COMPUTER-AIDED DESIGN AND ANALYSIS OF SERIES RESONANT CONVERTERS

by

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(ABSTRACT)

A software program was developed to facilitate the design and analysis of a series resonant converter. Using the program, the values of the inductor and capacitor of the resonant tank can be easily determined to meet design specifications. Following the design, a dc analysis is performed to determine such salient parameters as peak inductor current and peak capacitor voltage. The program is user-friendly with graphic capabilities and is written for the IBM-PC.

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1. INTRODUCTION

1.1 General Background

Electronic power processing technology has evolved around two fundamentally different circuit schemes: duty-cycle modulation, commonly known as Pulse-Width Modulation (PWM), and resonance. The PWM technique processes power by interrupting the power flow and controlling the duty ratio of the power switches. This processing method results in pulsating current and voltage waveforms. On the other hand, the resonant technique processes power in a sinusoidal fashion. The PWM technique has been used predominantly in today's power electronics industry and is a mature technology.

The continued demands for smaller, lighter, and more efficient power processing equipment have been the main motivation for the introduction of new circuit topologies with progressively increasing internal conversion frequencies. However, there are two major difficulties associated with the higher switching frequency,

namely, high switching stresses and switching losses of the power switch in the circuit.

The switch dissipates energy both during turn-on and turn-off. Therefore, the total switching power loss increases rapidly with the switching frequency. During the turn-on period, the overlap of current and voltage transition across the switch constitutes the turn-on loss. Due to the parasitic inductance of the circuit, the switching device switches off at an inductive load. Consequently, voltage spikes are induced by the di/dt across the parasitic inductance and high stresses are imposed on the switching device. The overlap of current and voltage transition in the turn-off period accounts for the turn-off loss.

Resonant converters reduce or eliminate either the turn-on loss, the turn-off loss or both by properly shaping the current or voltage waveforms across the switch using the resonant phenomenon. For a series resonant converter (SRC) operating above tank resonant frequency, the switches are turned on at zero current and zero voltage. Therefore, the turn-on loss can be eliminated. For an SRC operating below resonant frequency, the switches are turned off at zero current. Thus, the turn-off loss can be eliminated. By this natural commutation of power switches, the di/dt problem is alleviated; thus, the switching stress is minimized. As a result of reduced switching losses and stresses, the switching frequency can be increased to high levels without sacrificing the efficiency. The resonant converter is an important technological development towards the further miniaturization of power electronics equipments.

The development of resonant converters has gained significant interest from industry and has been the focus of considerable research and development. Analyses of series resonant converters have been performed [1-5]. However, these analytical

techniques are rather complex and they do not directly identify all the possible modes of an SRC operation when load and switching frequency are varied. To design and use an SRC effectively, it is necessary that its characteristics under different operating modes be investigated thoroughly. The state-plane analysis of an SRC performed by Oruganti and Lee has been shown to be a powerful method which can clearly portray the steady-state and transient operation of an SRC [6-10]. Using a state-plane analysis method, all the possible modes of operation can be identified. Furthermore, the dc characteristics of an SRC in each mode can be determined. However, the actual analysis procedure is complex and the results are not easily applied for design purposes [11].

When designing a series resonant converter, several important aspects must be considered. The first is the peak stress. For example, the maximum switching current for all possible input and output variations must be less than the maximum ratings of the switching devices used in the SRC. Second, the switching frequency range, which accommodates the input and output variations, should be narrow to facilitate ripple filtering and feedback control to achieve desired regulation and dynamic properties. Third, the converter's output current should be sufficiently large to provide a desired maximum load current. The maximum output current of an SRC is limited by the operating frequency range and parasitic losses. Last, the design of an SRC should meet the specifications of smaller size and lighter weight. However, these various design constraints are interlinked and trade-offs must be made. For example, increasing the switching frequency will allow lower values for the tank inductor, capacitor, and output filter capacitor, but the parasitic losses will have a more profound affect on converter operation. Because of the interactions between the design aspects, the design of an SRC is iterative and based on trial-and-error.

1.2 Present Work

Since the operation of an SRC is complex and the available methods of the analysis are tedious to carry out, a computer-aided analysis method is necessary to facilitate the analysis of an SRC. Furthermore, this analysis tool should be readily incorporated into the design of an SRC. The iterative nature of the design of an SRC makes a computer-aided design method necessary. The major objective of the present work is to introduce the development of a software program which is written to facilitate the design and analysis of an SRC.

The software program incorporates analysis and design of the SRC shown in Fig. 1.1. The basic analysis equations and part of the design guidelines are taken from Ref. [9]. This program can design and analyze an SRC operating above or below resonant frequency and with or without parasitic losses in the tank circuit. Figure 1.2 shows a block diagram of the program.

In the analysis program, the given conditions are input voltage, output voltage, values of the tank circuit elements, transformer's turns ratio, and switching frequency or load current. DC analysis is performed at the given operating conditions. The operating mode of the converter is identified. Salient parameters, such as peak inductor current and peak capacitor voltage, are calculated and plotted to give the user a complete view of converter operation.

In the design program, the user designs an SRC by choosing the user-specified parameters. These parameters are ***transformer's turns ratio, tank resonant frequency, and upper or lower bound of switching frequency.*** The design is done in a step-by-

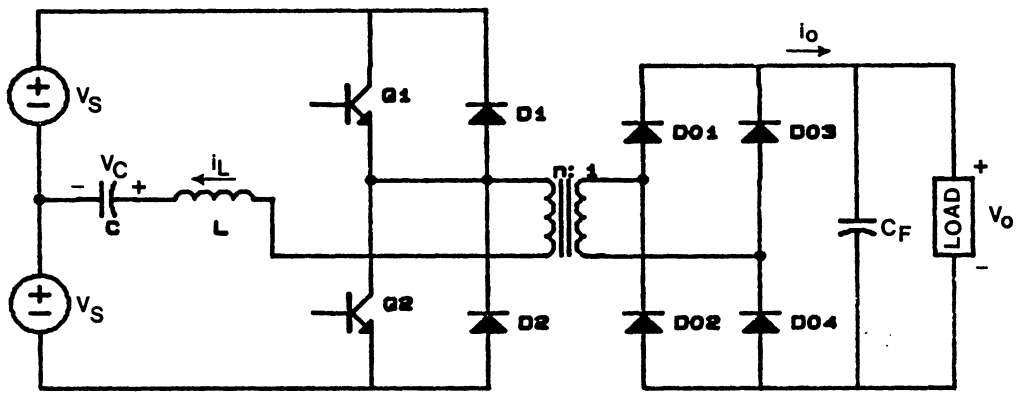


Fig. 1.1 A half-bridge series resonant converter

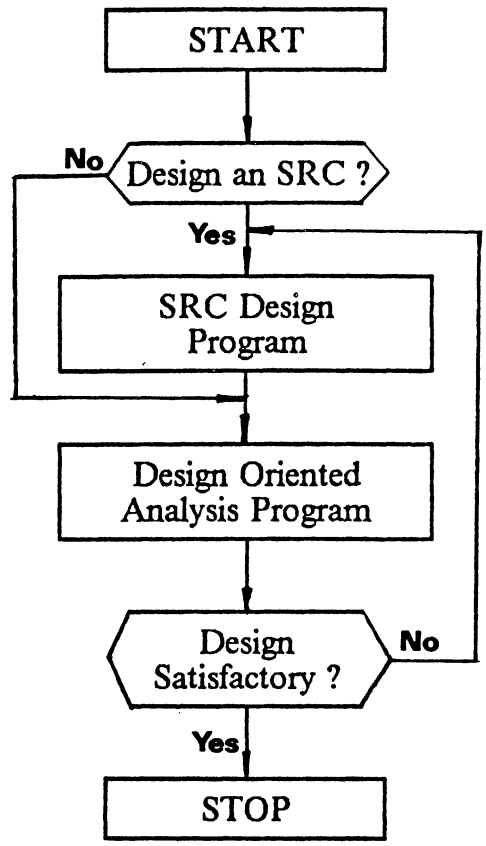


Fig. 1.2 A simplied block diagram of the package

step manner. Design guidelines and normalized design curves are provided at each step to assist both the experienced and the novice designer. Immediately following the design, a dc analysis is performed to validate the design. If the results of the analysis are not satisfactory, the user can reiterate the design procedure following directions suggested by the program to meet the given design criteria.

The generation of various graphs does not interrupt the program execution. The graphic capability of the program enhances user-friendliness and insight into the design and analysis of the SRC. This interactive program is very easy to use and requires no special background in computer programming and simulation. The program is written for the IBM-PC.

2. DESIGN ORIENTED ANALYSIS OF SRC

In this chapter, the analysis of an SRC using the software program as a tool is presented. The objective of the analysis program is to analyze an SRC at a given operating condition to find certain circuit parameters, such as peak inductor current and peak capacitor voltage. This program is used to check the design and can also be used independently as shown in Fig. 1.2. The analysis procedure and method used in the analysis program are discussed. This chapter also provides background information for the SRC design which is discussed in the next chapter.

2.1 State-Plane Analysis

A graphical state-plane technique has been successfully adapted for understanding the complicated operation of an SRC [6,7,8,9]. Using a state-plane analysis technique, various operating modes and operating regions of an SRC are identified. Furthermore, the characteristics of an SRC in each operating mode are established. This

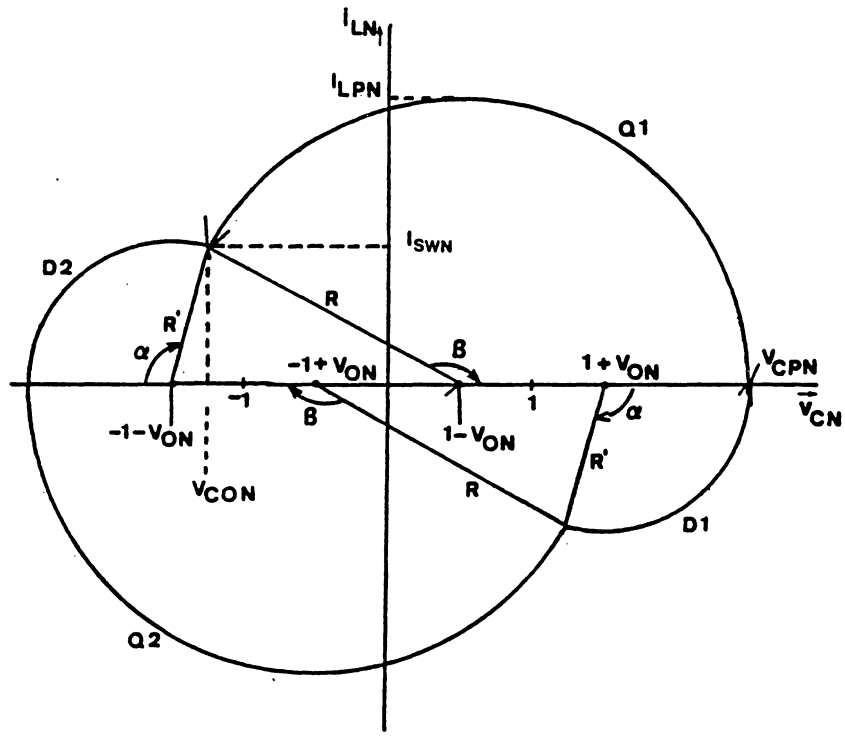


Fig. 2.1 An SRC steady-state trajectory under continuous-conduction mode below resonance (V_{ON} = 0.5).

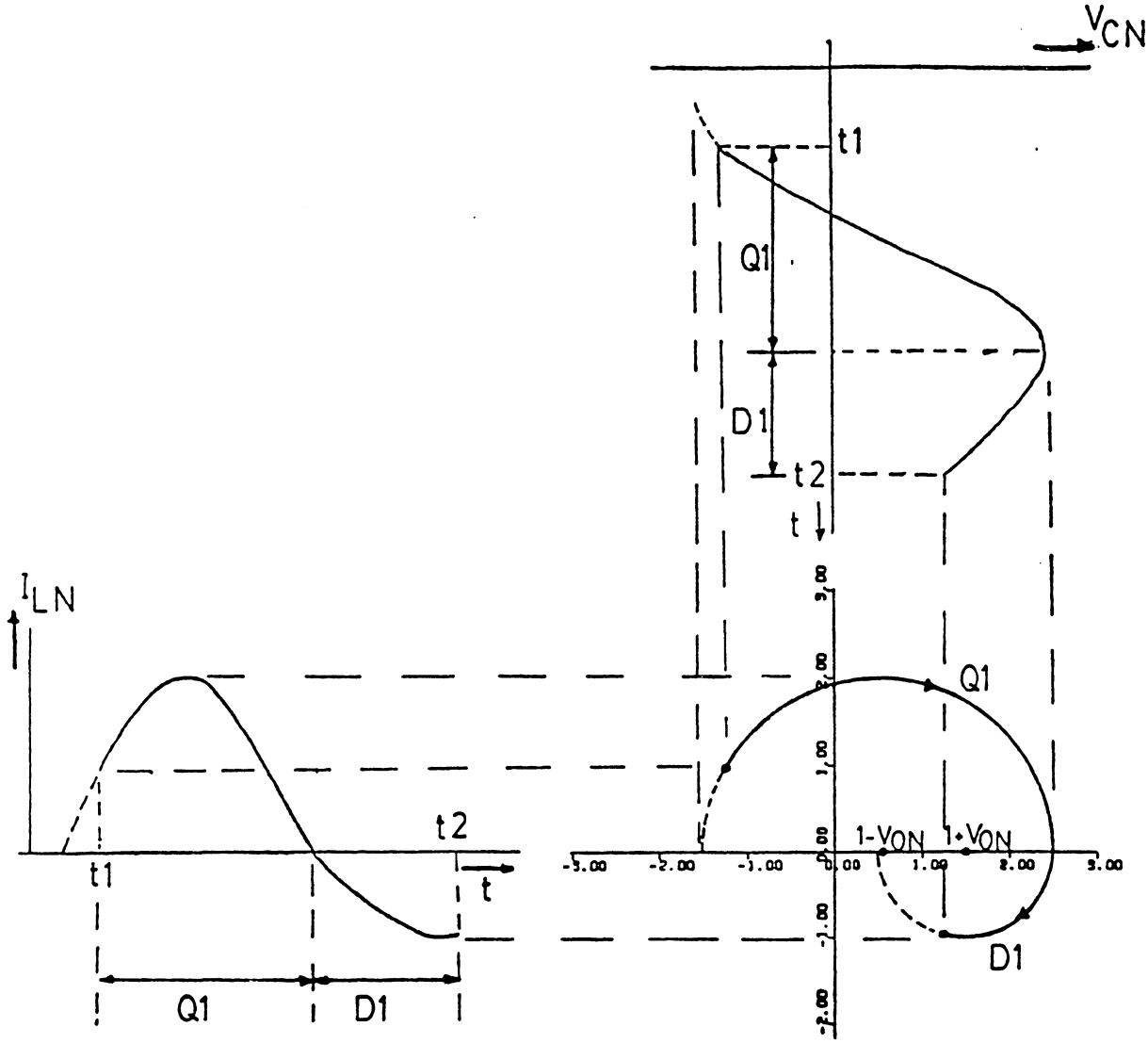


Fig. 2.2 Diagram showing the construction of tank waveform from steady-state trajectory

program is built upon the state-plane analysis of series resonant converters performed by Oruganti and Lee [6,7,8,9]. Some key results of the state-plane analyses are reviewed here. For more detailed explanations, refer to Refs. [6] and [9].

Each steady-state trajectory on the state plane represents one unique operating condition of an SRC corresponding to a unique input voltage, output current, and switching frequency. Figure 2.1 shows one steady-state trajectory in the continuous-conduction mode (CCM) with the switching frequency below the resonant frequency. It is assumed that the tank circuit does not have loss in this case. The state-plane analysis is done with the normalized circuit in which all circuit parameters are normalized. In this figure, v_{CN} and i_{LN} are the normalized state variables with normalizing factors defined later in this section. The tank waveform can be drawn from the steady-state trajectory as shown in Fig. 2.2. The characteristic impedance is Z_o where $Z_o = \sqrt{L/C}$. The normalized output voltage reflected to the resonant tank side of the converter is V_{ON} where $V_{ON} = nV_o/V_s$. Trajectory segments are circular arcs with centers determined by the state of the switching devices. The four centers are given by {Q1: $1 - V_{ON}$, 0}, {D1: $1 + V_{ON}$, 0}, {Q2: $-1 + V_{ON}$, 0}, and {D2: $-1 - V_{ON}$, 0}. The trajectory radius during the transistor's conduction interval is R, while R' is the trajectory radius during the diode conduction interval. Devices Q_1 and D_1 in Fig. 1.1 form a bidirectional switch which is shown in Fig. 2.1 by the opposite polarity of the normalized inductor current, i_{LN}. Likewise, it can be seen that devices Q_2 and D_2 form another bidirectional switch. The angle subtended to the trajectory center is proportional to the time elapsed, $\theta = \omega_o t$ where $\omega_o = 1/\sqrt{LC}$. The instantaneous tank energy is proportional to the square of the distance between the present state of the SRC and the origin in Fig. 2.1. The operating conditions of an SRC can be shown on the state plane as steady-state trajectories with radius R. Therefore, the trajectory

radius is the parameter characterizing the steady-state operation of an SRC. It was shown in Ref. [9] that all key circuit parameters, such as peak inductor current and peak capacitor voltage, can be calculated directly from a steady-state trajectory as a function of trajectory radius using simple geometric relations. The normalizing factors are defined as follows:

$$N_v = \text{Voltage Normalizing Factor}$$
$$= V_S = \text{Input Voltage}$$

$$N_i = \text{Current Normalizing Factor}$$
$$= \frac{V_S}{Z_O}$$

$$N_f = \text{Frequency Normalizing Factor}$$
$$= \omega_o = \text{Tank Resonant Frequency}$$

With the aid of the steady-state trajectory shown in Fig. 2.1, the following normalized circuit parameters may be easily calculated.

$$I_{LPN} = R$$
$$= \text{normalized peak inductor current} \tag{1}$$

$$V_{CPN} = R + 1 - V_{ON}$$
$$= \text{normalized peak capacitor voltage} \tag{2}$$

Other parameters derived from Fig. 2.1 are listed below.

$$R' = R - 2V_{ON} \tag{3}$$

$$\alpha = \pi - \cos^{-1}\frac{R'^2 + 4 - R^2}{4R'} = \omega_o t_d \tag{4}$$

= diode conduction angle

Where t_d = diode conduction interval.

$$\beta = \pi - \cos^{-1}\frac{R^2 + 4 - R'^2}{4R} = \omega_o t_q \tag{5}$$

= transistor conduction angle

Where t_q = transistor conduction interval.

$$\omega_N = \frac{\pi}{\alpha + \beta} = \frac{\omega}{\omega_o} \quad \text{where} \quad \omega_o = \frac{1}{\sqrt{LC}} \tag{6}$$

= normalized switching frequency

$$V_{CON} = -V_{ON}(R + 1 - V_{ON}) \tag{7}$$

= normalized capacitor voltage at switching point

$$I_{SWN} = R \sin \beta \tag{8}$$

= normalized transistor current at switching point

$$I_{LAVN} = \frac{2V_{CPN}}{\alpha + \beta} \tag{9}$$

= normalized (half-cycle) average current of the inductor

$$I_{DAVN} = \frac{V_{CPN} + V_{CON}}{2(\alpha + \beta)} \tag{10}$$

= normalized average current of the diode

$$I_{QAVN} = \frac{V_{CPN} - V_{CON}}{2(\alpha + \beta)} \tag{11}$$

= normalized average current of the transistor

$$I_{DRN} = \frac{R - 2V_{ON}}{2}\sqrt{\frac{\alpha - (1/2)\sin 2\alpha}{\alpha + \beta}} \tag{12}$$

= normalized rms current of the diode

$$I_{QRN} = \frac{R}{2}\sqrt{\frac{\beta - (1/2)\sin 2\beta}{\alpha + \beta}} \tag{13}$$

= normalized rms current of the transistor

$$I_{LRN} = \sqrt{2(I_{DRN}^2 + I_{QRN}^2)} \tag{14}$$

= normalized rms current of the inductor

Figure 2.3 shows the circuit diagram of a nonideal SRC with parasitic losses in the tank circuit, while Fig. 2.4 shows one steady-state trajectory in CCM. Various parasitic losses are modeled by a lumped resistor, R, in series with the resonant tank. The tank quality factor, Q, is defined by

$$Q = \frac{\omega_o L}{R} = \frac{Z_O}{R} \quad \text{with} \quad Z_O = \sqrt{\frac{L}{C}} \tag{15}$$

When this trajectory is compared with that of an ideal SRC (Fig. 2.1), it can be seen that the trajectory radius, R, is no longer a constant. The trajectory radius decreases after switches are turned on. Therefore, the closed-loop trajectory on the state plane is a spiral rather than a circular arc as in the case of an ideal SRC. The analysis equations have been derived from Fig. 2.4 and are shown below [9].

