (AI = 1) OR ((AI = 2) OR (AI = 3)) THEN GOTO 150
150 ON AI GOSUB 180, 1900, 6380
170 GOTO 110
180 '**********************************
190 '*   BUS ADMITANCE MATRIX      *
200 '**********************************
210 CLS
220 SCREEN 2
225 DIM Y(N,N), G(N,N), B(N,N), H(N,N), F(N,N)
230 PRINT "         Create Bus Admitance Matrix "
240 PRINT "         (by using line admitance)  "
250 PRINT " "
260 PRINT "                 Y = G+jB          "
270 FOR I = 5 TO 15
280 LOCATE I, 7
290 NEXT I
300 LOCATE 5, 8: INPUT "Number of generators  = ", G
310 LOCATE , 8: INPUT "Number of load buses  = ", L
320 T = L + G
330 LOCATE , 8: PRINT "Total number of buses ="; N
370 PRINT "   "
390 PRINT "         BUS #. ";
400 LOCATE , 25: PRINT CHR$(61) + CHR$(62); " Y = G+jB"
410 FOR I = 1 TO N
420 LOCATE 5, 8: PRINT " BUS #. "; I
430 FOR J = I TO N
460 PRINT STRING$(50, " ")
480 PRINT CHR$(61) + CHR$(62);
500 PRINT " Y("; I; ","; J; ") =";
510 INPUT " ", G(I, J)
530 INPUT "jB(+/-) ", B(I, J)
550 F(I, J) = SQR(G(I, J) ^ 2 + B(I, J) ^ 2)
560 IF G(I, J) = 0 THEN GOTO 580
570 GOTO 620
580 IF B(I, J) > 0 THEN H(I, J) = 3.1416/ 2
590 IF B(I, J) < 0 THEN H(I, J) = -3.1416/ 2
```

```
600 IF B(I, J) = 0 THEN H(I, J) = 0
610 GOTO 680
620 IF G(I, J) > 0 THEN GOTO 640
630 IF G(I, J) < 0 THEN GOTO 660
640 H(I, J) = ATN(B(I, J) / G(I, J))
650 GOTO 670
660 H(I, J) = ATN(B(I, J) / G(I, J)) + 3.1416
670 IF I = J THEN GOTO 700
680 G(J, I) = G(I, J)
690 B(J, I) = B(I, J)
700 NEXT J
710 NEXT I
720 OPEN "O", #2, "AZI1"
730 OPEN "O", #3, "AZI2"
740 FOR I = 1 TO N
750 FOR J = I TO N
760 WRITE #2, F(I, J), H(I, J)
770 WRITE #3, G(I, J), B(I, J)
780 NEXT J
790 NEXT I
800 CLOSE #2
810 CLOSE #3
820 FOR I = 1TO N
830 FOR J = 1 TO N
840 IF I = J THEN GOTO 870
850 G(I, I) = G(I, I) + G(I, J)
860 B(I, I) = B(I, I) + B(I, J)
870 NEXT J
880 NEXT I
890 FOR I = 1 TO N
900 FOR J = I TO N
910 IF I = J THEN GOTO 960
920 G(I, J) = -G(I, J)
930 G(J, I) = G(I, J)
940 B(I, J) = -B(I, J)
950 B(J, I) = B(I, J)
960 NEXT J
970 NEXT I
980 FOR I = 1TO N
990 FOR J = 1 TO N
1000 Y(I, J) = SQR(G(I, J) ^ 2 + B(I, J) ^ 2)
1010 IF G(I, J) = 0 THEN GOTO 1120
1120 NEXT J
1130 NEXT I
1140 OPEN "O", #1, "AZI"
1150 WRITE #1, G, L, T
1160 FOR I = 1 TO N
1170 FOR J = 1 TO N
1190 WRITE #1, Y(I, J)
1200 NEXT J
1210 NEXT I
1220 CLOSE #1
1230 ERASE G, B, Y, F, H
1240 RETURN
1250 '******************************
1260 '*     JACOBIAN MATRIX        *
1270 '******************************
1280 CLS
1290 DIM J(2* (S+T+1), 2* (S+T+1))
1300 FOR I = 2 TO T
1310 FOR J = 2 TO T
1320 IF I <> J THEN GOTO 1380
```

```