$$V_{CPN} = 1 - V_{ON} + R_1 \tag{16}$$

$$\omega_N = \frac{\pi}{\alpha_d + \alpha_q} \tag{17}$$

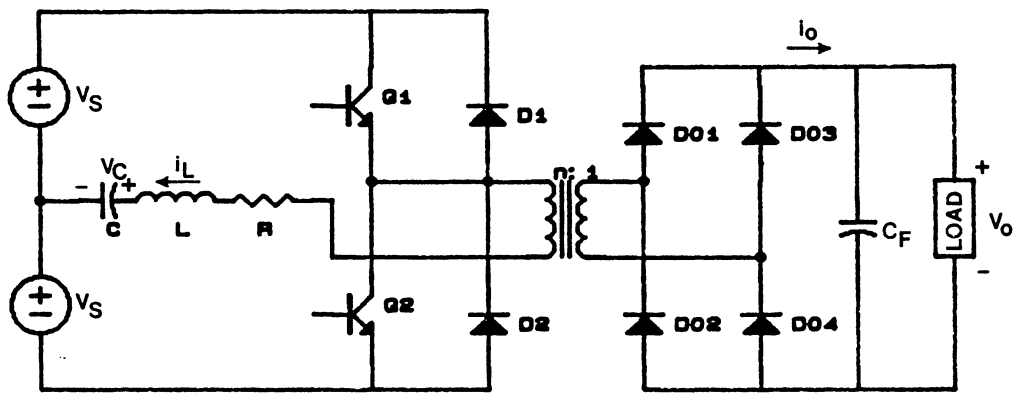


Fig. 2.3 A half-bridge SRC with losses in the tank circuit

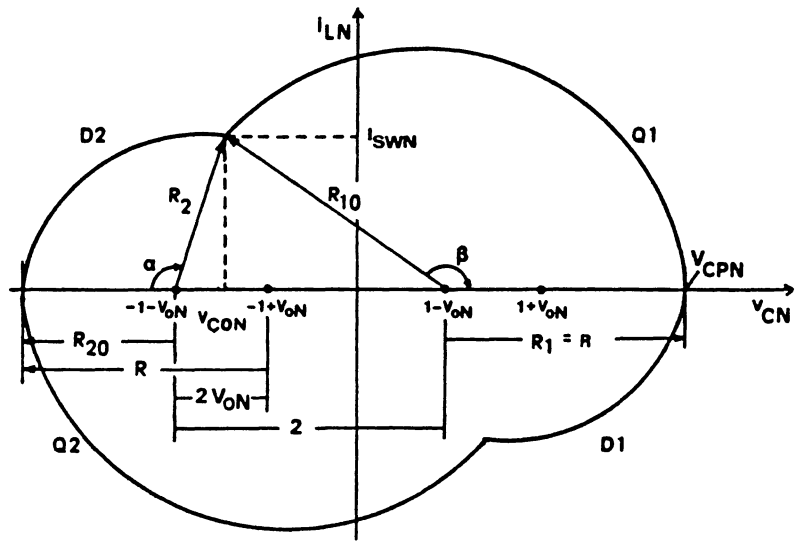


Fig. 2.4 A steady-state trajectory of a nonideal SRC in CCM

The derivations of the diode conduction angle α_d and transistor conduction angle α_q are shown in Ref. [9].

$$V_{CON} = 1 - V_{ON} + R_{10} \cos \beta \tag{18}$$

$$I_{SWN} = R_{10} \sin \beta \tag{19}$$

$$I_{LAVN} = \frac{2V_{CPN}\sqrt{1 - \zeta^2}}{\alpha_d + \alpha_q} \tag{20}$$

where $\zeta = \frac{1}{2Q}$ = damping factor

$$I_{DAVN} = \frac{(V_{CPN} + V_{CON})\sqrt{1 - \zeta^2}}{2(\alpha_d + \alpha_q)} \tag{21}$$

$$I_{QAVN} = \frac{(V_{CPN} - V_{CON})\sqrt{1 - \zeta^2}}{2(\alpha_d + \alpha_q)} \tag{22}$$

The definitions of the variables are the same as before. It has been shown that the state-plane analysis of an SRC with parasitic losses in the tank circuit is much more complicated [9]. Furthermore, there are less circuit analysis equations derived from the steady-state trajectory. These basic, normalized, circuit parameter equations are used in the analysis and design programs.

2.2 Analysis Of An Ideal SRC

For an ideal SRC, the tank circuit is assumed lossless. Figure 2.5 is a simplified flow chart showing the analysis of an ideal SRC. First, the circuit operating condition is provided by the user. It includes input voltage V_s, output voltage V_o, transformer's primary-to-secondary turns ratio n, values of the resonant tank's inductor L and capacitor C, and either the SRC's switching frequency f or the load current I_o. Second, the operating mode of the SRC is determined. The procedure is explained in detail in Sec. 2.2.1. The trajectory radius corresponding to the operating condition is found numerically. The method is explained in Sec. 2.2.2. Third, the various circuit parameters listed in Eqs. (1)-(14) will be calculated. Fourth, the various circuit parameters calculated can be plotted at the user's choice to give a complete view of converter operation. Last, the state-plane diagram at the given operating condition can be plotted to show the tank behavior.

2.2.1 Determination Of SRC Operating Mode

Figure 2.6 shows a more detailed flow chart of the analysis of an ideal SRC. The program is written in such a way that the user has the option to do the SRC analysis either with a normalized circuit or with an actual circuit. The following analysis of an SRC refers to the analysis of an actual circuit.

The program employs a state-plane analysis method as an intermediate step to perform the SRC analysis. The variables needed to perform state-plane analysis are

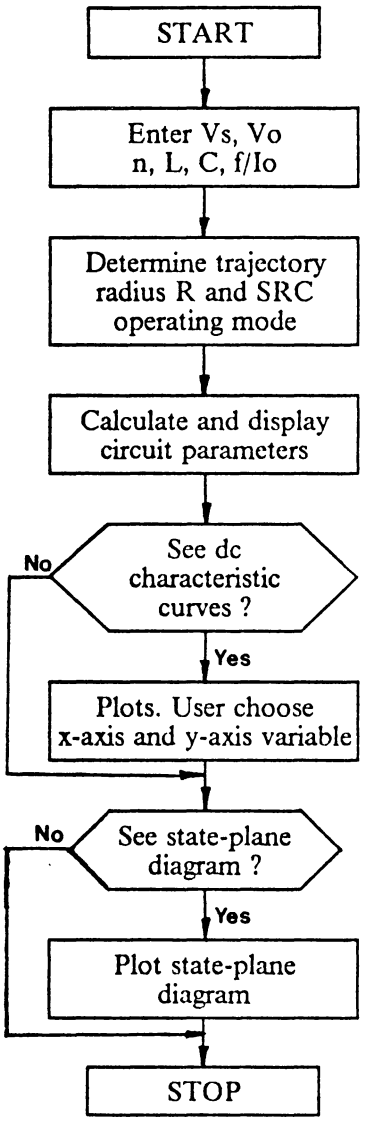


Fig. 2.5 Simplified flow chart of ideal SRC analysis program

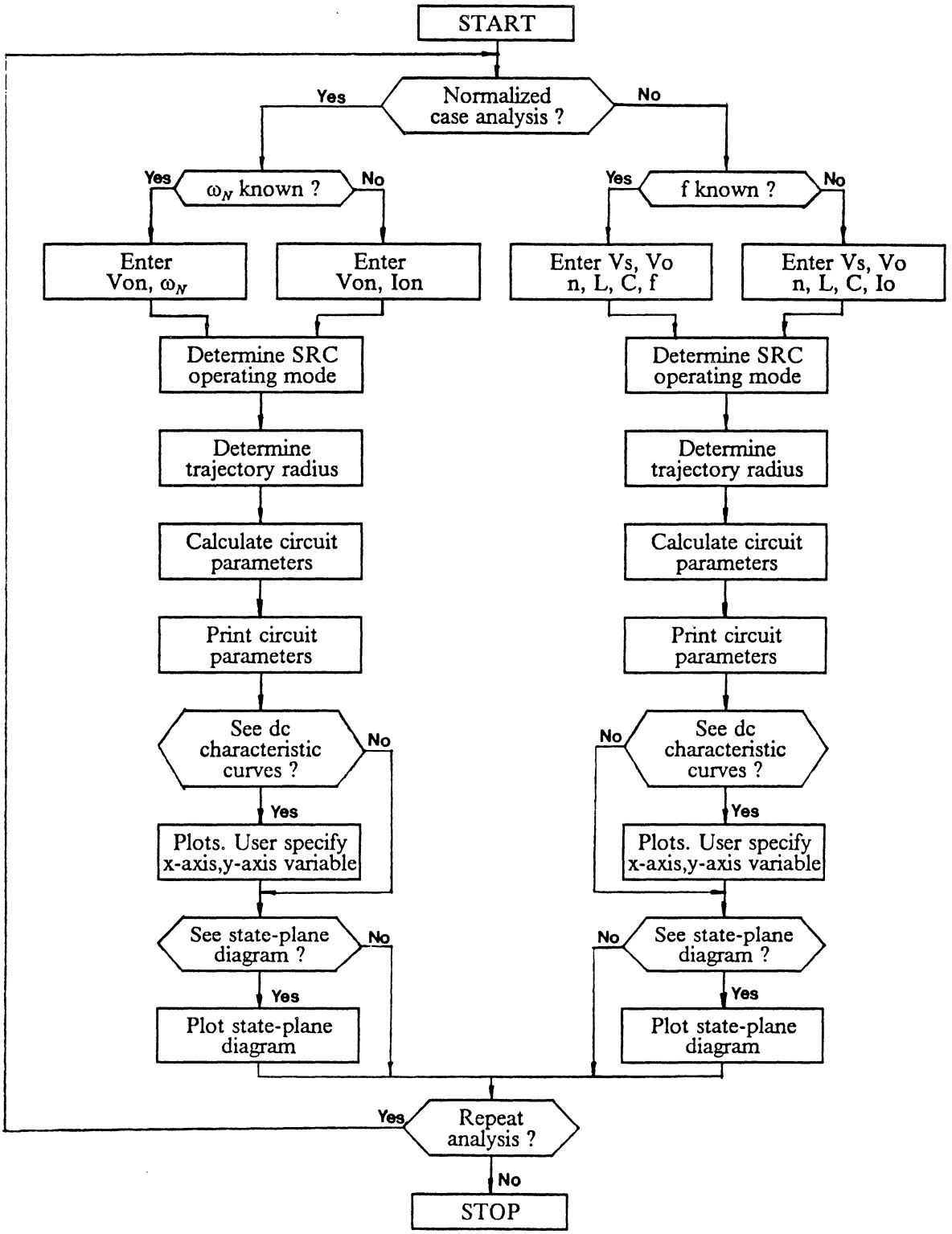


Fig. 2.6 Flow chart of ideal SRC analysis program

V_{ON} and either ω_N or I_{ON}. Therefore, the given SRC is normalized first to find these variables. This is done easily through the division of V_o and either ω or I_o with the corresponding normalizing factors.

Assuming the Q1 (Q2) base drive is removed whenever the antiparallel diode D1 (D2) is conducting, i.e., Q1 (Q2) is not permitted to switch on more than once in each half cycle of converter operation, an ideal SRC has four different modes of operation [9]. These modes are 1)type-1 discontinuous-conduction mode (DCM-1), 2)type-2 discontinuous-conduction mode (DCM-2), 3)CCM below resonance, 4)CCM above resonance. Figures 2.7 through 2.14 are examples of the steady-state trajectory and tank circuit waveforms in each operating mode. In DCM-1, each transistor conducts for a duration of π and naturally commutates without the diodes conducting. Therefore, there is only one current pulse in each half cycle of SRC operation. In DCM-2, each transistor and diode conducts for an angle of π. There are two current pulses in each half cycle of SRC operation. DCM-1 occurs at the following conditions:

$$V_{ON} = 1 \quad \text{and} \quad \omega_N < 1$$

DCM-2 occurs at the following conditions:

$$V_{ON} < 1 \quad \text{and} \quad \omega_N \leq 0.5$$

CCM below tank resonant frequency is the region where

$$V_{ON} < 1 \quad \text{and} \quad 0.5 < \omega_N \leq 1$$

CCM above tank resonant frequency is the region where

$$V_{ON} < 1 \quad \text{and} \quad \omega_N > 1$$

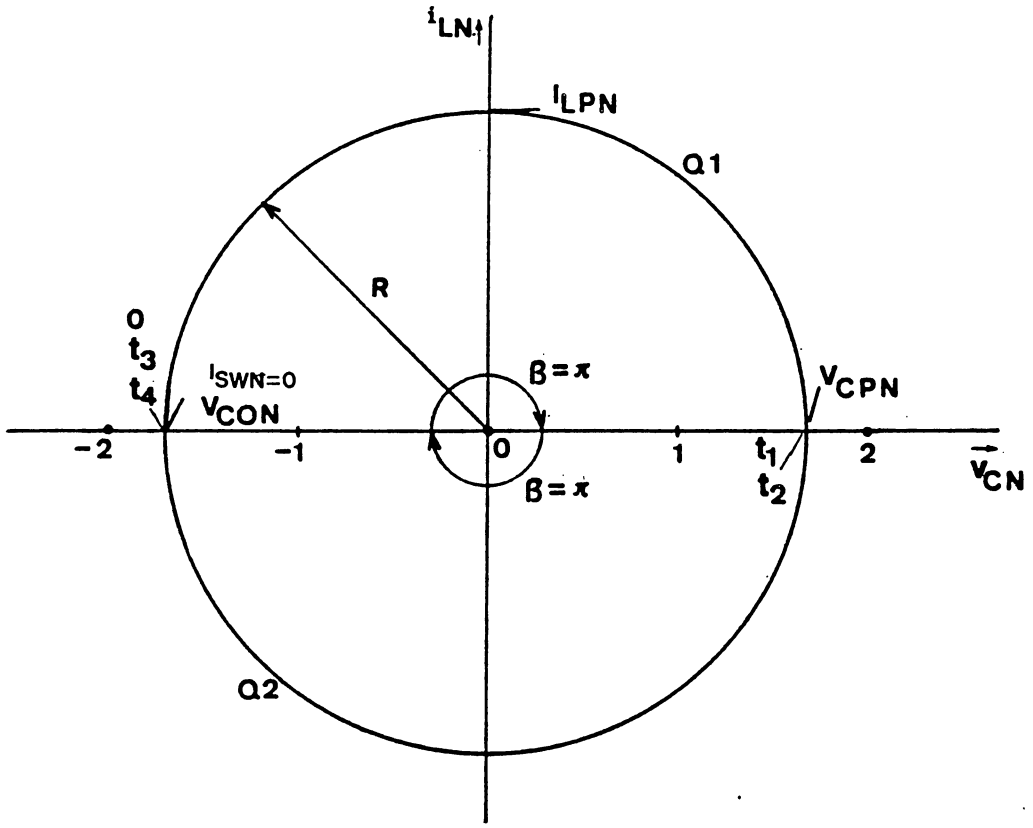


Fig. 2.7 A steady-state trajectory of an ideal SRC in DCM-1

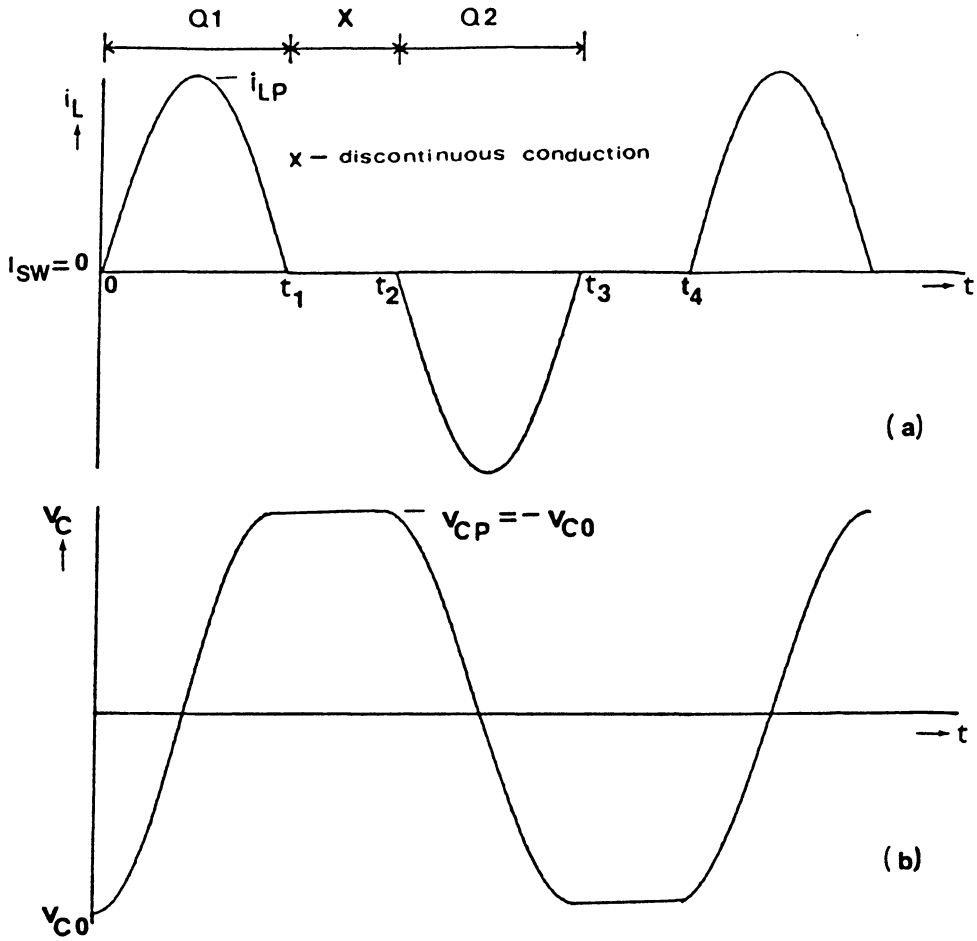


Fig. 2.8 Tank waveforms of an ideal SRC in DCM-1

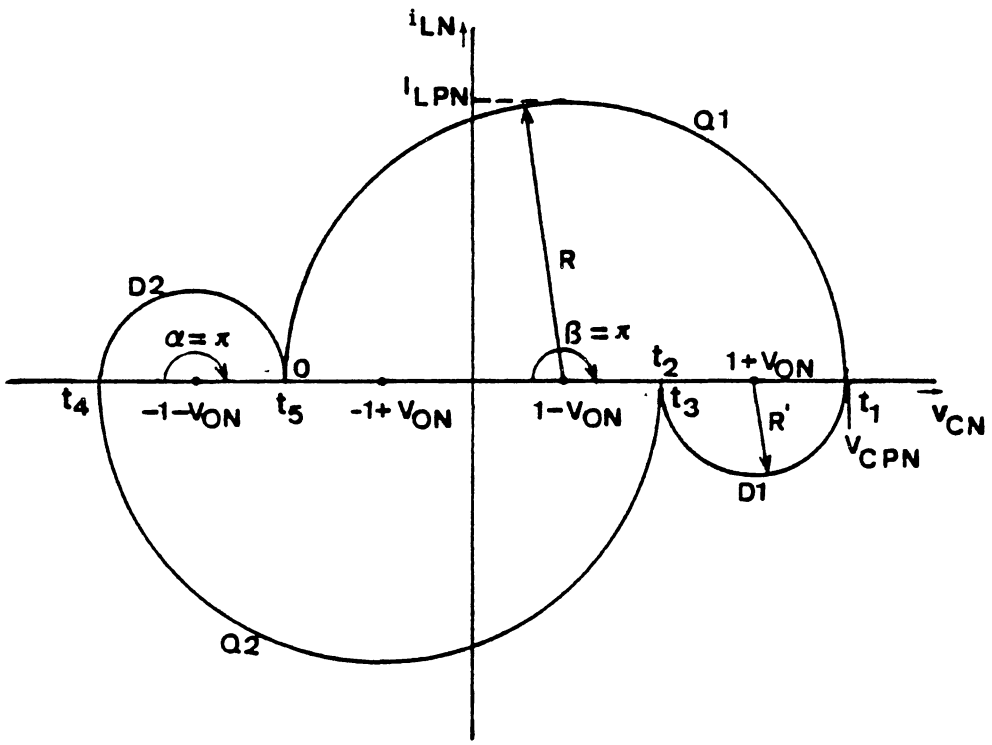


Fig. 2.9 A steady-state trajectory of an ideal SRC in DCM-2

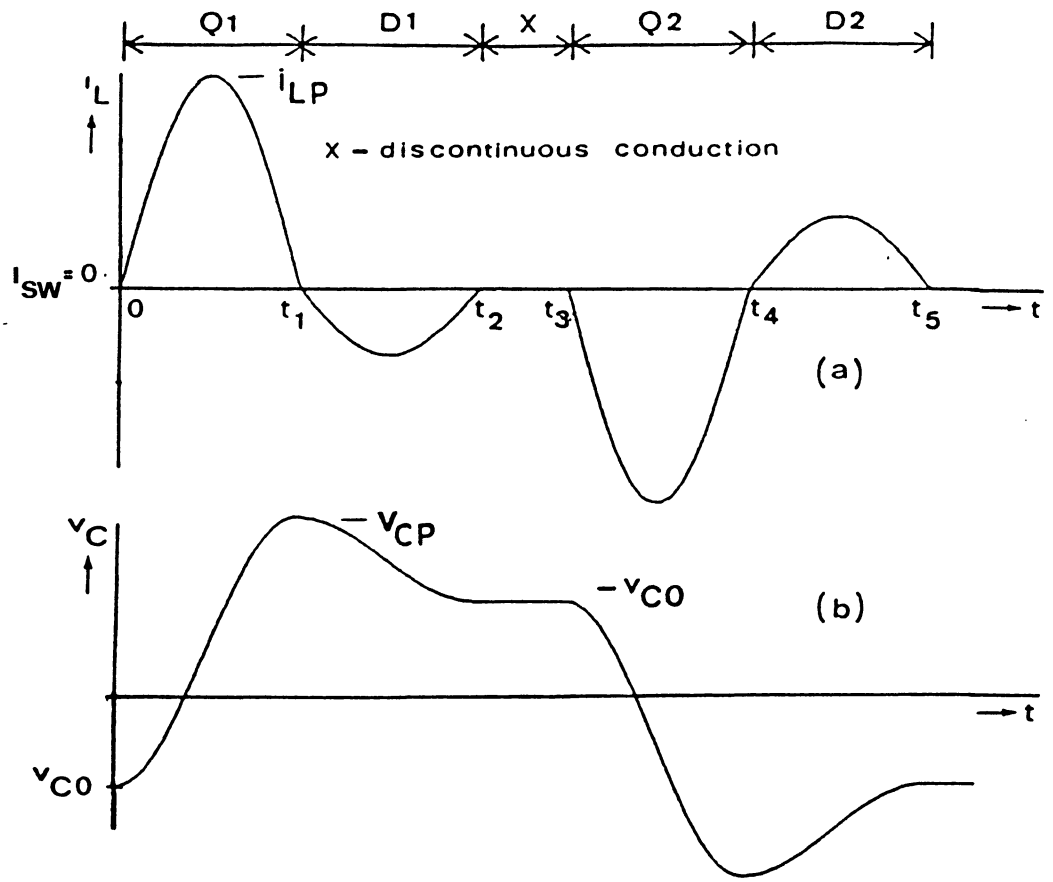


Fig. 2.10 Tank waveforms of an ideal SRC in DCM-2

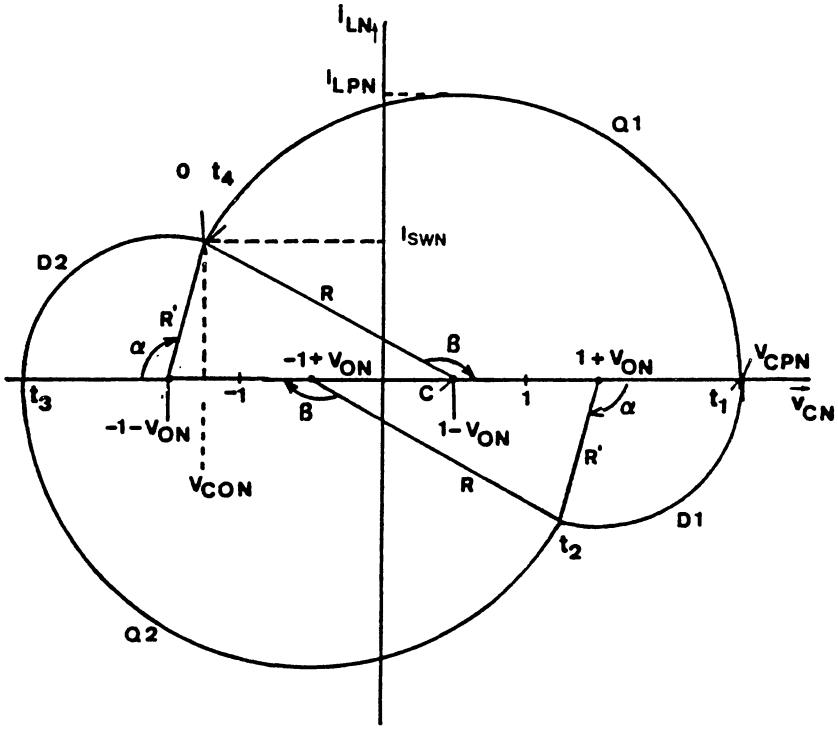


Fig. 2.11 A steady-state trajectory of an ideal SRC in CCM below resonance

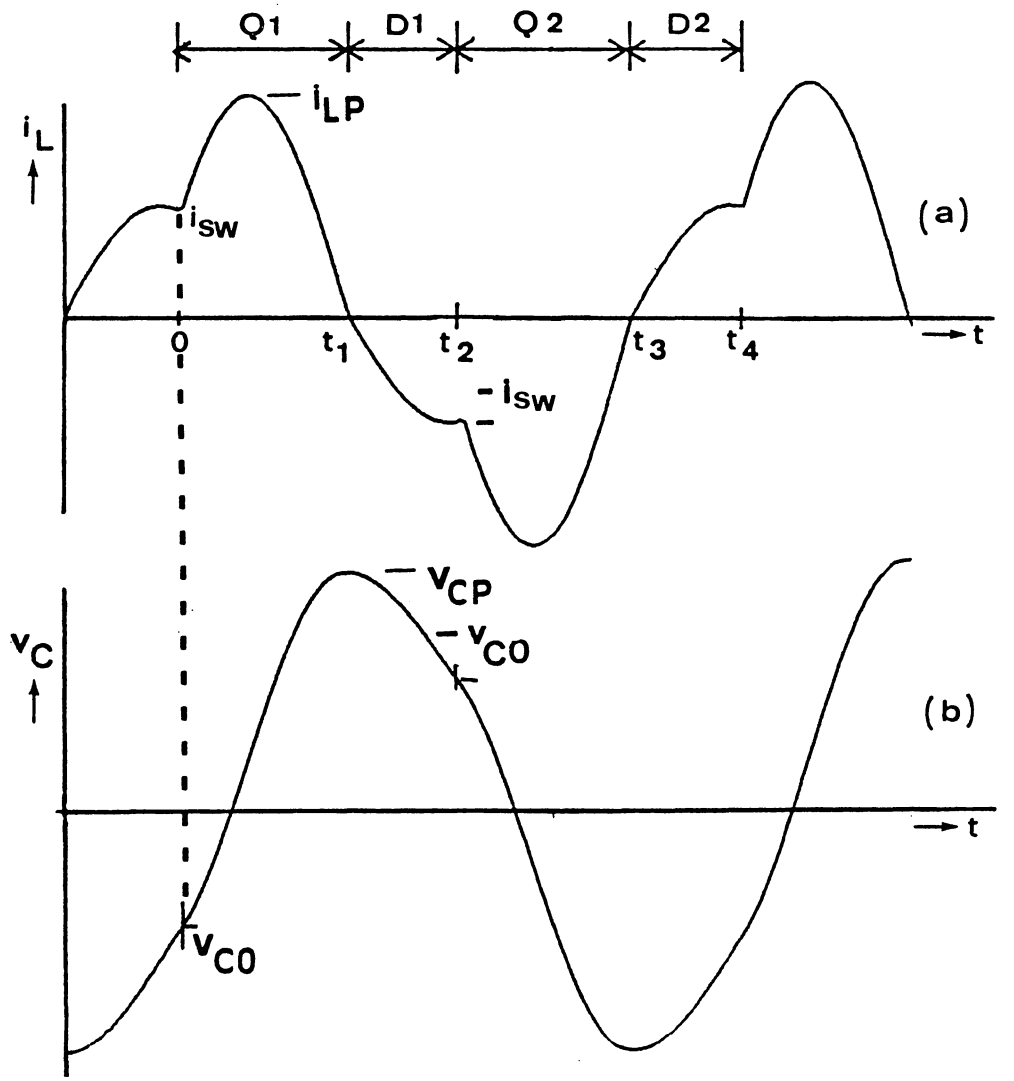


Fig. 2.12 Tank waveforms of an ideal SRC in CCM below resonance

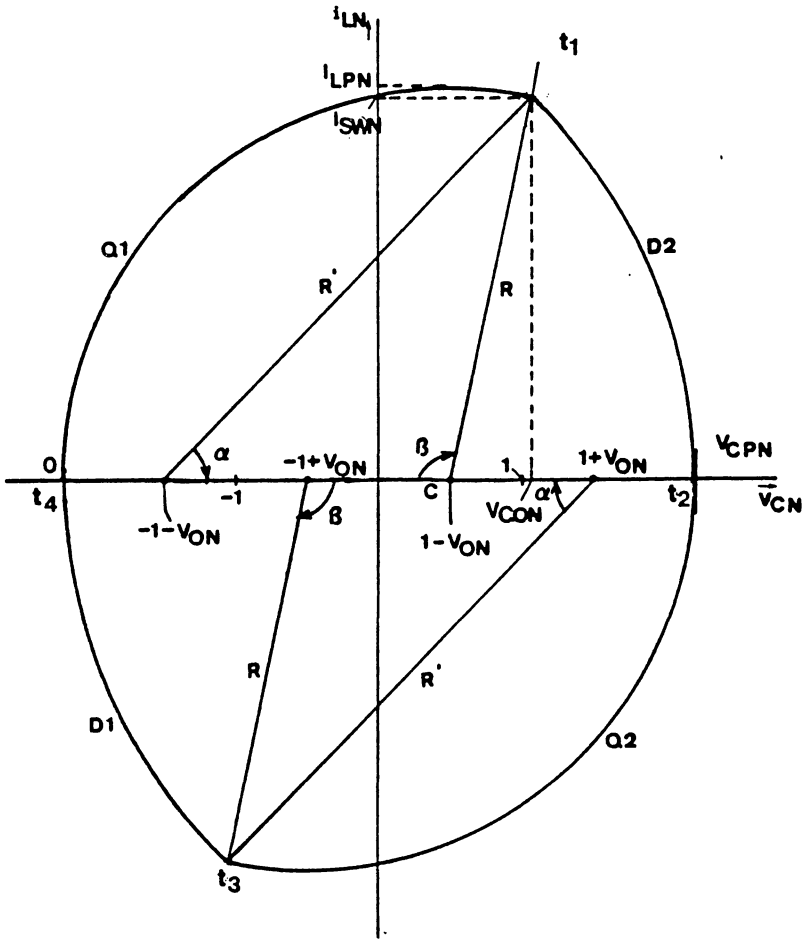


Fig. 2.13 A steady-state trajectory of an ideal SRC in CCM above resonance

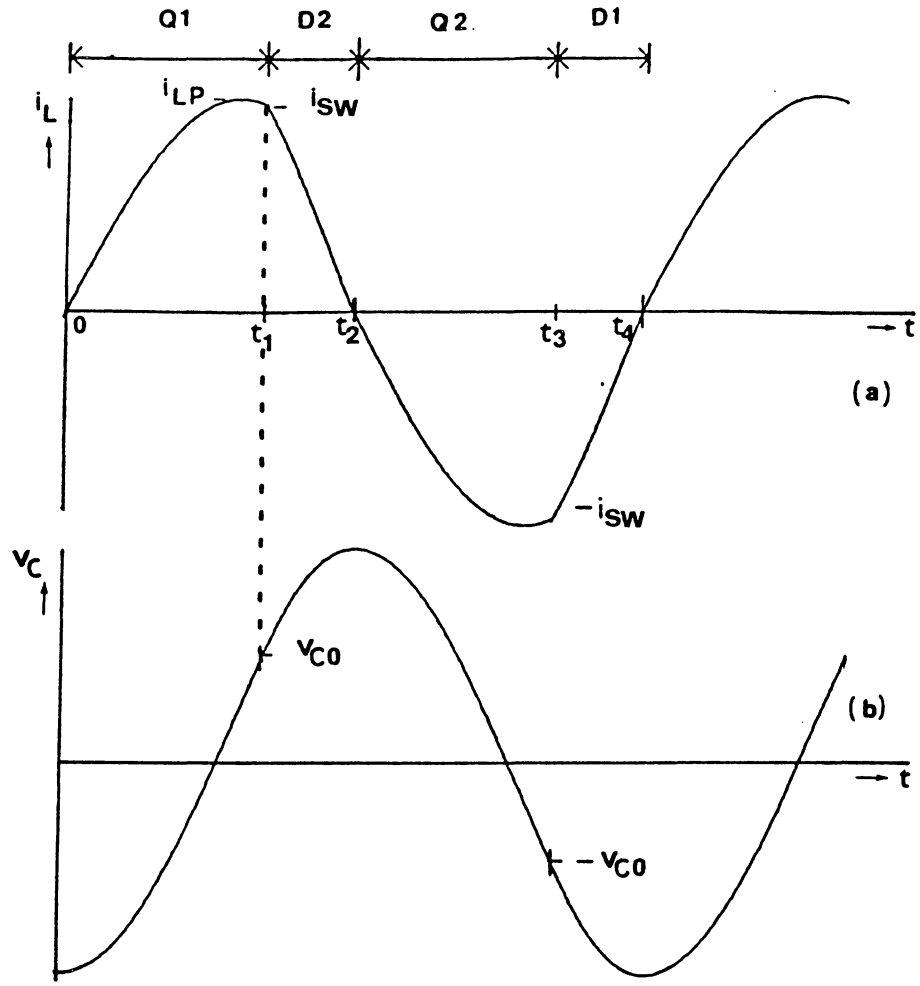


Fig. 2.14 Tank waveforms of an ideal SRC in CCM above resonance

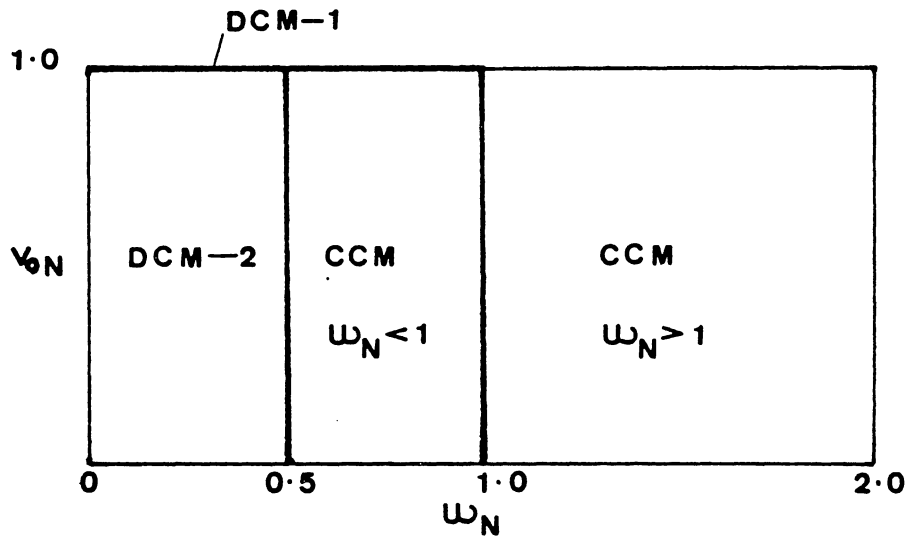


Fig. 2.15 Operating regions of an ideal SRC

Figure 2.15 shows the operating regions of an ideal SRC. When V_{ON} and ω_N are known, the particular mode of SRC operation is determined easily by comparing V_{ON} and ω_N with the above four boundary conditions.

On the other hand, the operating mode of an SRC can not be determined if only V_{ON} and I_{ON} are known. As discussed in Ref. [1], the same load current can be provided by an SRC either operating above or below resonant frequency. Therefore, the user has to specify whether the converter is operating above or below resonant frequency. If the converter is operating below resonance, the operating mode between DCM-2 and CCM needs to be further identified. The boundary between DCM-2 and CCM is at $\omega_N = 0.5$. The normalized (half-cycle) average inductor current, I_{LAVN}, at this boundary has been found [9].

$$I_{LAVN} = \frac{2}{\pi}$$

The value of I_{LAVN} at a given operating condition is calculated by the program as follows:

$$I_{LAVN} = \frac{I_{ON}}{n} = \frac{I_O Z_O}{n V_S}$$

This value is compared with the boundary value of I_{LAVN}. If the calculated value is less than $2/\pi$, SRC is in DCM-2; otherwise, the SRC is in CCM provided that $V_{ON} < 1$.

2.2.2 Determination Of Steady-State Trajectory Radius

After the operating mode of an SRC is determined at a given condition, the trajectory radius, R, is calculated numerically. Since R is uniquely determined with each operating condition, it can be calculated given V_{ON} and ω_N or V_{ON} and I_{ON}. The range of R in different operating modes was discussed in Ref. [9].

Since the range of R and V_{ON} are known, a binary search method is used to find R which results in the given ω_N or I_{ON}. A brief description for determining R with V_{ON} and ω_N given is shown below.

Case 1 : $\omega_N < 1$. Here an SRC is operating below resonance. The switching frequency is directly proportional to the trajectory radius. In the first iteration, the mean value in the range of R ($\frac{R_{MIN} + R_{MAX}}{2}$) is used to compute ω_N. If the result is smaller than the given ω_N, the target trajectory radius is in the range of $\frac{R_{MIN} + R_{MAX}}{2}$ to R_{MAX}. If the result is greater than the given ω_N, the target trajectory radius is in the range of R_{MIN} to $\frac{R_{MIN} + R_{MAX}}{2}$. Next, the mean value in the reduced radius range is used to compute ω_N again. This iterative procedure is carried on until the error between computed ω_N and given ω_N falls into the specified tolerance range. The trajectory radius in the last iteration is the target trajectory radius and is used to compute other normalized circuit parameters.

Case 2: $\omega_N > 1$. In this case an SRC is operating above resonance. The switching frequency is inversely proportional to the trajectory radius. The mean value of the radius range is used to compute first ω_N as in case 1. However, if the result is less than the given value, the target trajectory radius is in the range of

R_{MIN} to $\frac{R_{MIN} + R_{MAX}}{2}$, which differs from case 1. If the result is greater than the given value, the target trajectory radius is in the other half of the radius range. In the next iteration, the mean value of a properly reduced radius range is used for the computation. With the relation between R and ω_N known, the direction of the next iteration is selected properly by the program to approach the target trajectory radius.

After R is calculated, various normalized circuit parameters are calculated using Eqs. (1)-(14). The actual circuit parameters are calculated through the multiplication of the normalized circuit parameters with their corresponding normalizing factors.

2.2.3 Switching Frequency Below Resonance

In this section, the analysis of an SRC (Fig. 1.1) operating below resonant frequency is demonstrated. In this switching frequency range, switches are naturally commutated. In this example, load current is chosen as the known quantity and is varied to show the behavior of an SRC. The analysis is shown below.

Enter circuit information.

Input voltage V_s = 50 volts

Output voltage V_o = 110 volts

Load current I_o range = 4-6 amps

Transformer's primary-to-secondary turns ratio n = 0.3

Value of the resonant inductor L = 9.030848 μH

Value of the resonant capacitor C = 0.2804863 μF

The converter is operating **below** resonant frequency.

DC analysis. The dc analysis at the given operating conditions is performed. The results are listed below.

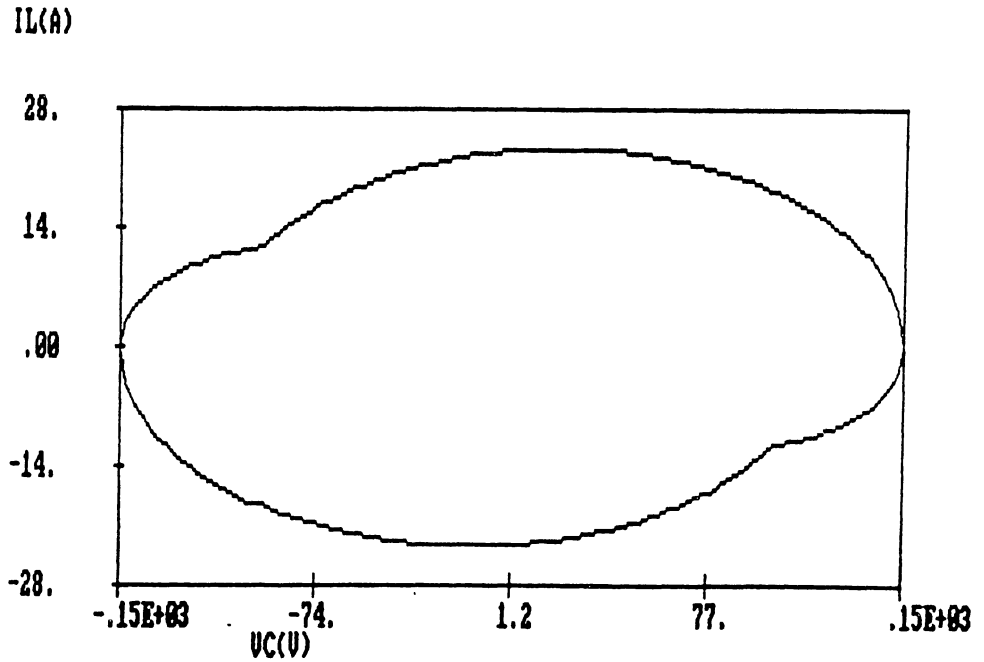
Io(A)	F(kHz)	ILAV(A)	ILR(A)	VCO(V)	ISW(A)	IQAV(A)	ILP(A)	VCP(V)
4.0	79.30	13.33	15.19	98.91	11.44	5.53	23.41	149.86
6.0	86.36	20.00	22.49	136.24	19.62	8.30	33.38	206.43

Definitions of the variables are listed below.

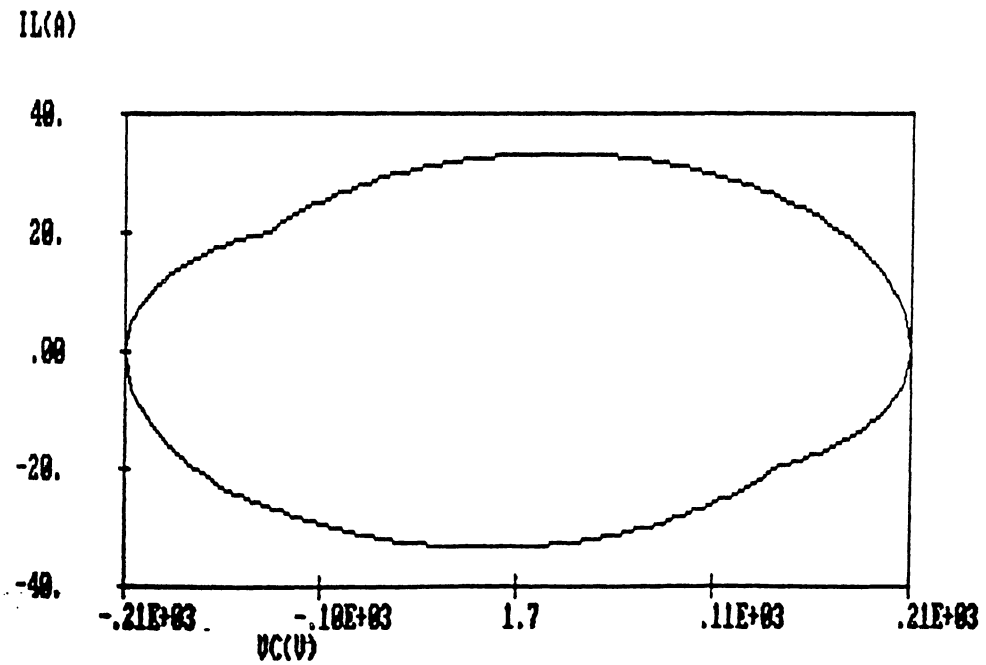
f	Switching frequency
ILAV	(Half-Cycle) Average current of the inductor
ILR	RMS current of the inductor
VCO	Capacitor voltage at switching point
ISW	Transistor current at switching point
IQAV	Average current of the transistor
ILP	Peak inductor current
VCP	Peak capacitor voltage

All the variables can be plotted at the user's choice. Figure 2.16 shows the state-plane diagrams of the above example. Figures 2.17 and 2.18 are of selected variables plotted as a function of the switching frequency. These graphs clearly show the behavior of the SRC as the load varies. As load varies from 4 to 6 amps, the switching frequency varies from 79.3 kHz to 86.4 kHz to maintain the output voltage V_o at 110 volts.