1330 FOR K = 1 TO N
1340 IF I = K THEN GOTO 1360
1350 J(I, I) = J(I,I) + V(I)* Y(I,K)* V(K)* SIN(ANG(I,K) + VA(K)-VA(I))
1360 NEXT K
1370 GOTO 1390
1380 J(I, J) = -V(I)*Y(I,J)*V(J)*SIN(ANG(I,J) + VA(J)-VA(I))
1390 NEXT J
1400 NEXT I
1410 FOR I = 2 TO T
1420 FOR J = G + 1 TO T
1430 IF I < > J THEN GOTO 1520
1440 FOR K = 1 TO T
1450 IF I = K THEN GOTO 1470
1460 GOTO 1490
1470 J(I, T+J-G) = J(I,T+J-G) + 2*V(I)*Y(I,K)*V(K)*COS(ANG(I,K) + VA(K)-VA(I))
1480 GOTO 1500
1490 J(I, T+J-G) = J(I, T+J-G) + Y(I,K)*V(K)*COS(ANG(I,K) + VA(K)-VA(I))
1500 NEXT K
1510 GOTO 1530
1520 J(I, T+J-G) = V(I)*Y(I,J)*COS(ANG(I,K) + VA(J)-VA(I))
1530 NEXT J
1540 NEXT I
1550 FOR I = G + 1 TO T
1560 FOR J = 2 TO T
1570 IF I < > J THEN GOTO 1630
1580 FOR K = 1 TO T
1590 IF I = K THEN GOTO 1610
1600 J(T+I-G, J) = J(T+I-G, J) + V(I)*Y(I,K)*V(K)*COS(ANG(I,K) + VA(K)-VA(I))
1610 NEXT K
1620 GOTO 1640
1630 J(T+I-G, J) = -V(I)*Y(I,J)*V(J)*COS(ANG(I,K) + VA(J)-VA(I))
1640 NEXT J
1650 NEXT I
1660 FOR I = G + 1 TO T
1670 FOR J = G + 1 TO T
1680 IF I < > J THEN GOTO 1770
1690 FOR K = 1 TO T
1700 IF I = T THEN GOTO 1720
1710 GOTO 1740
1720 J(T+I-G, T+J-G) = J(T+I-G, T+J-G)-2*V(I)*Y(I,K)* SIN(ANG(I,K) + VA(K)-VA(I))
1730 GOTO 1750
1740 J(T+I-G, T+J-G) = J(T+I-G, T+J-G)-Y(I,K)*V(K)*SIN(ANG(I,K) + VA(K)-VA(I))
1750 NEXT K
1760 GOTO 1780
1770 J(T+I-G, T+J-G) = -V(I)*Y(I,J)*SIN(ANG(I,J) + VA(J)-VA(I))
1780 NEXT J
1790 NEXT I
1800 U = T + S - 1
1810 FOR I = 1 TO U
1820 FOR J = 1 TO U
1830 J(I, J) = J(I + 1, J + 1)
1840 NEXT J
1850 NEXT I
1860 RETURN
1900 '*******************************************
1910 '    Newton-Raphson Power Flow         *
1920 '*******************************************
1925 DIM ANG(N,N), VA(N,N), V(N), Y(N,N), QP(N), RP(N)
1926 DIM QPC(N), RPC(N), Q(N), P(N)
1930 FOR I = 2 TO T
1940 RP(I) = 0
1950 FOR J = 1 TO T
```

```
1960 RP(I) = RP(I) + V(I)*Y(I,J)*V(J)*COS(ANG(I,J) + VA(J)-VA(I))
1970 NEXT J
1980 NEXT I
1990 FOR I = G + 1 TO T
2000 QP(I) = 0
2010 FOR J = 1 TO T
2020 QP(I) = QP(I)-V(I)*Y(I,J)*V(J)*SIN(ANG(I,J) + VA(J)-VA(I))
2030 NEXT J
2040 NEXT I
2050 FOR I = 2 TO T
2060 RPC(I) = P(I) - RP(I)
2070 NEXT I
2080 FOR I = G + 1 TO T
2090 QPC(I) = Q(I) - QP(I)
2100 NEXT I
2110 RETURN
2120 '************************
2180 CLS
2190 SCREEN 2
2200 PRINT "        INPUT DATA FOR LOADFLOW CALCULATION"
2210 ON A2 GOTO 2220
2220 OPEN "I", #1, "AZI"
2230 INPUT #1, G, L, T
2240 DIM PG(N), QG(N), PL(N), QL(N), DV(N), DVA(N)
2270 DIM J(S+T+1, S+T+1)
2310 FOR I = 1 TO T
2320 FOR J = 1 TO T
2330 F(I,J) = SQR(G (I, J) ^ 2 + B(I, J) ^ 2)
2340 NEXT J
2350 NEXT I
2360 CLOSE #1
2370 PRINT "    Number of generators  = "; G
2380 PRINT "    Number of load buses  = "; L
2390 PRINT "    Total number of buses = "; T
2400 FOR I = 8 TO 16
2410 LOCATE I, 4: PRINT STRING$(70, " ")
2420 NEXT I
2430 SCREEN 2
2440 LOCATE 8 , 10: PRINT " BUS #. 1
2450 LOCATE 10, 10: PRINT "  P,gen  =   "
2460 LOCATE   , 10: PRINT "  V,bus  =   "
2470 LOCATE   , 10: PRINT "  P,load =   "
2480 LOCATE   , 10: PRINT "  Q,load =   "
2500 LOCATE 10, 21: PRINT " -"
2510 LOCATE  , 21: INPUT " ", V(1)
2520 LOCATE   , 21: INPUT " ", PL(1)
2530 LOCATE   , 21: INPUT " ", QL(1)
2540 LOCATE  8, 10: PRINT "   BUS #. 2 "
2550 FOR I = 2 TO G
2560 LOCATE 8 , 10: PRINT " BUS #."; I
2570 LOCATE 10, 21: PRINT STRING$(20, " ")
2580 LOCATE   , 21: PRINT STRING$(20, " ")
2590 LOCATE   , 21: PRINT STRING$(20, " ")
2600 LOCATE   , 21: PRINT STRING$(20, " ")
2610 LOCATE 10, 21: INPUT " ", PG(I)
2620 LOCATE   , 21: INPUT " ", V(I)
2630 LOCATE   , 21: INPUT " ", PL(I)
2640 LOCATE   , 21: INPUT " ", QL(I)
2650 P(I) = PG(I) - PL(I)
2660 NEXT I
2670 LOCATE 8, 10: PRINT " BUS #. "
2680 FOR I = G + 1 TO T
```

```
2690 LOCATE 8 , 10: PRINT " BUS #."; I
2700 LOCATE 10, 21: PRINT STRING$(20, " ")
2710 LOCATE   , 21: PRINT STRING$(20, " ")
2720 LOCATE   , 21: PRINT STRING$(20, " ")
2730 LOCATE   , 21: PRINT STRING$(20, " ")
2740 LOCATE 10, 21: PRINT " - "
2750 LOCATE   , 21: PRINT " - "
2760 LOCATE   , 21: INPUT " ", PL(I)
2770 LOCATE   , 21: INPUT " ", QL(I)
2780 P(I) = - PL(I)
2790 Q(I) = - QL(I)
2800 NEXT I
2810 U = S + T - 1
2820 PRINT "  "
2830 VA(1) = 0
2840 FOR I = 2 TO T
2850 VA(I) = 0
2860 NEXT I
2870 FOR I = G + 1 TO T
2890 V(I) = 1
2900 NEXT I
2940 L= L + X(I)* X(I)
2950 NEXT I
2960 P1 = -M/ (L* MAG)
2970 IF P1 < 1 THEN GOTO 4000
2980 P1 = 0
2990 GOTO 4010
2995 RETURN
2996 '*****************************
3000 GOSUB 1900
3010 D = 1
3020 FOR I = 2 TO T
3030 FUNC(D) = 0
3040 FUNC(D) = -PRC(I)
3050 D= D + 1
3060 NEXT I
3070 FOR I = G + 1 TO T
3080 FUNC(D) = 0
3090 FUNC(D) = -QPC(I)
3100 D= D + 1
3110 NEXT I
3120 RETURN
3200 AA = 0
3210 FOR I = 1 TO U
3220 AA = AA + FUNC(I) * FUNC(I)
3230 NEXT I
3240 RETURN
3250 FOR I = 1 TO U
3260 R(I) = 0
3270 FOR J = 1 TO U
3280 R(I) = R(I)+ J(J,I) * FUNC(J)
3290 NEXT J
3300 R(I) = 2 * R(I)
3310 NEXT I
3320 RETURN
3370 DIM R(U),TOL(U),Z(U),T(U)
3380 DIM W(U,U), C(U,U), M(U,U)
3390 DIM FUNC(U)
3400 TOL (.1*.1) * U
3420 R = SQR( M *(DV^ 2)+ T*(DA^2))
3430 IT = 0
3440 GOSUB 1250
```

```
3450 GOSUB 3000
3460 GOSUB 3200
3470 VALUE= AA
3480 GOSUB 3250
3490 MAG = 0
3500 FOR I = 1 TO U
3510 MAG = MAG+ R(I)* R(I)