The SRC in the example is simulated by the SPICE program under the same operating conditions [12]. Figure 2.19 is the simulation result when I_o = 4 amps, while Fig. 2.20

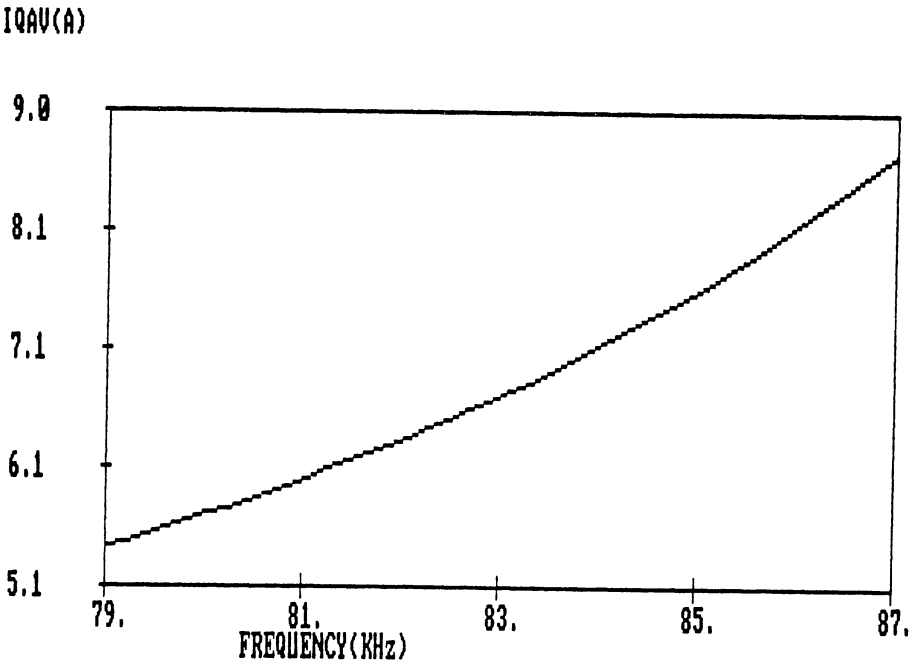


(a)

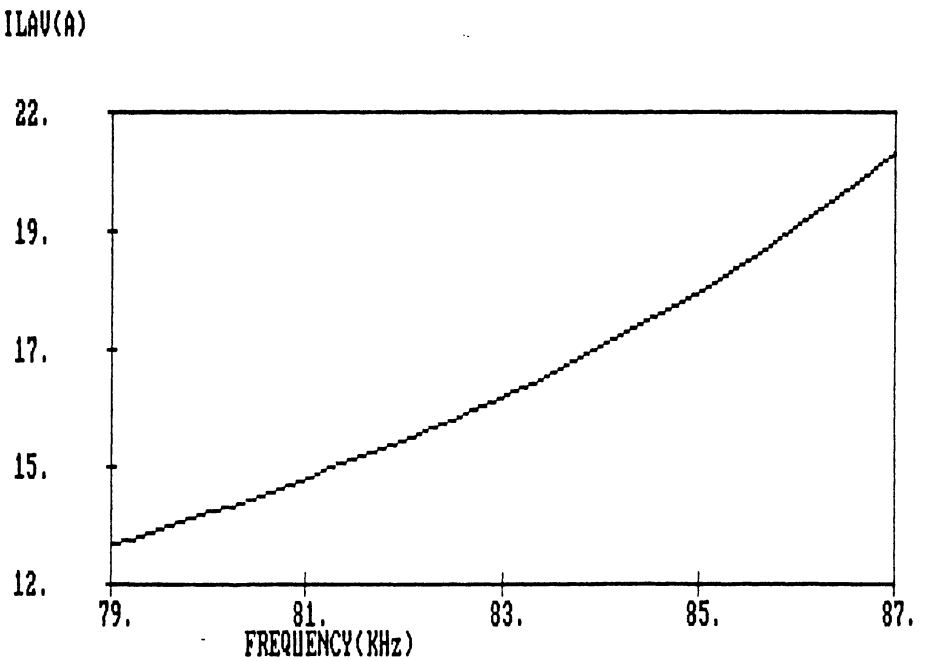


(b)

Fig. 2.16 State-plane diagrams
(a) I_o = 4 amps.
(b) I_o = 6 amps.

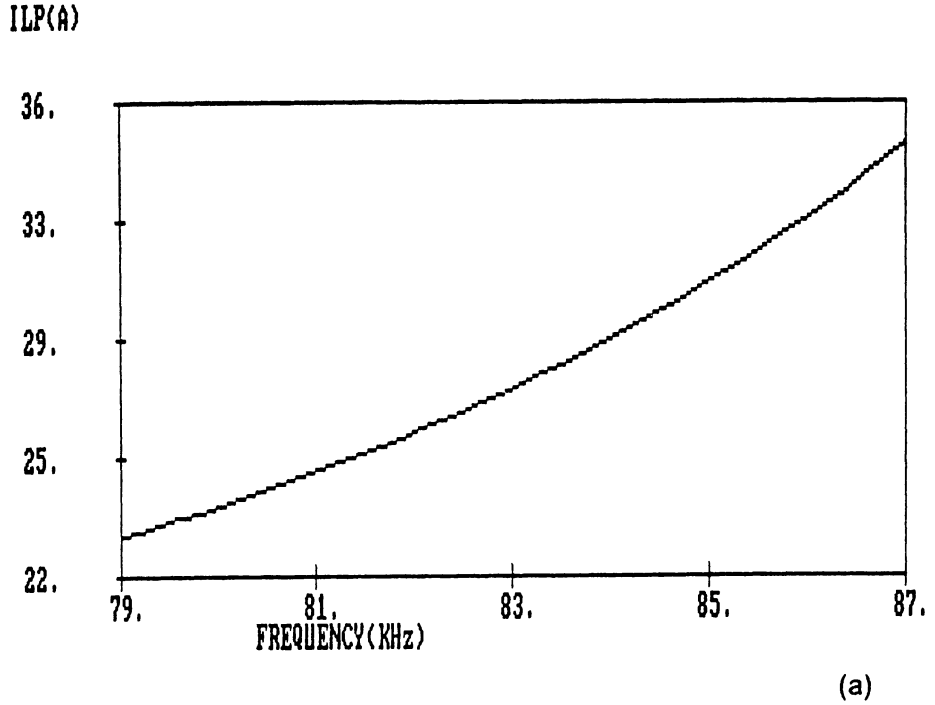


(a)

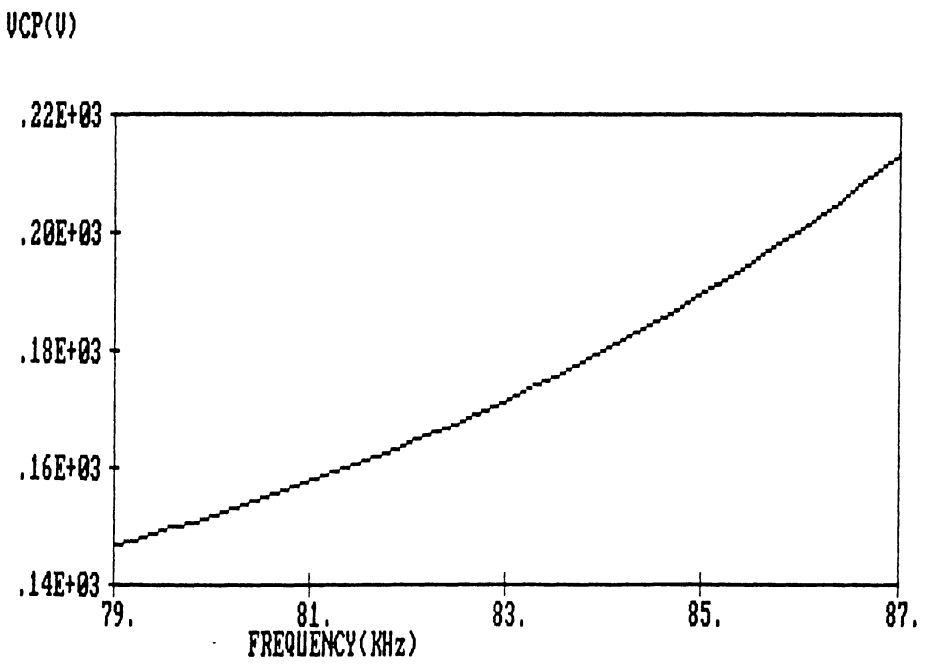


(b)

Fig. 2.17 DC characteristic curves as function of switching frequency
(a) Average transistor current
(b) Average inductor current



(a)



(b)

Fig. 2.18 DC characteristic curves as function of switching frequency
(a) Peak inductor current
(b) Peak capacitor voltage

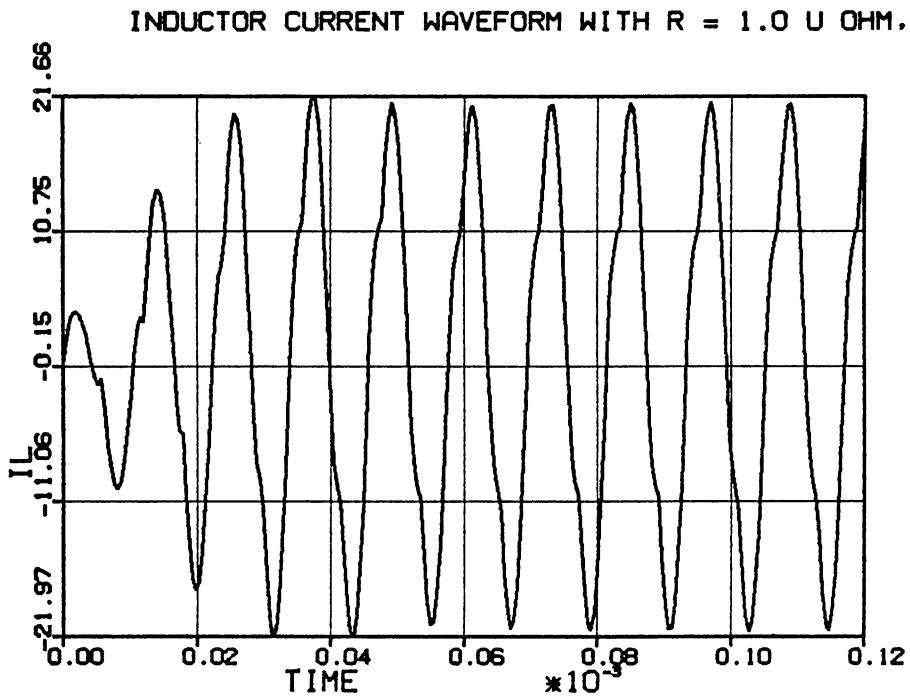
is the simulation result when I_o = 6 amps. The circuit model for the simulation is shown in Fig. 2.35. Based on the simulated data, the average and rms inductor currents are calculated. A program is written to read the discrete data and find the average and rms value. The program is listed in Appendix B. The analysis program is named SRCA. The results calculated from two different methods are listed below.

Method	f (kHz)	I_{LAV} (A)	I_{LR} (A)	I_{LP} (A)	V_{CP} (V)
SRCA	79.3	13.33	15.19	23.41	149.86
SPICE	79.3	12.89	14.72	21.66	142.7

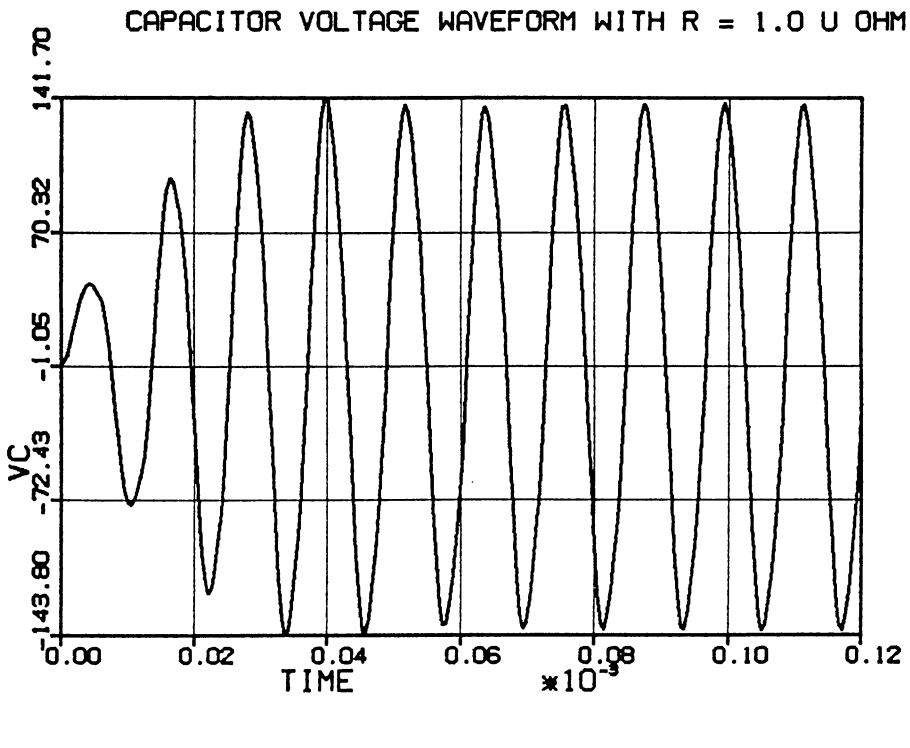
Method	f (kHz)	I_{LAV} (A)	I_{LR} (A)	I_{LP} (A)	V_{CP} (V)
SRCA	86.4	20.00	22.49	33.38	206.43
SPICE	86.4	18.92	20.64	34.11	213.2

2.2.4 Switching Frequency Above Resonance

In this section, the analysis of the SRC operating above the tank's resonant frequency is given. In this switching frequency range, the switches are forced to turn-off but they are turned on at zero current. The analysis is shown below.

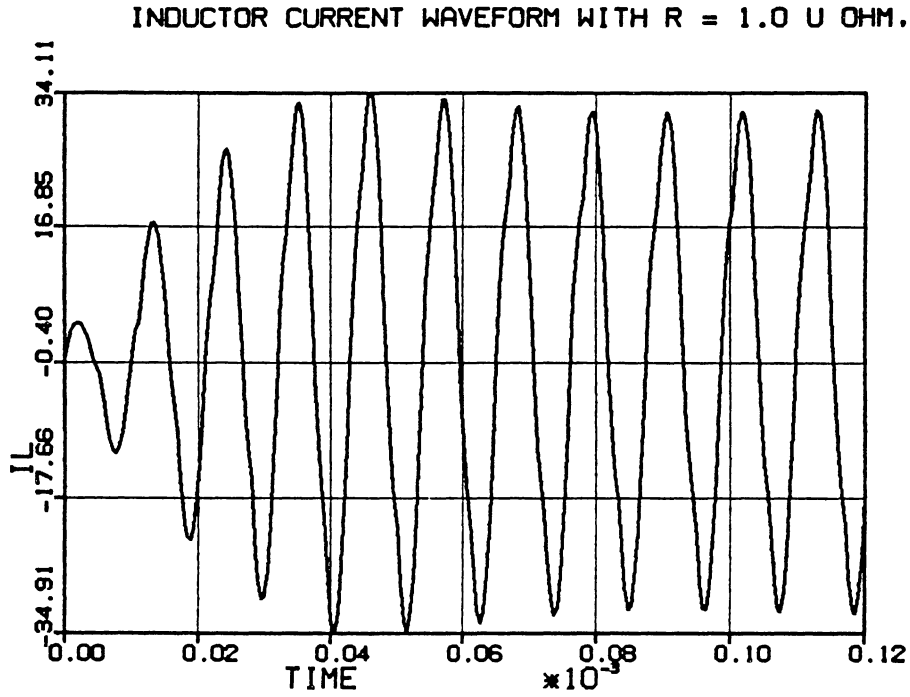


(a)

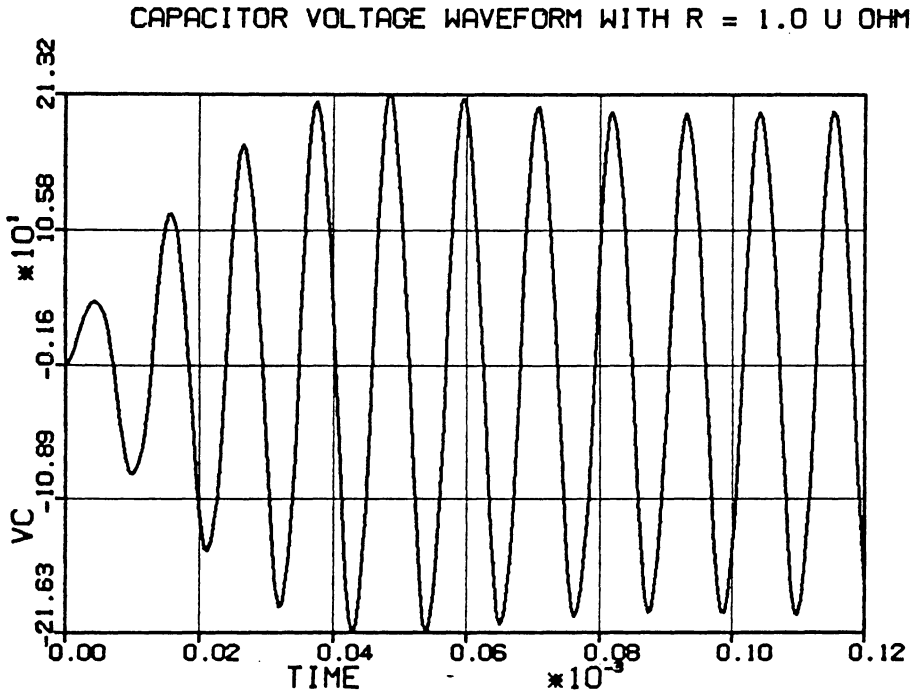


(b)

Fig. 2.19 SPICE simulation results when I_o = 4 amps.
(a) Inductor current waveform
(b) Capacitor voltage waveform



(a)



(b)

Fig. 2.20 SPICE simulation results when I_o = 6 amps.
(a) Inductor current waveform
(b) Capacitor voltage waveform

Enter circuit information.

Input voltage V_s = 50 volts

Output voltage V_o = 110 volts

Load current I_o range = 4-6 amps

Transformer's primary-to-secondary turns ratio n = 0.3

Value of the resonant inductor L = 9.030848 μH

Value of the resonant capacitor C = 0.2804863 μF

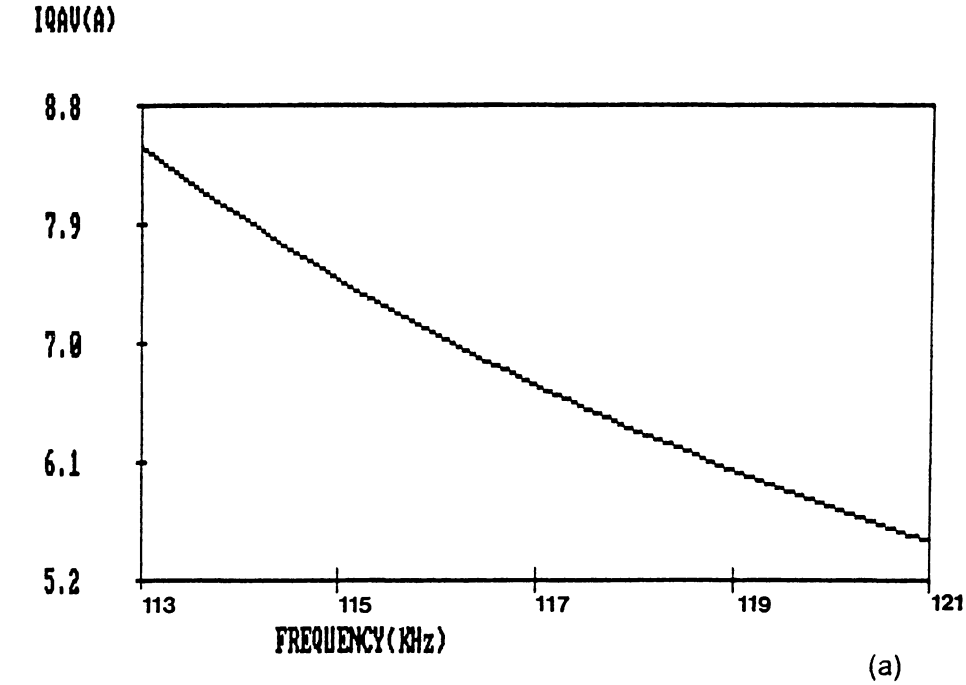
The converter is operating **above** resonant frequency.