3520 NEXT I
3530 MAG = SQR(MAG)
3540 GOSUB 6320
3550 IF VALUE < = TOL THEN RETURN
3560 IF MAG < .001 THEN RETURN
3580 FOR I = 1 TO U
3590 TOL(I) = -R(I)
3600 NEXT I
3610 GOTO 3860
3630 CP = MAG* MAG* MAG/ Q
3640 IF CP >R THEN GOTO 3860
3650 FOR I = 1 TO U
3660 FOR J = 1 TO U
3670 INV(I, J) = W(I, J)
3680 NEXT J
3690 NEXT I
3710 FOR I = 1 TO U
3720 Z(I) = 0
3730 FOR J = 1 TO U
3740 Z(I) = Z(I)+ INV(I, J)* R(J)
3750 NEXT J
3760 Z(I) = -Z(I)
3770 NEXT I
3780 NX = 0
3790 FOR I = 1 TO U
3800 NX = NX+ Z(I)* Z(I)
3810 NEXT I
3820 NX = SQR(NX)
3830 IF NX < R THEN NN = 1 ELSE D = 0
3840 IF NX > R THEN GOTO 3860
3860 FOR I = 1 TO U
3870 Z(I) = (TOL(I) / MAG)*R
3880 NEXT I
3890 GOTO 4010
3900 M = 0
3910 L = 0
3920 FOR I = 1 TO U
3930 M = M+ R(I)* Z(I)
3940 L = L+ Z(I)* Z(I)
3950 NEXT I
3960 P1 = -M/(L* MAG)
3970 IF P1 < 1 THEN GOTO 4000
3980 P1 = 0
3990 GOTO 4010
4000 P1 = 57.278* ATN(SQR((1 - P1*P1)/(P1 * P1)))
4010 D = 1
4020 FOR I = 2 TO T
4030 VA(I) = VA(I) + Z(D)
4040 D = D + 1
4050 NEXT I
4060 FOR I = G + 1 TO T
4070 V(I) = V(I) + Z(D)
4080 D = D + 1
4090 NEXT I
4100 GOSUB 3000
```

```
4110 GOSUB 3200
4120 VAL = AA
4130 IF VAL > VALUE THEN GOTO 4140 ELSE GOTO 4270
4140 D = 1
4150 FOR I = 2 TO T
4160 VA(I) = VA(I) - Z(D)
4170 D = D + 1
4180 NEXT I
4190 FOR I = G + 1 TO T
4200 V(I) = V(I) - Z(D)
4210 D = D + 1
4220 NEXT I
4230 FOR I = 1 TO U
4240 Z(I) = Z(I)/4
4250 NEXT I
4260 GOTO 4010
4270 IT = IT + 1
4280 GOTO 3360
4310 '*************************************
4320 '*  COMPUTE RESULTS          *
4340 '*************************************
4350 FOR I = 1 TO U
4360 FOR J = 1 TO U
4370 J(I + 1, J + 1) = INV(I, J + U)
4380 NEXT J
4390 NEXT I
4400 FOR I = 2 TO T
4410 DVA(I) = 0
4420 FOR J = 2 TO T
4430 DVA(I) = DVA(I)+ J(I, J)* RPC(J)
4440 NEXT J
4450 FOR K =T+1 TO T+S
4460 DVA(I) = DVA(I)+ J(I,K)* QPC(K+G-T)
4470 NEXT K
4480 NEXT I
4490 FOR I = G + 1 TO T
4500 DV(I) = 0
4510 FOR J = 2 TO T
4520 DV(I) = DV(I)+ J(T+I-G, J)* RPC(J)
4530 NEXT J
4540 FOR K = T+1 TO T+S
4560 DV(I) = DV(I) + J(T+I-G, K)* QPC(K+G-T)
4570 NEXT K
4580 NEXT I
4590 RETURN
4595 DIM BB(N,N), H(N,N), B(N,N), F(N,N), G(N,N)
4596 DIM I(N,N), PLINE(N,N), QLINE(N,N)
4600 FOR I = 2 TO T
4610 VA(I) = VA(I)+ DVA(I)
4620 NEXT I
4630 FOR I = G + 1 TO T
4640 V(I) = V(I) + DV(I)
4650 NEXT I
4660 RETURN
4670 FOR J = 1 TO T
4680 P(1) =P(1)+V(1)*Y(1,J)*V(J)*COS(ANG(1,J)+VA(J)-VA(1))
4690 Q(1) =Q(1)-V(1)*Y(1,J)*V(J)*SIN(ANG(1,J)+VA(J)-VA(1))
4700 NEXT J
4710 FOR I = 2 TO G
4720 FOR J = 1 TO T
4730 Q(I) =Q(I)-V(I)*Y(I,J)*V(J)*SIN(ANG(I,J)+VA(J)-VA(I))
4740 NEXT J
```

```
4750 NEXT I
4760 PG(1) = P(1) - PL(1)
4770 QG(1) = Q(1) - QL(1)
4780 FOR I = 2 TO G
4790 QG(I) = Q(I) - QL(I)
4800 NEXT I
4810 ERASE J, PRC, QPC, QP, Y, ANG
4840 OPEN "I", #2, "AZI1"
4850 OPEN "I", #3, "AZI2"
4860 FOR I = 1 TO T
4870 FOR J = I TO T
4880 INPUT #2, F(I, J), H(I, J)
4890 INPUT #3, G(I, J), B(I, J)
4900 NEXT J
4910 NEXT I
4920 CLOSE #2
4930 CLOSE #3
4940 FOR I = 1 TO T
4950 FOR J = I TO T
4960 IF I = J THEN GOTO 5300
4970 VR = 0
4980 VI = 0
4990 VV = 0
5000 DV = 0
5010 VR = V(I) * COS(VA(I)) - V(J) * COS(VA(J))
5020 VI = V(I) * SIN(VA(I)) - V(J) * SIN(VA(J))
5030 VV = SQR(VR ^ 2 + VI ^ 2)
5040 IF VR = 0 THEN GOTO 5060
5050 GOTO 5100
5060 IF VI > 0 THEN DV = 3.1416/ 2
5070 IF VI < 0 THEN DV = -3.1416/ 2
5080 IF VI = 0 THEN DV = 0
5090 GOTO 5150
5100 IF VI > 0 THEN GOTO 5120
5110 IF VI < 0 THEN GOTO 5140
5120 DV = ATN(VI / VR)
5130 GOTO 5150
5140 DV = ATN(VI / VR) + 3.1416
5150 I(I, J) = VV * F(I, J)
5160 BB(I, J) = DV + H(I, J)
5170 PLINE(I, J) = V(I)*I(I,J)*COS(VA(I)-BB(I,J))
5180 QLINE(I, J) = V(I)*I(I,J)*SIN(VA(I)-BB(I,J))
5190 PLINE(J, I) = -V(J)*I(I,J)*COS(VA(J)-BB(I,J))
5200 QLINE(J, I) = -V(J)*I(I,J)*SIN(VA(J)-BB(I, J))
5210 NEXT J
5220 NEXT I
5300 '******************
5310 '*  RESULTS       *
5320 '******************
5330 PRINT "         RESULTS........."
5340 PRINT "       1) PRINT OUT RESULT"
5350 PRINT "       2) GO BACK TO MAIN MENU....."
5360 PRINT "        SELECT OPTIONS ..... ";
5370 B$ = INPUT$(1)
5380 B = VAL(B$)
5390 IF (B = 1) OR (B = 2)  THEN GOTO 5400
5400 IF B = 2 THEN RETURN
5410 ON B GOSUB 5500
5420 GOTO 5300
5430 PRINT " "
5440 GOTO 5360
5450 RETURN
```

```
5460 '*************************
5500 LPRINT "RESULTS FROM POWER FLOW CALCULATION";
5510 FOR I = 1 TO 80
5520 LPRINT CHR$(95);
5530 NEXT I
5540 LPRINT
5550 LPRINT "BUS NO."; SPACE$(2); "TYPE"; SPACE$(3);"VOLTS"; SPACE$(3);       "ANGLE"; SPACE$(7);
5560 LPRINT "   GENERATION    "; "    LOAD "; 5570 LPRINT TAB(26);
5580 FOR I = 30 TO 75
5590 LPRINT CHR$(95);
5600 NEXT I
5610 LPRINT TAB(40);"MW";SPACE$(7);"Mvar";SPACE$(12);"MW";SPACE$(7);"Mvar"
5620 FOR I = 1 TO 80
5630 LPRINT CHR$(95);