DC analysis. The dc analysis at the given operating conditions is performed. The results are listed below.

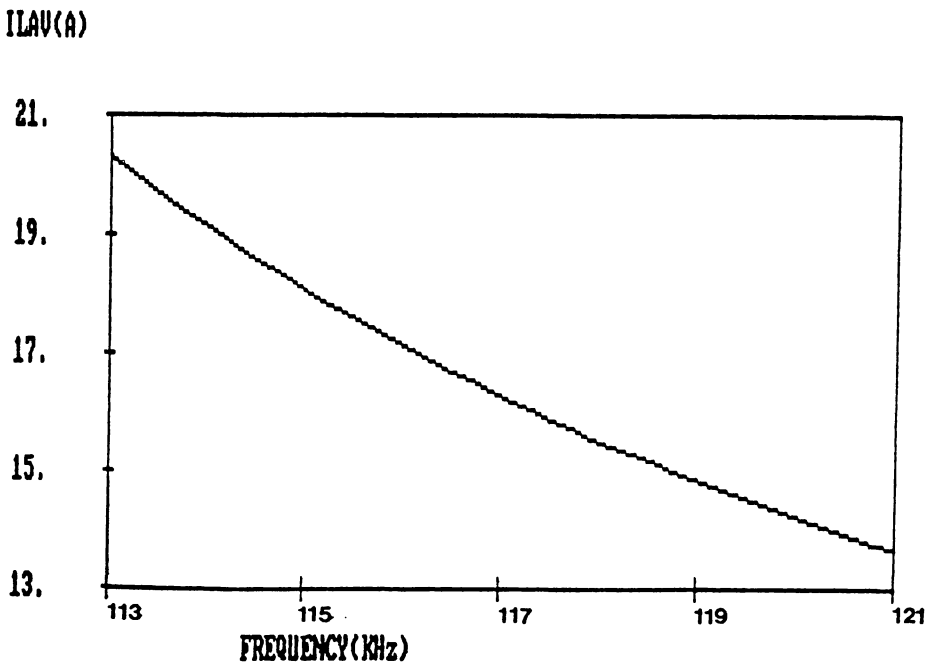
Io(A)	F(kHz)	ILAV(A)	ILR(A)	VCO(V)	ISW(A)	IQAV(A)	ILP(A)	VCP(V)
4.0	119.96	13.33	14.79	65.38	18.59	5.53	20.46	99.07
6.0	113.32	20.00	22.17	103.83	26.64	8.30	30.72	157.32

Figures 2.21 and 2.22 are selected variables plotted as a function of the switching frequency. In this case, the switching frequency is varied from 120 kHz to 113.32 kHz to accommodate the load range of 4 amps to 6 amps. Within this load range, all circuit parameters can be read directly from their corresponding graphs.

The above results are again compared with those obtained by SPICE simulation. Figures 2.23 and 2.24 are the simulated waveforms of the resonant tank. The average inductor current and rms inductor current are calculated using simulated data points in the steady state. The results obtained from the two different methods are shown below.

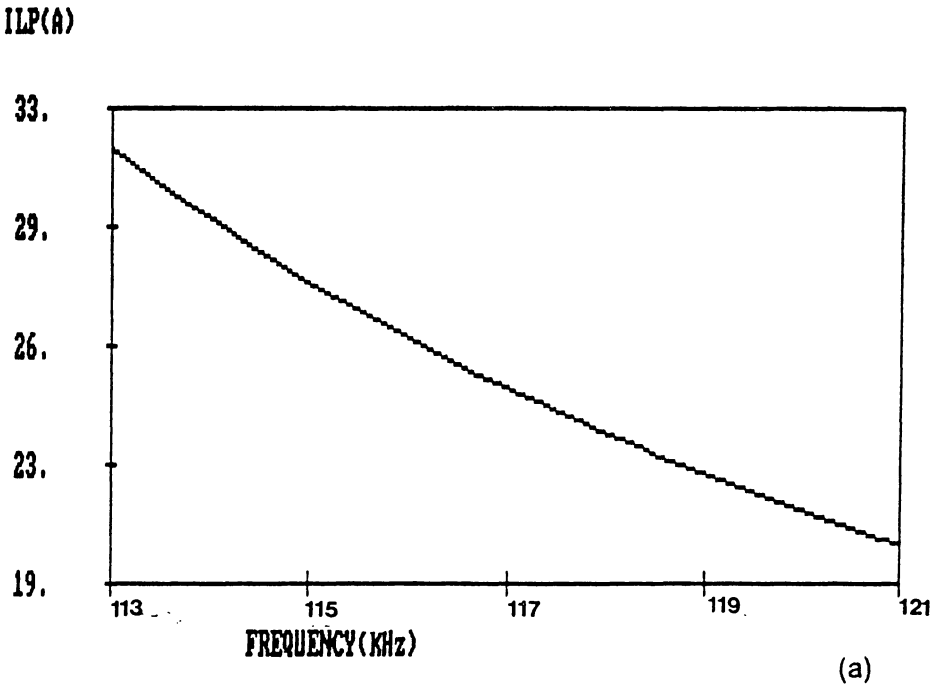


(a)



(b)

Fig. 2.21 DC characteristic curves as function of switching frequency
(a) Average transistor current
(b) Average inductor current



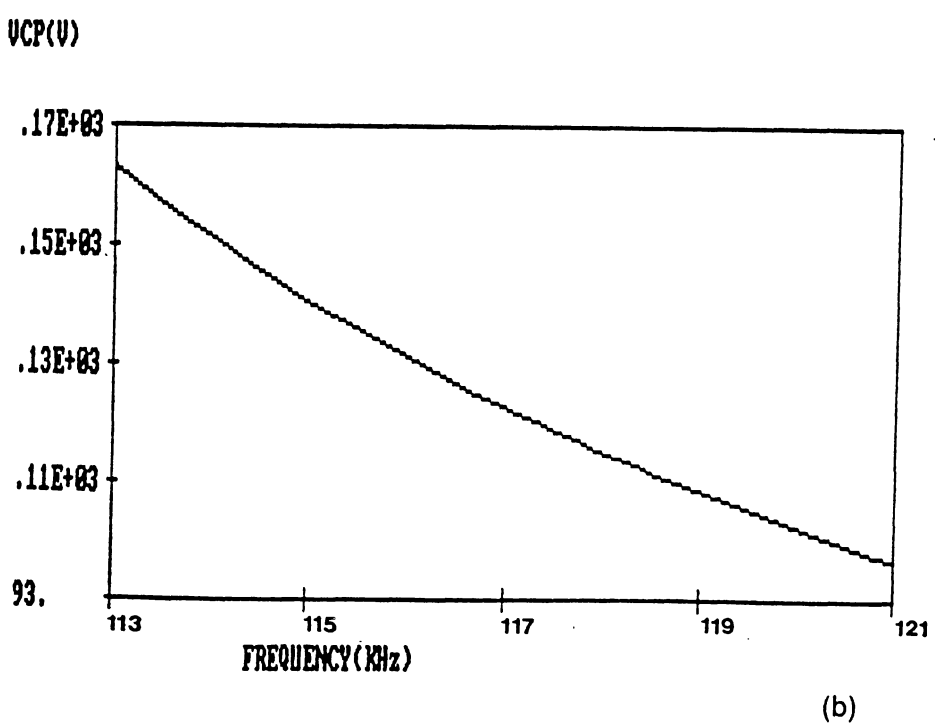
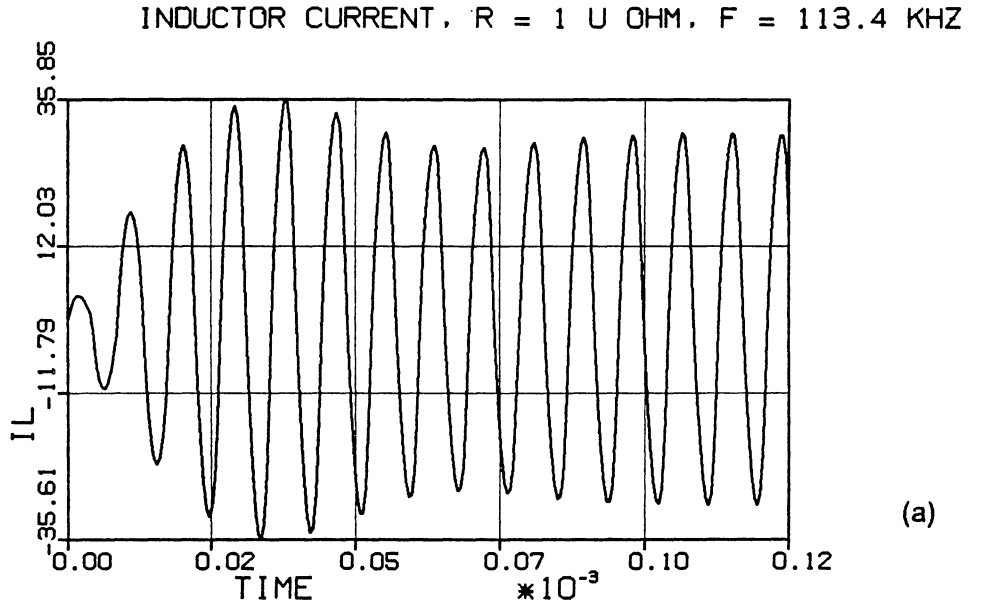


Fig. 2.22 DC characteristic curves as function of switching frequency
(a) Peak inductor current
(b) Peak capacitor voltage

Method	f (kHz)	I_{LAV} (A)	I_{LR} (A)	I_{LP} (A)	V_{CP} (V)
SRCA	113.32	20.00	22.17	30.72	157.32
SPICE	113.4	23.76	25.68	30.13	154.3

Method	f (kHz)	I_{LAV} (A)	I_{LR} (A)	I_{LP} (A)	V_{CP} (V)
SRCA	119.96	13.33	14.79	20.46	99.07
SPICE	120.0	15.26	16.70	22.86	107.6

From the above two examples, it can be seen that the characteristics of an SRC operating below resonance differ from those of an SRC operating above resonance. When an SRC operates below resonance, the values of all its circuit parameters increase with the switching frequency. This indicates that the tank energy level increases with the switching frequency. On the other hand, when an SRC operates above resonance, all its circuit parameters decrease with the increase of the switching frequency. This indicates that the tank energy level decreases with the increase of the switching frequency. Comparing the two cases at the same load condition, the peak inductor current, I_{LP}, is increased slightly but the peak capacitor voltage, V_{CP}, is significantly higher when the SRC operates below resonance.



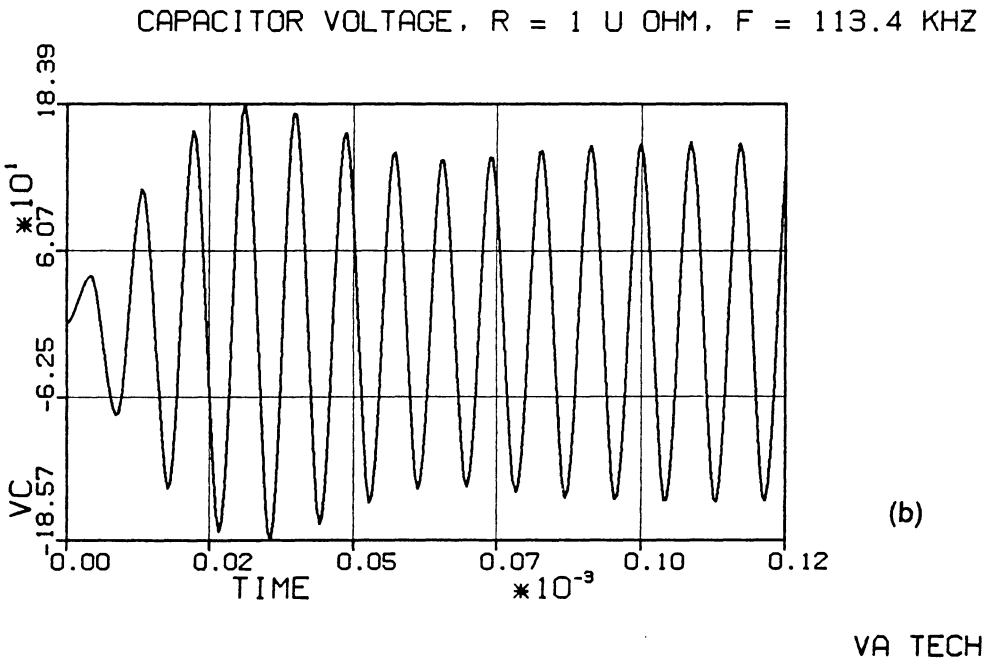
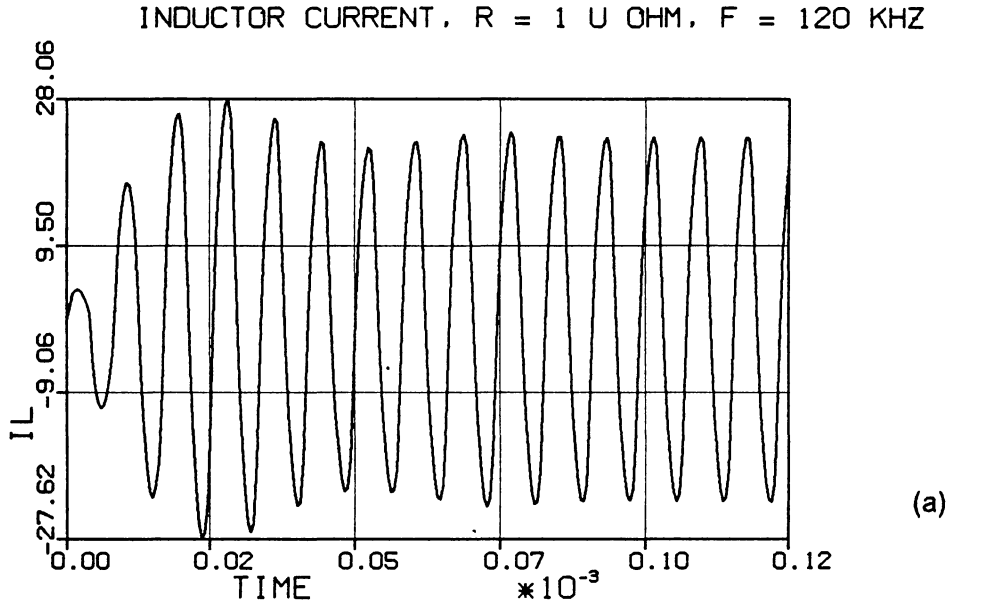


Fig. 2.23 SPICE simulation results when I_o = 6 amps.
(a) Inductor current waveform
(b) Capacitor voltage waveform



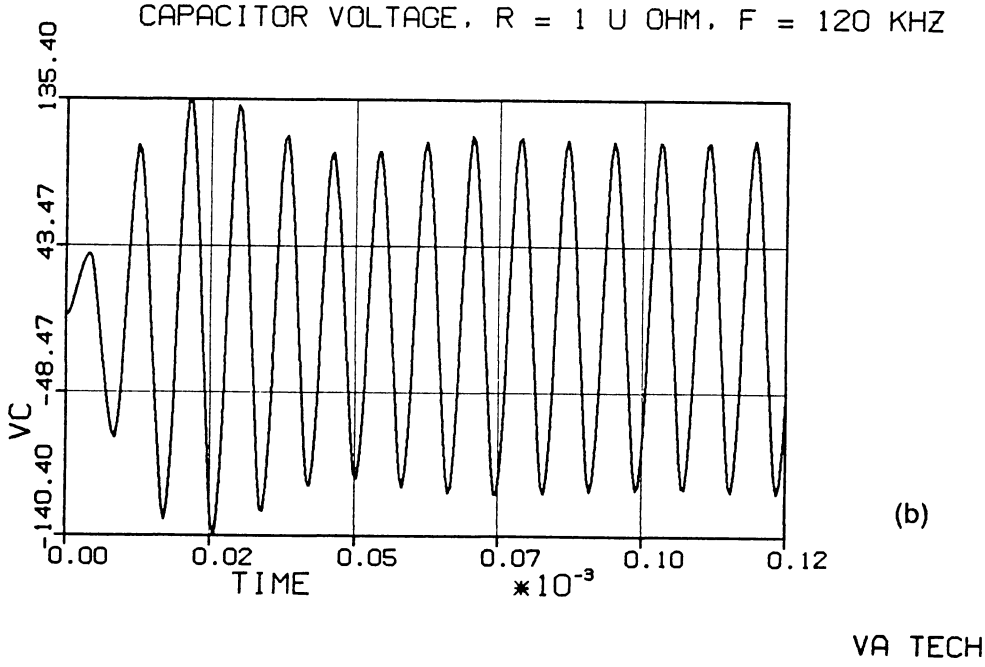


Fig. 2.24 SPICE simulation results when I_o = 4 amps.
(a) Inductor current waveform
(b) Capacitor voltage waveform

2.3 Analysis Of A Nonideal SRC

The dc analysis discussed in Sec. 2.2 is performed on an ideal SRC in which all parasitic losses are assumed zero. The tank quality factor, Q, equals infinity. However, it is found that in certain regions of operation, such as when the operating frequency is close to the tank's resonant frequency, the characteristics of an SRC are quite sensitive to the parasitic losses. The detailed analysis of an SRC with parasitic losses can be found in Refs. [7] and [9]. The analysis of a nonideal SRC using the analysis program is discussed in this section.

For a nonideal SRC, Q is finite. Unlike the ideal SRC, the tank's maximum energy level is limited to a finite amount by the losses. A maximum current is delivered to the load when the switching frequency equals the damped natural frequency f_D.

$$f_D = f_O\sqrt{1-\zeta^2} \quad \text{with} \quad f_O = \frac{1}{2\pi\sqrt{LC}}$$

Figure 2.25 is a simplified flow chart showing the analysis of a nonideal SRC. The analysis procedure is similar to that of an ideal SRC with Q specified by the user in the beginning.

2.3.1 Determination Of SRC Operating Mode

Figure 2.26 shows a more detailed flow chart of the analysis of a nonideal SRC. As in the case of the analysis of an ideal SRC, the user has the option to perform the SRC

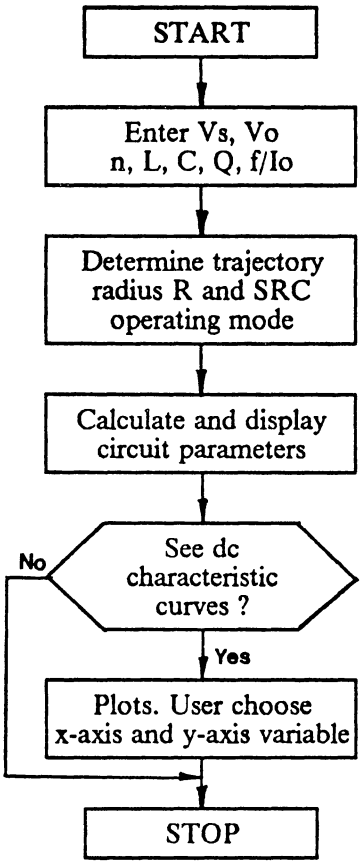


Fig. 2.25 Simplified flow chart of the nonideal SRC analysis program

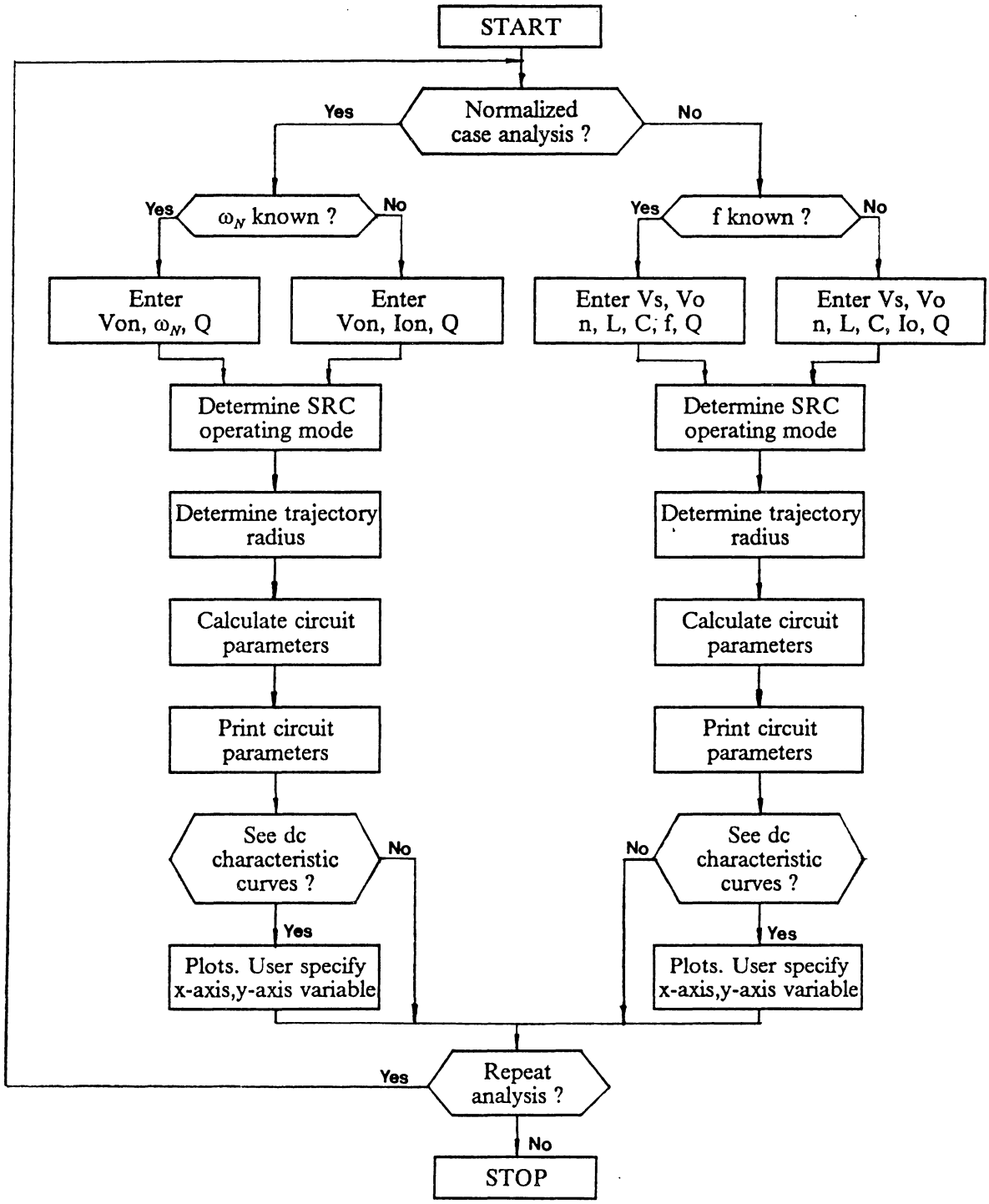


Fig. 2.26 Flow chart of the nonideal SRC analysis program

analysis either with normalized circuit or with actual circuit. The analysis of an SRC refers to the actual circuit analysis in the following text.

The analysis is carried out through the state-plane technique again. The variables needed to perform state-plane analysis are V_{ON}, Q , and either ω_N or I_{ON}. The given SRC is normalized first to find these variables. The voltage normalizing factor is V_s and the current normalizing factor is V_s/Z_o as before. The frequency normalizing factor is f_D which is the damped natural frequency.

The analysis of a nonideal SRC is limited to the region where the switching frequency is less than the damped natural frequency of the resonant tank. There are three different modes of operation [9]: 1)DCM-1, 2)DCM-2, and 3)CCM. Figure 2.27 shows examples of the steady-state trajectory in each operating mode. DCM-1 occurs at the following conditions:

$$k < V_{ON} < 1 \quad \text{and} \quad \omega_N < 1$$

$$\text{where} \quad k = \exp\{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}\}$$

DCM-2 occurs at the following conditions:

$$0 < V_{ON} < k \quad \text{and} \quad \omega_N < 0.5$$

CCM is the region where

$$0 < V_{ON} < k \quad \text{and} \quad 0.5 < \omega_N < 1$$

Figure 2.28 shows the operating regions of a nonideal SRC with a switching frequency up to the damped natural frequency. When V_{ON}, Q, and ω_N are known, the operating

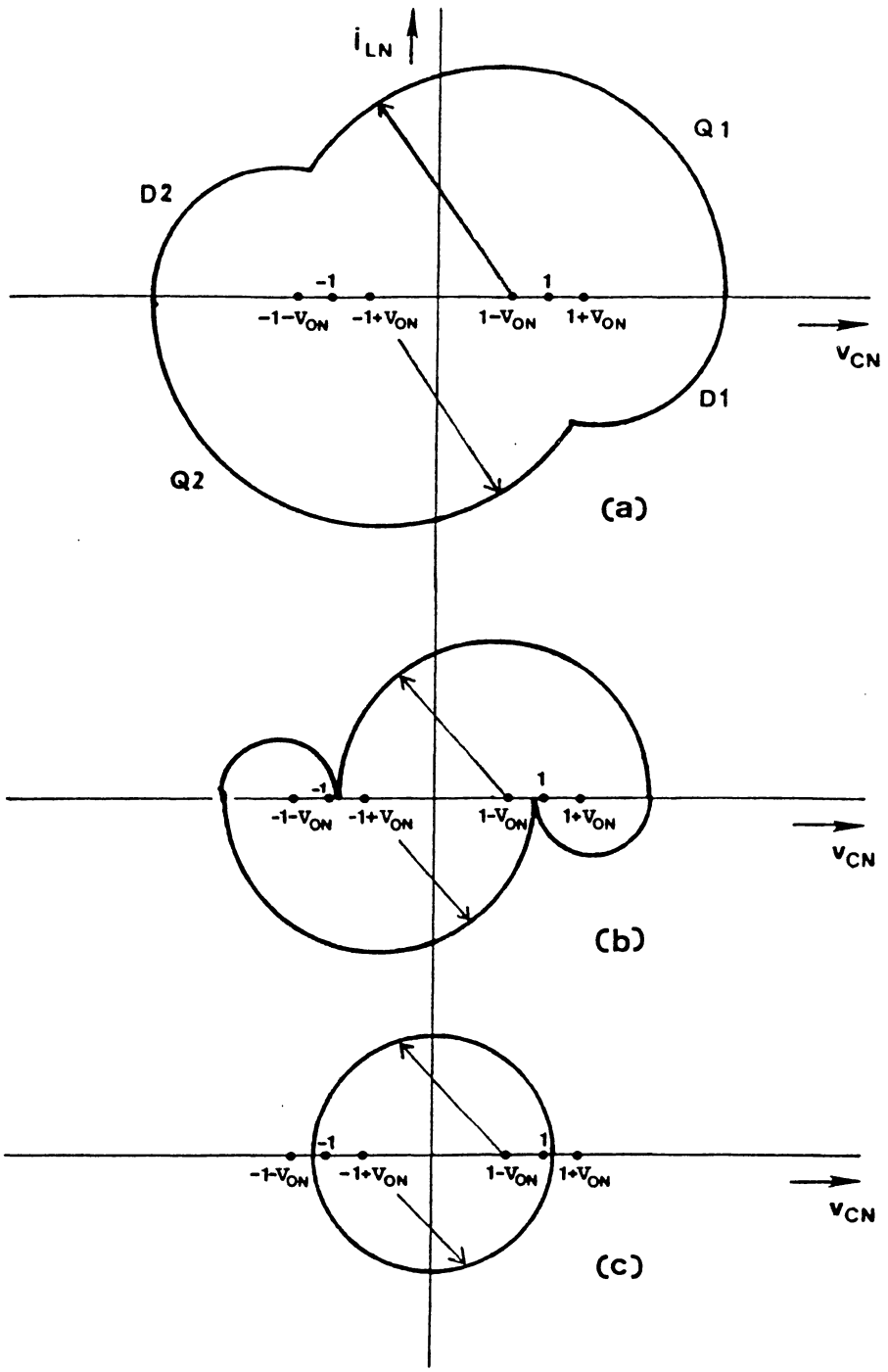


Fig. 2.27 Steady-state trajectories of a nonideal SRC
(a) CCM (b) DCM-1 (c) DCM-2

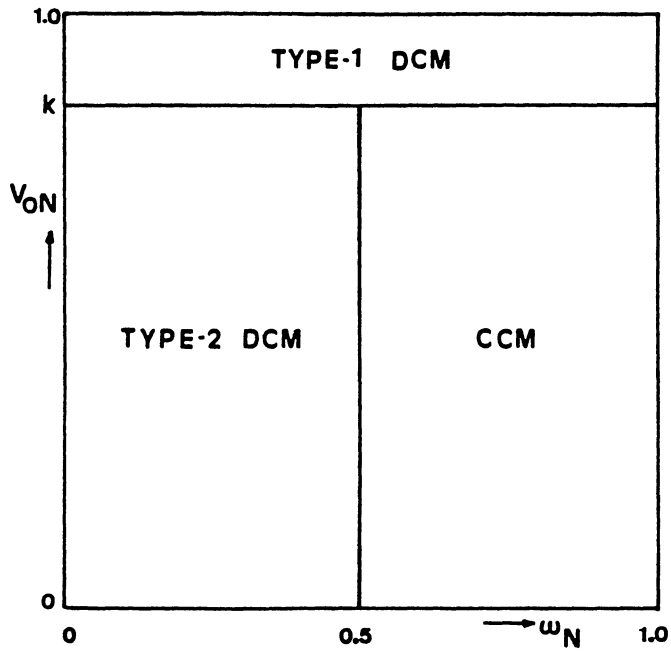


Fig. 2.28 Operating regions of a nonideal SRC

mode of the SRC is determined easily by comparing V_{ON} and ω_N with the above three boundary conditions.

When V_{ON}, Q, and I_{ON} are known, the operating mode of SRC can also be easily determined. DCM-1 is distinguished from the other two modes by comparing V_{ON} with k. The boundary between DCM-2 and CCM is at $\omega_N = 0.5$. The normalized (half-cycle) average inductor current, I_{LAVN}, at this boundary condition is calculated by the following equation [9]:

$$I_{LAVN} = \frac{(1 - V_{ON}^2 + 2k + k^2 + V_{ON}k^2)\sqrt{1 - \zeta^2}}{\pi(1 + k^2)} \tag{23}$$

The value of I_{LAVN} at given I_O is calculated by the program as follows:

$$I_{LAVN} = \frac{I_O Z_O}{nV_S}$$

This value is compared with the value calculated by Eq. (23). If it is less than that calculated by Eq. (23), the SRC is in DCM-2; otherwise, the SRC is in CCM, provided $V_{ON} < k$

2.3.2 Determination Of Steady-State Trajectory Radius

The steady-state trajectory is a spiral for a nonideal SRC. The final trajectory radius, at which the switch is turned off, is used in the program to find desired circuit parameters. In DCM-1 and DCM-2, the circuit parameters are calculated as the function of V_{ON}, k, and ω_N or I_{ON} directly [9]. In DCM-1,

$$I_{LAVN} = 2\omega_N(1 - V_{ON})\sqrt{1 - \zeta^2}\,\frac{1 + k}{\pi(1 - k)} \tag{24}$$

$$V_{CPN} = (1 - V_{ON})\frac{1 + k}{1 - k} \tag{25}$$

$$V_{CON} = V_{CPN} \tag{26}$$

$$I_{SWN} = 0 \tag{27}$$

$$I_{QAVN} = \frac{I_{LAVN}}{2} \tag{28}$$

$$I_{DAVN} = 0 \tag{29}$$

In DCM-2,

$$I_{LAVN} = 2\omega_N\sqrt{1 - \zeta^2}\,\frac{1 - V_{ON} + 2k + k^2 + V_{ON}k^2}{\pi(1 + k^2)} \tag{30}$$

$$V_{CPN} = \frac{1 - V_{ON} + 2k + k^2 + V_{ON}k^2}{1 + k^2} \tag{31}$$

$$I_{SWN} = 0 \tag{32}$$

$$\alpha = \pi \tag{33}$$

$$\beta = \pi \tag{34}$$

In CCM, the circuit parameters are found by utilizing the final trajectory radius, R, in Fig. 2.4. The minimum trajectory radius, R_{MIN}, is the boundary trajectory radius between DCM-2 and CCM. It is found in Ref. [9] and listed below.

$$R_{MIN} = \frac{2k(1 + kV_{ON})}{1 + k^2}$$

The maximum trajectory radius, R_{MAX}, is the radius when the switching frequency equals the damped natural frequency. This is the maximum tank energy trajectory and the maximum current is delivered to the load when the SRC is operating along this trajectory. R_{MAX} is given below [9].

$$R_{MAX} = \frac{2k(1 - V_{ON})}{1 - k}$$

Since the range of R and V_{ON} are known, the binary search method is used again to find R which results in the given ω_N or I_{ON} . Desired circuit parameters will be calculated accordingly by utilizing the trajectory radius.

2.3.3 Analysis Example

The analysis example in Sec. 2.2.3 is modified in this section. A single loss resistor which accounts for various tank circuit parasitic losses is added into the tank circuit (Fig. 2.3). The tank's quality factor, Q, has to be provided by the user. In this section, two examples are given with different values of Q. The analysis is shown below.

Enter circuit information.

Input voltage V_S = 50 volts

Output voltage V_O = 110 volts

Load current I_O range = 4-6 amps

Transformer's primary-to-secondary turns ratio n = 0.3

Value of the resonant inductor L = 9.030848 μH

Value of the resonant capacitor C = 0.2804863 μF

Case 1: Q = **40**

DC analysis. The dc analysis at the given operating conditions is performed. The results are listed below.

Io(A)	F(kHz)	ILAV(A)	VCO(V)	ISW(A)	IQAV(A)	IDAV(A)	VCP(V)
4.0	80.30	13.33	105.0	10.64	5.70	0.97	147.98
6.0	87.47	19.99	149.23	17.63	8.662	1.34	203.78

Case 2: Q = **15**

DC analysis. The dc analysis at the given operating conditions is performed. The results are listed below.

Io(A)	F(kHz)	ILAV(A)	VCO(V)	ISW(A)	IQAV(A)	IDAV(A)	VCP(V)
4.0	82.42	13.33	114.45	8.99	5.98	0.69	144.12
6.0	90.12	19.99	169.04	13.13	9.27	0.72	197.71

Figure 2.29 shows the selected variables plotted as a function of the switching frequency when Q equals 40; while Fig. 2.30 shows similar plots when Q equals 15. Within this load range and with the same quality factor, circuit parameters can be read directly from the corresponding graphs.

The above analysis is verified by the SPICE simulations. The characteristic impedance, calculated by Eq. (15), equals 5.674249 ohms. Therefore, the lumped resistor in the tank circuit equals 0.1419 ohm and 0.3783 ohm for the quality factor of

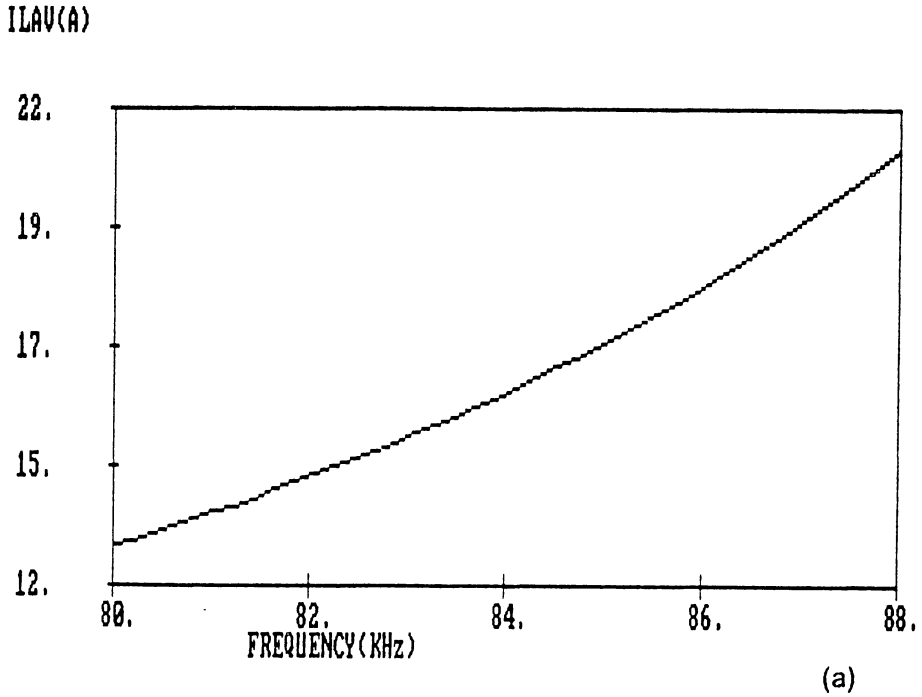
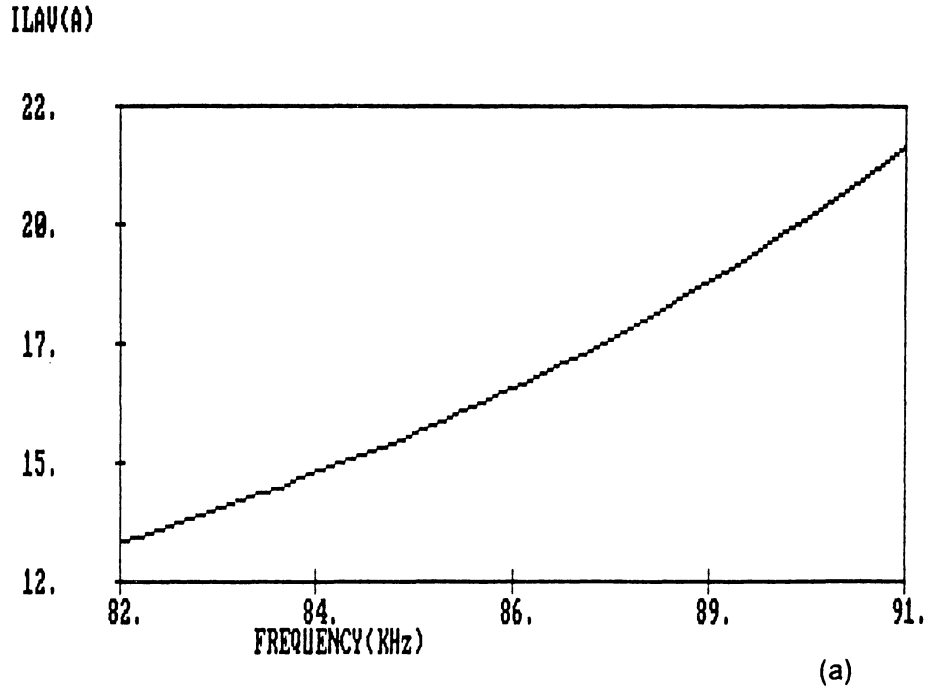


Fig. 2.29 DC characteristic curves as function of switching frequency with Q = 40
(a) Average inductor current
(b) Peak capacitor voltage



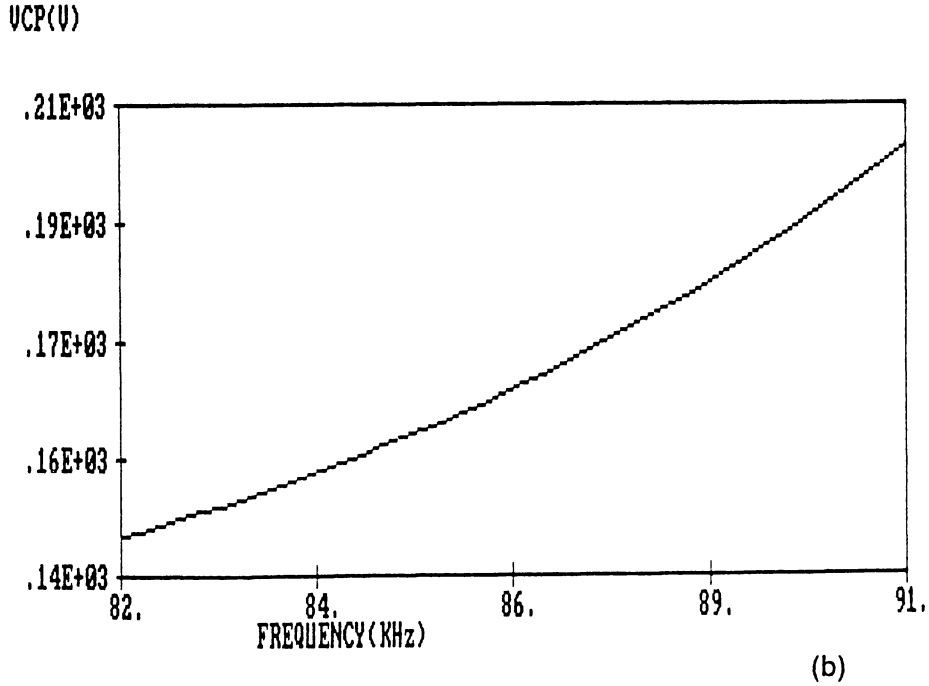


Fig. 2.30 DC characteristic curves as function of switching frequency with Q = 15
(a) Average inductor current
(b) Peak capacitor voltage

40 and 15, respectively. The time domain waveforms are shown in Figs. 2.31 through 2.34. The comparison between the two sets of results obtained from different methods are shown below.