5640 NEXT I
5650 LPRINT
5660 LPRINT TAB(4); "1 ."; TAB(9); "SW"; TAB(14);
5670 LPRINT USING "##.###"; V(1);
5680 LPRINT TAB(22); USING "##.####"; VA(1);
5690 LPRINT TAB(33);USING "##.####"; PG(1);
5700 LPRINT TAB(42);USING "##.####"; QG(1);
5710 LPRINT TAB(57);USING "##.####"; PL(1);
5720 LPRINT TAB(67);USING "##.####"; QL(1);
5730 FOR I = 2 TO G
5740 LPRINT TAB(4); I; "."; TAB(9); "P-V"; TAB(14);
5750 LPRINT USING "##.###"; V(I);
5760 LPRINT TAB(22);USING "##.####";VA(I)
5770 LPRINT TAB(33);USING "##.####"; PG(I);
5780 LPRINT TAB(42);USING "##.####"; QG(I);
5790 LPRINT TAB(57);USING "##.####"; PL (I);
5800 LPRINT TAB(67);USING "##.####"; QL(I);
5810 NEXT I
5820 FOR I = G + 1 TO T
5830 LPRINT TAB(4); I; "."; TAB(9); "P-Q"; TAB(14);
5840 LPRINT USING "##.###"; V(I);
5850 LPRINT TAB(22);USING "##.####"; VA(I);
5860 LPRINT TAB(33); "-"; TAB(45); "-";
5870 LPRINT TAB(57); USING "##.####"; -P(I);
5880 LPRINT TAB(67);USING "##.####'; -Q(I);
5890 NEXT I
5900 LPRINT
5910 FOR I = 1 TO 80
5920 LPRINT CHR$(95);
5930 NEXT I
5950 FOR I = 1 TO 80
5960 LPRINT CHR$(95);
5970 NEXT I
5980 LPRINT
5990 LPRINT TAB(4); "BUS"; TAB(12); "ADMITANCE";
6000 LPRINT TAB(24); "I";
6010 LPRINT TAB(29);'
6020 LPRINT SPACE$(7); "                LINE FLOW"
6030 LPRINT TAB(40);
6040 FOR I = 1 TO 40
6050 LPRINT CHR$(95);
6060 NEXT I
6070 LPRINT TAB(45); "MW"; SPACE$(9); "Mvar"
6080 FOR I = 1 TO 80
6090 LPRINT CHR$(95);
6100 NEXT I
6110 FOR I = 1 TO T
6120 FOR J = 1 TO T
```

```
6130 IF I = J THEN GOTO 6250
6140 IF G(I, J) = 0 AND B(I, J) = 0 THEN GOTO 6250
6150 LPRINT USING "##.###"; I;
6160 LPRINT "-";
6170 LPRINT USING "##.###"; J;
6180 LPRINT TAB(10);USING "##.###"; G(I, J);
6190 IF B(I, J) > = 0 THEN LPRINT " +j";
6200 IF B(I, J) < 0 THEN LPRINT "-j";
6210 LPRINT USING "##.###"; ABS(B(I, J));
6220 LPRINT TAB(19);USING "##.###"; I(I, J);
6230 LPRINT TAB(45);USING "###.####"; PLINE(I, J);
6240 LPRINT TAB(57);USING "###.####"; QLINE(I, J);
6250 NEXT J
6260 NEXT I
6270 LPRINT
6280 FOR I = 1 TO 80
6290 LPRINT CHR$(95);
6300 NEXT I
6310 RETURN
6320 SCREEN 2
6330 IF CSRLIN > 21 THEN GOTO 6340
6340 PRINT STRING $(67, "  " )