Method	Q	$I_o\,(A)$	$f\,(kHz)$	$I_{LAV}\,(A)$	$V_{CP}\,(V)$
SRCA	40	4.0	80.30	13.33	147.98
SPICE	40	4.0	80.30	13.21	142.7

Method	Q	$I_o\,(A)$	$f\,(kHz)$	$I_{LAV}\,(A)$	$V_{CP}\,(V)$
SRCA	40	6.0	87.47	19.99	203.78
SPICE	40	6.0	87.5	19.23	210.1

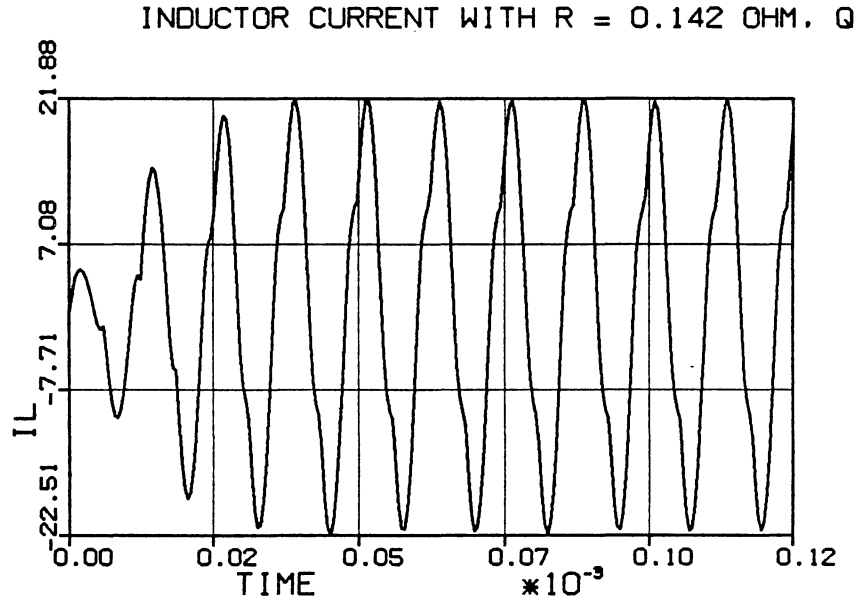
Method	Q	$I_o\,(A)$	$f\,(kHz)$	$I_{LAV}\,(A)$	$V_{CP}\,(V)$
SRCA	15	4.0	82.42	13.33	144.12
SPICE	15	4.0	82.40	13.07	138.2

Method	Q	I_o (A)	f (kHz)	I_{LAV} (A)	V_{CP} (V)
SRCA	15	6.0	90.12	19.99	197.71
SPICE	15	6.0	90.1	19.57	204.8

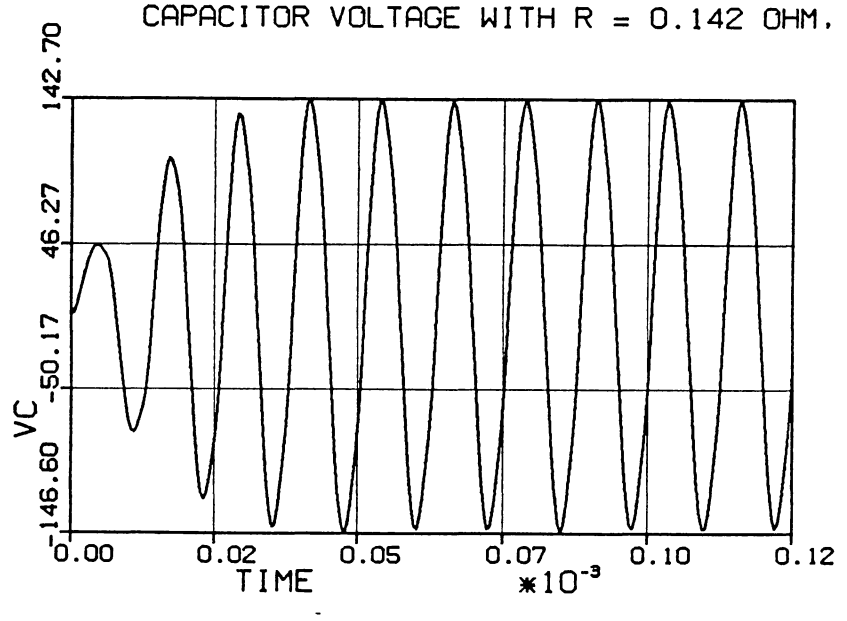
When the analysis results of an ideal SRC (Sec. 2.2.3) and a nonideal SRC are compared, it can be seen that for the same load current, I_o , the switching frequency is increased in the case with losses to compensate the parasitic losses in the converter. Due to the losses in the tank circuit, the peak capacitor voltage and switching current are decreased.

The results of various analyses have been verified closely by the SPICE simulation. Figure 2.35 shows the circuit model for the SPICE simulation. Resistor R in the tank circuit is adjusted to account for the tank's losses. The listings of the SPICE simulation program is shown in Appendix B.

A program using Simpson's rule for numerical integration is written to calculate the average and rms inductor current from the time domain waveform. The program is also listed in Appendix B.

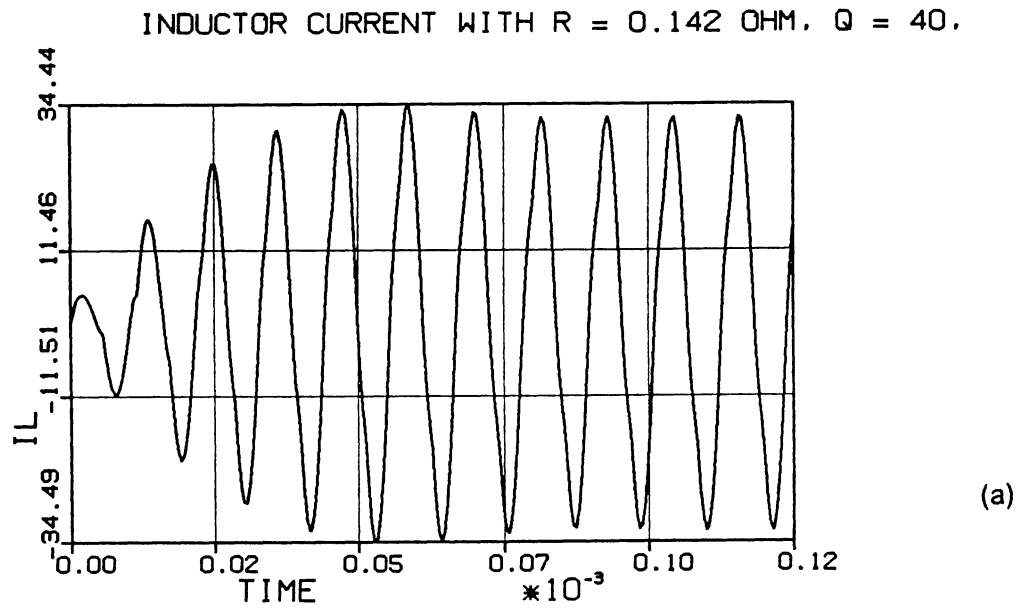


(a)

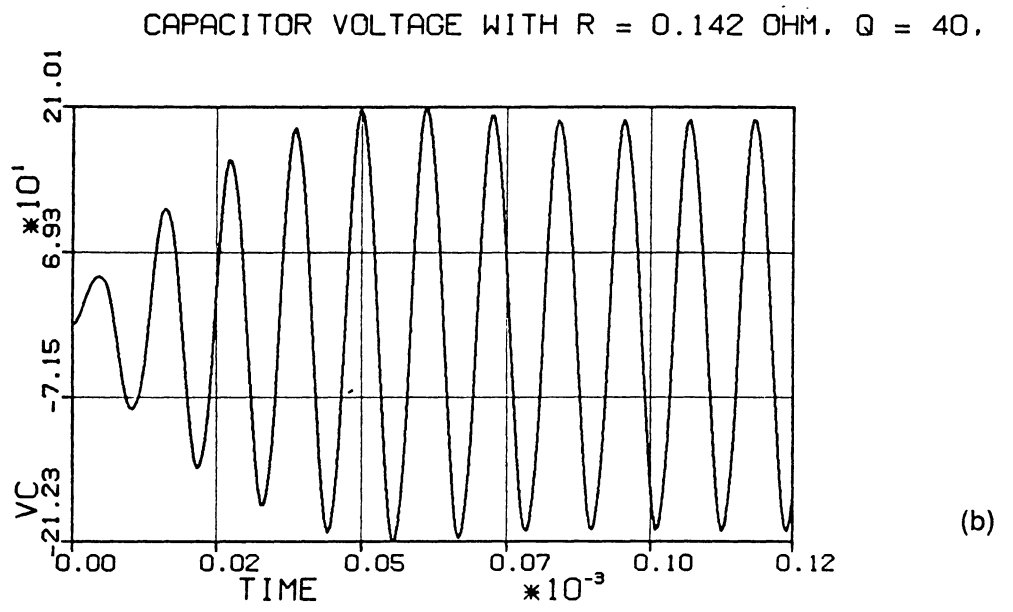


(b)

Fig. 2.31 SPICE simulation results when I_o = 4 amps and Q = 40
(a) Inductor current waveform
(b) Capacitor voltage waveform

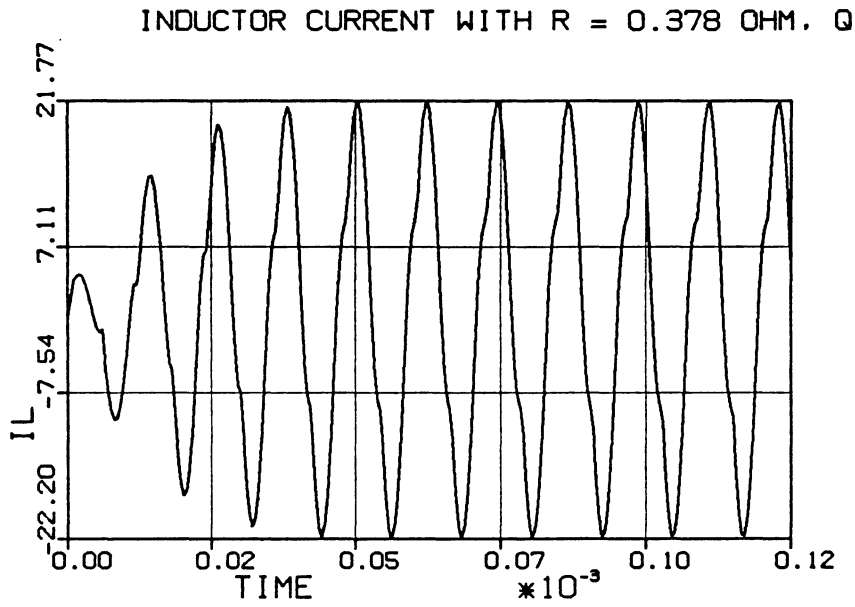


(a)

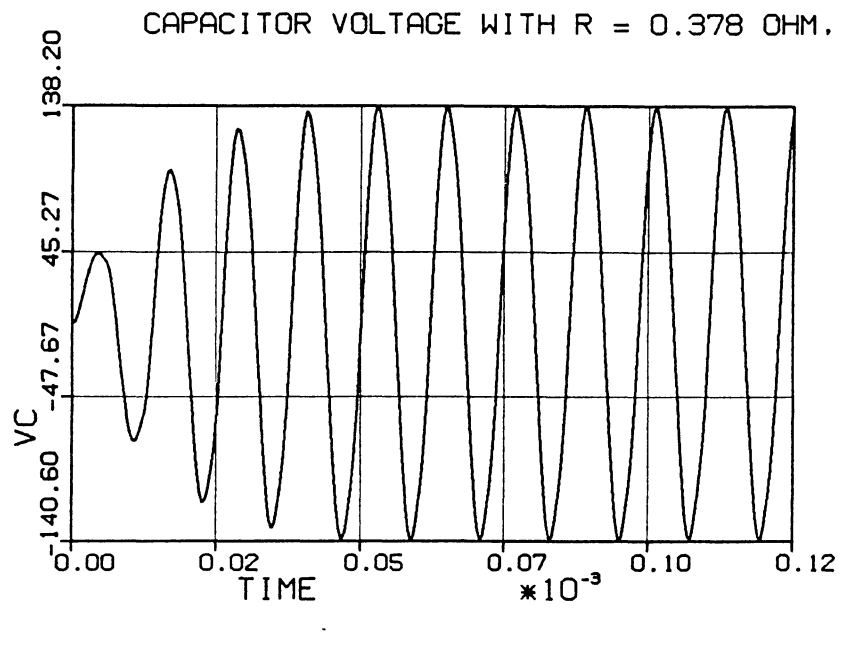


(b)

Fig. 2.32 SPICE simulation results when I_o = 6 amps and Q = 40
(a) Inductor current waveform
(b) Capacitor voltage waveform

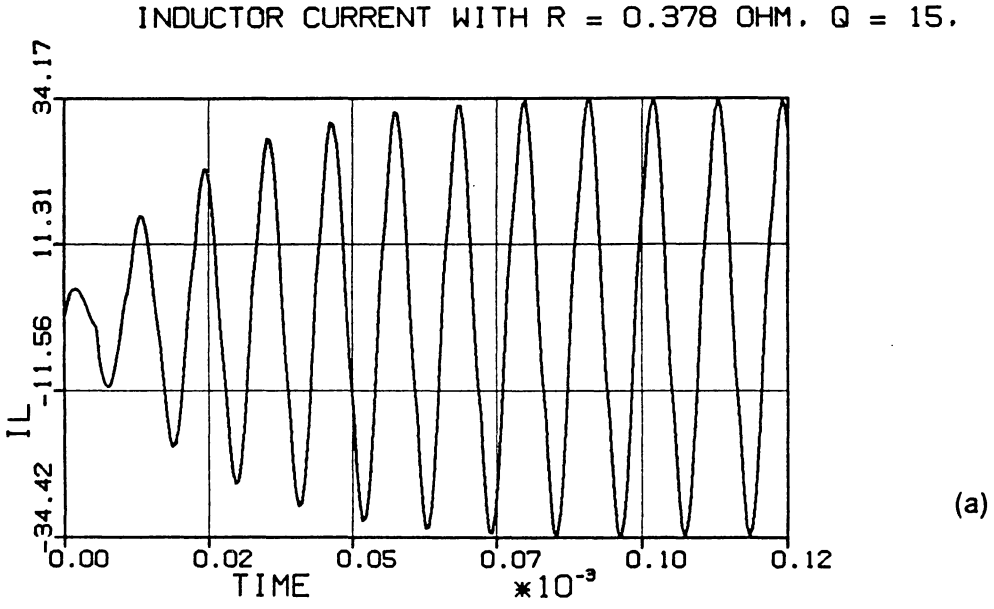


(a)

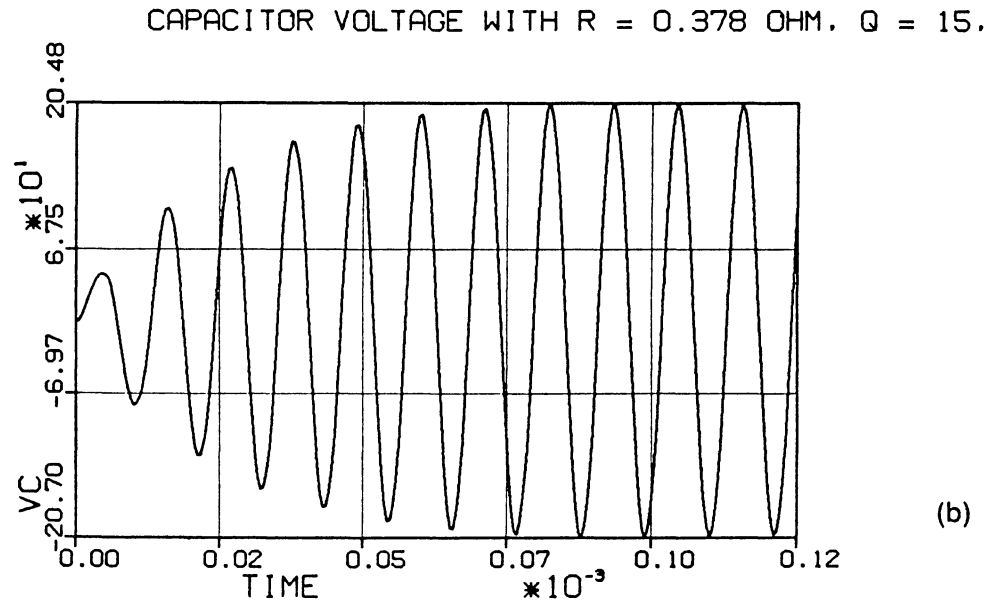


(b)

Fig. 2.33 SPICE simulation results when I_o = 4 amps and Q = 15
(a) Inductor current waveform
(b) Capacitor voltage waveform



(a)



(b)

Fig. 2.34 SPICE simulation results when I_0 = 6 amps and Q = 15
(a) Inductor current waveform
(b) Capacitor voltage waveform

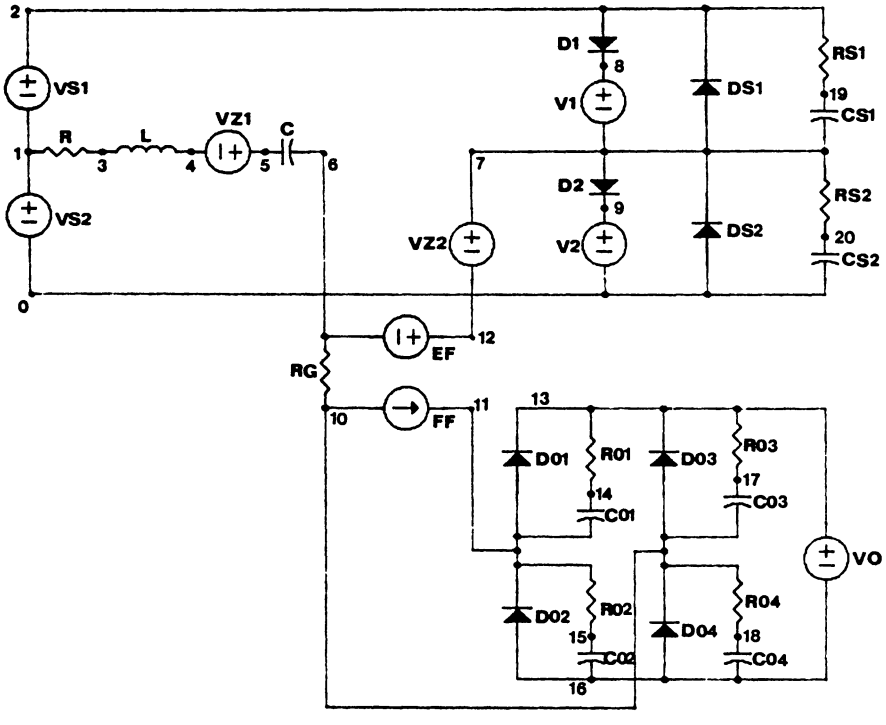


Fig. 2.35 Circuit model for SPICE simulation

3. SRC DESIGN

The design of a resonant converter is a complicated process. Given a set of design specifications, a converter can be designed to behave quite differently depending on the choice of inductor and capacitor for the resonant tank and the transformer's turns ratio. For example, for a given design that satisfies design specifications, the peak inductor current and peak capacitor voltage of the converter can vary widely according to the choices of transformer's turns ratios. The parasitic losses can significantly affect SRC operation and must be considered during the design. The design program aids in the design of an SRC to meet the given specifications. Design guidelines and design graphs are provided to facilitate the design process. The dc analysis is performed at the end of each design iteration to verify the design. If the results of the analysis are not satisfactory, the user can iterate the design.

3.1 Design Procedure And Considerations

Every SRC has parasitic losses and the behavior of such a nonideal SRC is very complicated [9]. Figures 3.1 and 3.2 show the graph of I_{LAVN} vs V_{ON} for an SRC with an infinite Q and a finite Q, respectively. These two graphs clearly show the effects of parasitic losses on the output characteristics of an SRC over the entire output voltage range and switching frequency range below resonance. When losses are included, fewer analysis equations are available, so less circuit information can be generated from a steady-state trajectory as discussed Sec. 2.1. Furthermore, even the available equations are difficult to solve. Consequently, the design is more tedious to carry out. However, it can be seen from Figs. 3.1 and 3.2 that the characteristics of an ideal SRC and a nonideal SRC are close when the following conditions hold.

$$f < f_o \quad \text{and} \quad V_{ON} < k$$

Therefore, if the switching frequency is away from resonant frequency and V_{ON} is away from unity, the SRC can be assumed lossless to simplify the design.

The design is made according to three user-specified parameter values and the design specifications. These parameters are the transformer's turns ratio, the tank resonant frequency, and the upper or lower bound of the switching frequency. Normalized design curves and design guidelines are provided to help the user choose these parameter values. The design is carried out in a step-by-step manner. Figure 3.3 shows a simplified flow chart of the design procedure which will be discussed according to each block in the flow chart.