6350 PRINT IT; TAB (20);
6360 PRINT USING " ###.#### ";VALUE;
6370 RETURN
6380 CHAIN "MENU"
```

APPENDIX D

Basic Program for Swing Equation

```
5 CLS
10 INPUT "DELTA = ";A
11 INPUT "DELTA CLEAR = ";B
12 INPUT "MAXIMUM POWER = ";C
13 INPUT "INITIAL DELTA = ";D
14 INPUT "POSTFAULT POWER =";E
20 DELTA = A
30 DLTCLR = B
40 J = 1
50 PMAX = C
60 PI = 3.1415927#
70 T = 0
80 X1 = D
90 X2 = 2*PI*60
100 LPRINT "  TIME     DELTA    OMEGA "
110 LPRINT "    s       rad      rad/s "
120 LPRINT USING "#####.###";T;X1;X2
130 FOR K=1 TO 86
140 X3=X2-(2*PI*60)
150 IF J=2 THEN GOTO 190
160 IF X1> DLTCLR OR X1 = DLTCLR THEN PMAX = E
170 IF X1 > DLTCLR OR X1 = DLTCLR THEN LPRINT " FAULT CLEARED"
180 IF X1 > DLTCLR OR X1 = DLTCLR THEN J = 2
190 X4 = 1-PMAX*SIN(X1)
200 X5 = X4*(2*PI*60)*(2*PI*60)/(6*X2)
210 X6 = X1+X3*DELTA
220 X7 = X2+X5*DELTA
230 X8 = X7-2*PI*60
240 X9 = 1-PMAX*SIN(X6)
250 X10 = X9*(2*PI*60)*(2*PI*60)/(6*X7)
260 X1 = X1+(X3+X8)*(DELTA/2)
270 X2 = X2+(X5+X10)*(DELTA/2)
280 T = K*DELTA
290 Z = K/2
300 M = INT(Z)
310 IF M=Z THEN LPRINT USING " #####.###";T;X1;X2
320 NEXT K
330 CHAIN "MENU"
```

APPENDIX E

Basic Progrm for Runge-Kutta Method

```
50 CLS
100 INPUT "2nd ORDER OF X "; A
110 INPUT "DELTA AFTER FAULT "; B
120 C = -(A*COS(B))
130 INPUT "DELTA MAX :";I
135 H=I
140 K = (C*H)
150 KK = H*(C+(K/2))
160 KKK = H*(C+(KK/2))
170 KKKK = H*(C+(KKK/2))
180 D = 1+(1/6)*(K+KK+KKK+KKKK)
190 E = D*(180/3.1415)
200 F= E+720
210 G =-F*(3.1415/180)
220 PRINT " THE CRITICAL CLEARANCE ANGLE ",G,"RADIANS"
225 LPRINT " THE CRITICAL CLEARANCE ANGLE ",G,"RADIANS"
230 CHAIN"MENU"
```

****

Basic Program for Menu

```
100 SCREEN 2:KEY OFF:WIDTH 80
110 CLS
180 PRINT"    "
190 PRINT:PRINT"          1. POWER FLOW PROGRAM."
200 PRINT:PRINT"          2. RUNGE-KUTTA METHOD."
210 PRINT:PRINT"          3. POWER SWING EQUATION."
215 PRINT:PRINT"          4. QUIT."
220 PRINT:INPUT"               Enter number :";A$
230 IF A$="1" THEN CHAIN"FLOW"
240 IF A$="2" THEN CHAIN"K-R"
250 IF A$="3" THEN CHAIN"SWING"
255 IF A$="4" THEN SYSTEM
260 GOTO 100
```

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