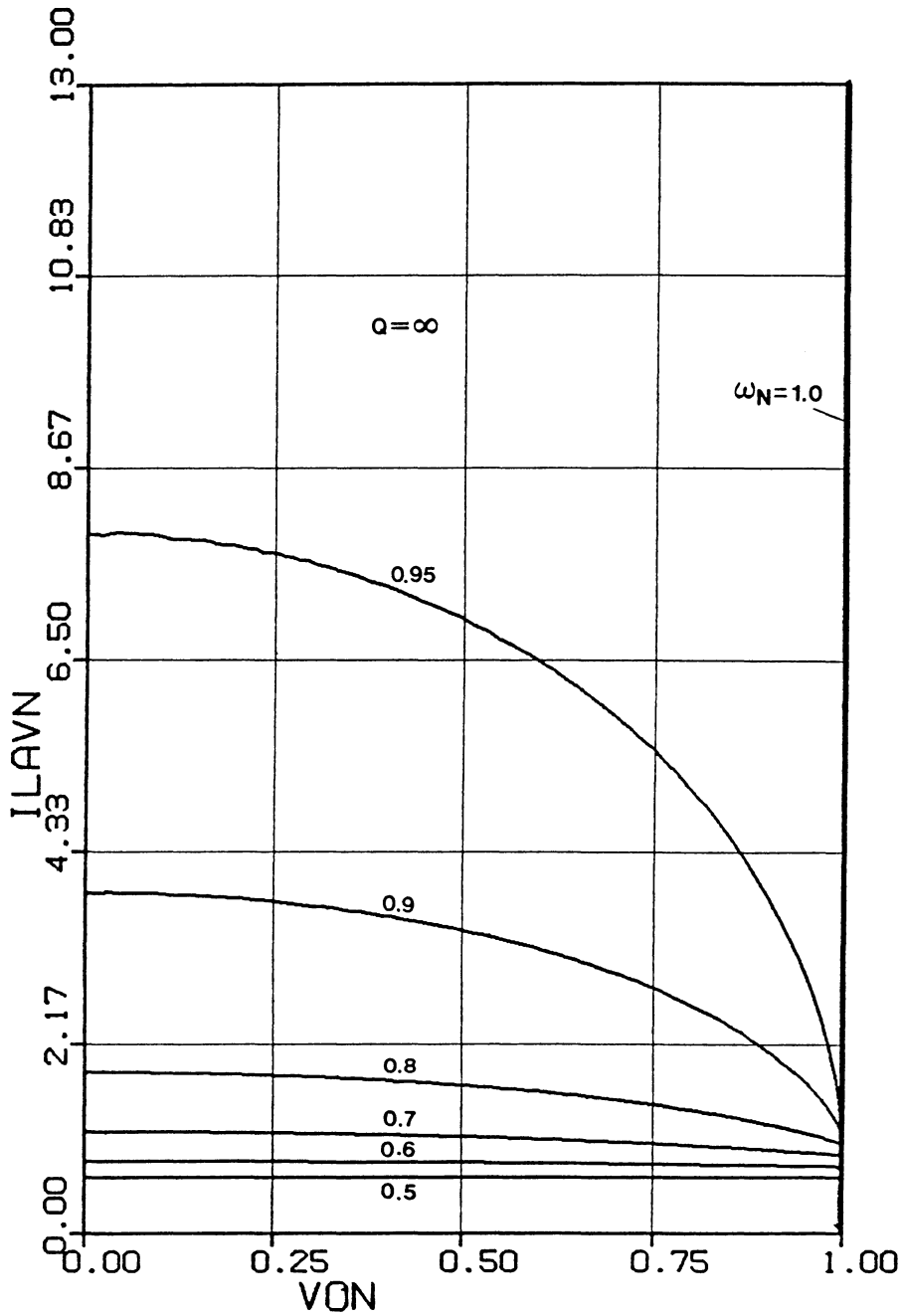


Fig. 3.1 Ideal SRC dc characteristic curve when $\omega_N \leq 1$

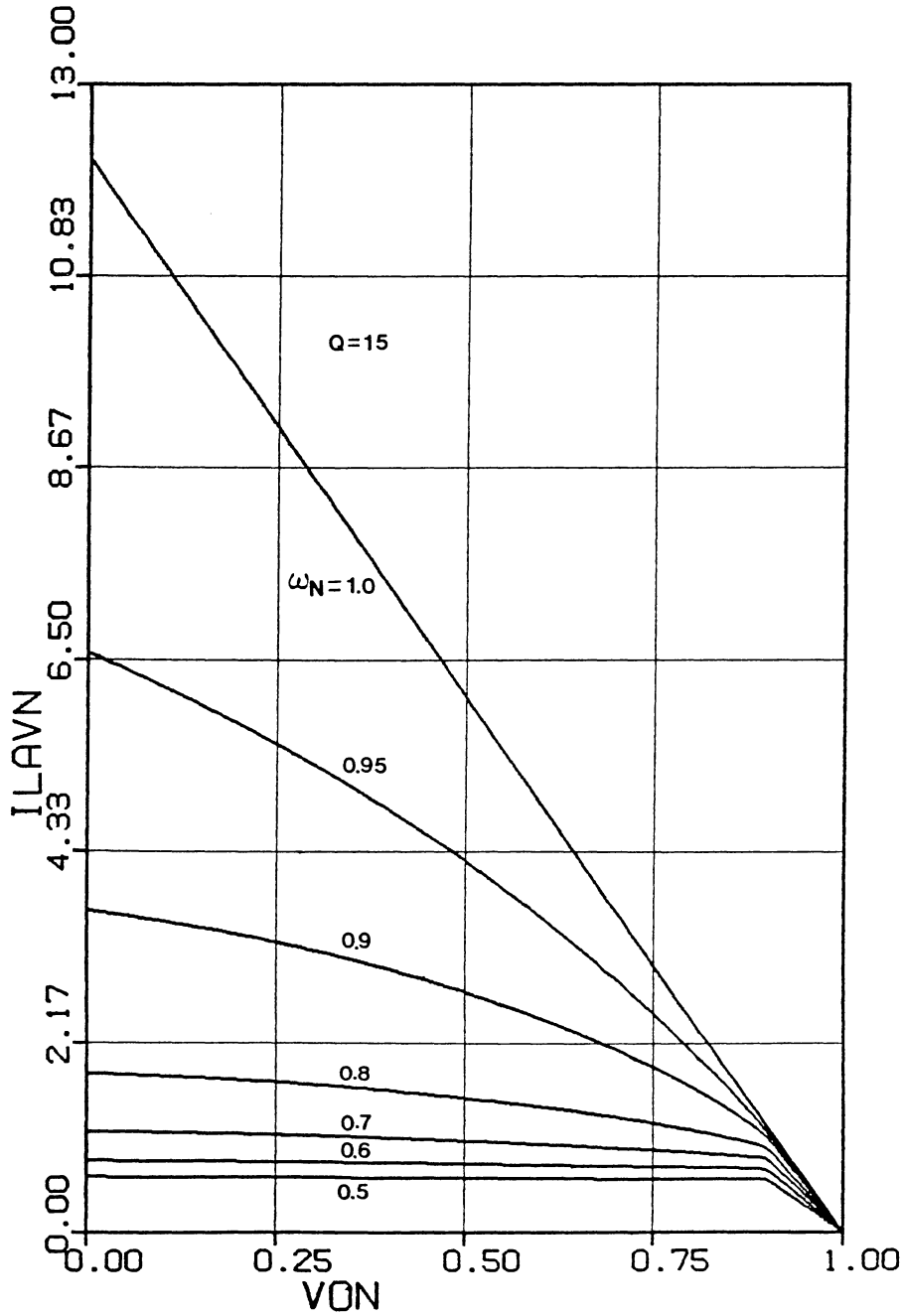


Fig. 3.2 Nonideal SRC dc characteristic curve when $\omega_N \leq 1$

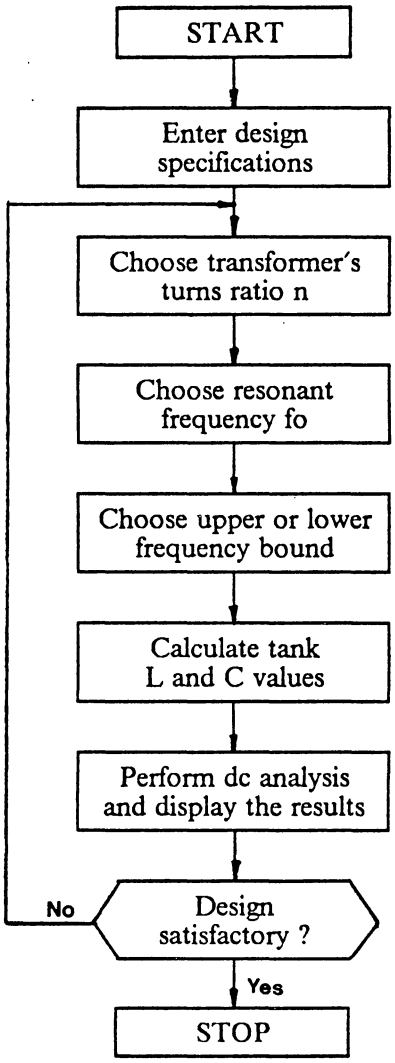
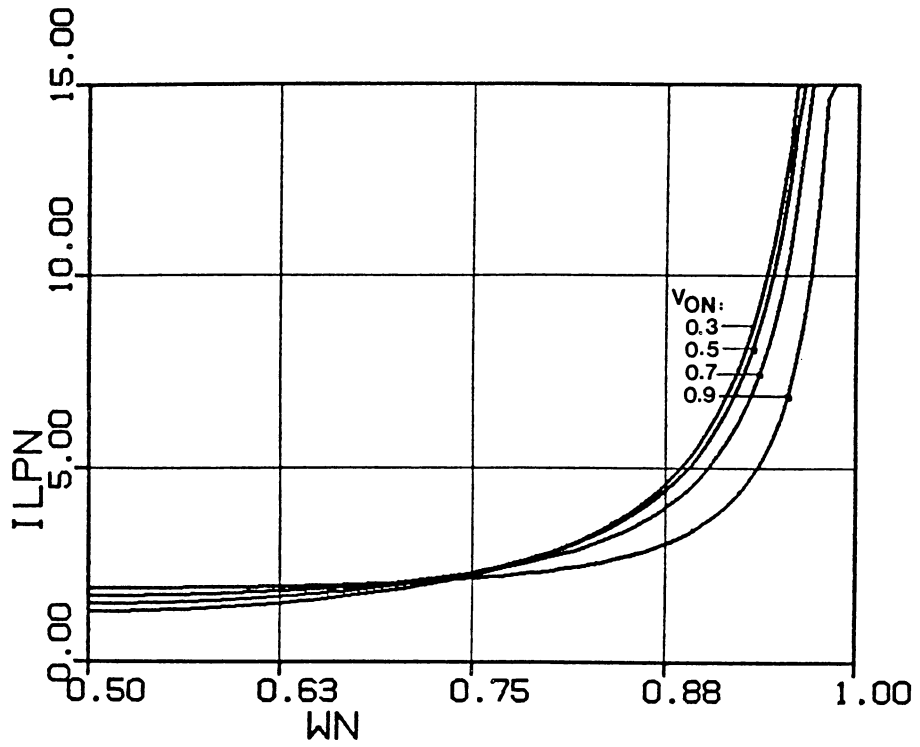


Fig. 3.3 Simplified flow chart of the SRC design program

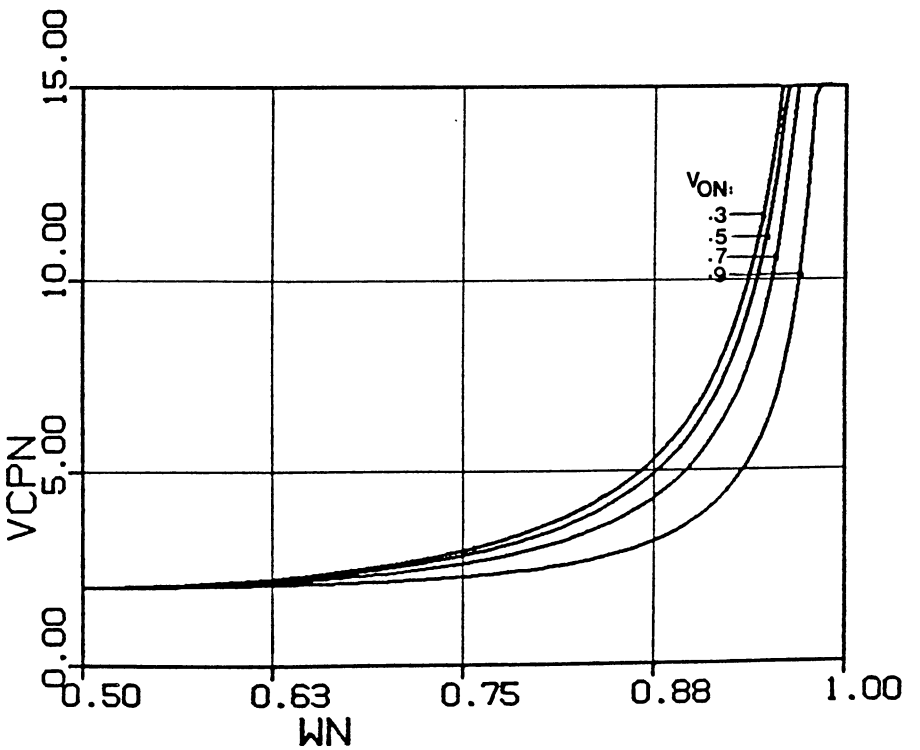
Step 1: Enter design specifications. The user provides input and output requirements on the converter. Design specifications are input voltage range, output current range, and output voltage.

Step 2: Choose transformer's turns ratio. The first user-specified parameter is the transformer's primary-to-secondary turns ratio. The normalized output voltage reflected to the resonant tank side is V_{ON} where $V_{ON} = nV_O/V_S$. For an SRC, the maximum V_{ON} equals unity. Once the value of the turns ratio is known, V_{ON} is known and can be used to locate the centers of the steady-state trajectory.

The maximum turns ratio will be calculated first according to design specifications. At this point the user has a range of turns ratios to choose from. However, the turns ratio will significantly affect the converter's operation. If a large turns ratio is chosen such that the value of the output voltage reflected to the primary side is nearly equal that of the input voltage (V_{ON} nearly equal to 1), then the required output voltage may not be reached under heavy load conditions due to losses in the tank circuit as shown in Fig. 3.2. Furthermore, converter response is slow [9]. On the other hand, if a small turns ratio is chosen such that the value of the primary side voltage is much less than that of the input voltage (V_{ON} nearly equal to zero), then the current in the switch will be unnecessarily high. The peak capacitor voltage will also be high. Figures 3.4 and 3.5 are the normalized design curves of the peak inductor current and peak capacitor voltage for an SRC operating below and above resonant frequency, respectively. It can be seen that the peak inductor current and peak capacitor voltage is higher at a lower V_{ON}. This observation will help the user in choosing the transformer's turns ratio.

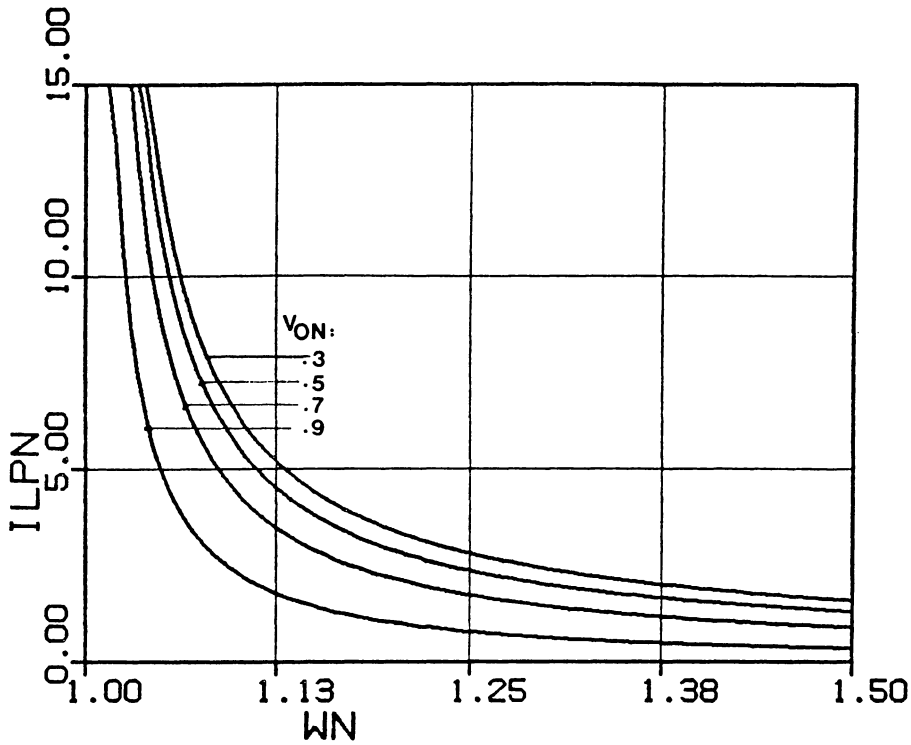


(a)

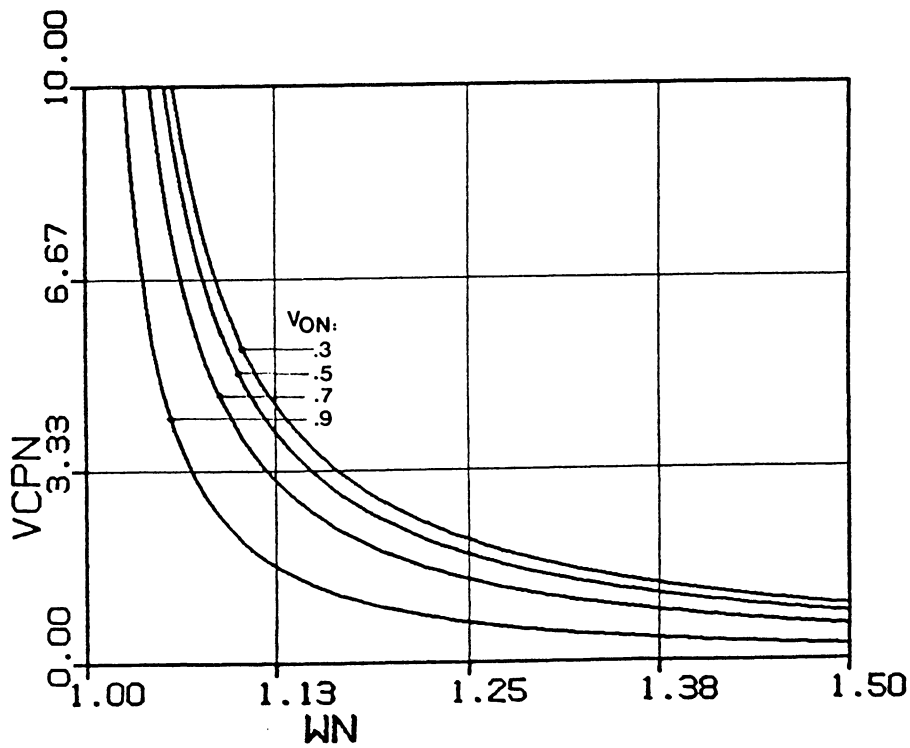


(b)

Fig. 3.4 Normalized design curves of the SRC operating below resonance (V_{ON} = .3, .5, .7, .9)
(a) Peak inductor current
(b) Peak capacitor voltage



(a)



(b)

Fig. 3.5 Normalized design curves of the SRC operating above resonance (V_{ON} = .3, .5, .7, .9)
(a) Peak inductor current
(b) Peak capacitor voltage

The L and C values of the tank are also dependent upon the turns ratio. If the other two user-specified parameters are fixed, then the increasing turns ratio will increase L and decrease C to meet the design specifications. As a result, the characteristic impedance, Z_o, of the resonant tank will increase, where $Z_o = \sqrt{L/C}$.

When losses are considered, the maximum I_{LAVN} can be calculated by the following equation [9].

$$I_{LAVN} = \frac{2(1 - V_{ON})(1 + k)\sqrt{1 - \zeta^2}}{\pi(1 - k)}$$

Thus, the normalized maximum power transfer, P_{ONMAX}, for a given V_{ON} can be calculated.

$$P_{ONMAX} = \frac{2V_{ON}(1 - V_{ON})(1 + k)\sqrt{1 - \zeta^2}}{\pi(1 - k)}$$

Finding the derivative of P_{ONMAX} with respect to V_{ON} gives the absolute maximum power transfer.

$$\frac{dP_{ONMAX}}{dV_{ON}} = \frac{2(1 - 2V_{ON})(1 + k)\sqrt{1 - \zeta^2}}{\pi(1 - k)} = 0$$

Solving the above equation, the absolute maximum power transfer, P_{ONAMAX}, is found.

$$P_{ONAMAX} = \frac{(1 + k)\sqrt{1 - \zeta^2}}{2\pi(1 - k)} \quad \text{when} \quad V_{ON} = 0.5$$

Thus, maximum power transfer occurs when the output voltage reflected to the primary side equals one half of the input voltage (V_{ON} = 0.5). This program calculates and displays this turns ratio for the user's convenience.

Step 3: Choose resonant frequency. The second user-specified parameter is the resonant frequency, f_0 , of the tank. For an SRC operating at higher switching frequencies, the resonant frequency shall increase accordingly. As a result, the values of the tank's inductor and capacitor, and the output filter capacitor will become smaller. Thus, the size of the converter will decrease. However, if the resonant frequency is too high, the effect of the parasitic loss will be more profound on the converter's operation and the power loss will increase. As a rule, the maximum operating frequency should be less than ninety percent of the resonant frequency if natural commutation of the power switches is desired.

Step 4: Choose upper or lower bounds of the switching frequency. The user specifies the maximum or minimum switching frequency within the operating frequency range. The user decides whether to operate the SRC above or below resonant frequency in this step. The desired operating region of an SRC is in CCM, therefore, the switching frequency range should be chosen as such. For an SRC operating below resonant frequency, the maximum switching frequency will occur at the minimum input voltage with maximum load. The minimum switching frequency will occur at the maximum input voltage with minimum load. On the other hand, when an SRC operates above resonant frequency, the maximum switching frequency will occur at the maximum input voltage with minimum load. The minimum switching frequency will occur at the minimum input voltage with maximum load.

Setting the lower or upper bound of the switching frequency range, however, will directly affect converter operation and component stresses and requires trade-offs. When designing an SRC working below resonance, if the minimum switching frequency is increased, the value of the inductor will increase, the value of the capacitor

will decrease, and the peak capacitor voltage will increase. On the other hand, if the maximum switching frequency is decreased, the converter may operate in the discontinuous-conduction mode (DCM). These conclusions can be drawn from the normalized design curves in Figs. 3.4 and 3.5 directly. When designing an SRC working above resonance, if the minimum switching frequency is increased, the value of the inductor will decrease and the value of the capacitor will increase, thus resulting in reduced peak capacitor voltage and a wider operating frequency range. Conversely, if the maximum switching frequency is decreased, the value of the inductor will increase and value of the capacitor will decrease, thus, resulting in a high peak capacitor voltage and a narrow switching frequency.

Since the parasitic losses have a more profound affect on the SRC near resonance, the effect of losses can be reduced by decreasing the switching frequency as shown in Figs. 3.1 and 3.2.

Step 5: Calculate L and C values of the tank. Since the bound of the switching frequency is set and the input voltage and the load current associated with it are known, the normalized average inductor current, I_{LAVN}, is found directly as shown in Sec. 2.1. Since I_{LAVN} is directly related to the output current of an SRC, the characteristic impedance, Z_0, is found next by solving the following equation.

$$I_{LAVN} = \frac{I_O Z_O}{nV_S}$$

Values of tank L and C are then calculated by solving the following two equations simultaneously.

$$Z_O = \sqrt{\frac{L}{C}} \quad \text{and} \quad f_O = \frac{1}{2\pi\sqrt{LC}}$$

The final expressions are shown below.

$$L = \frac{Z_O}{2\pi f_O} \quad \text{and} \quad C = \frac{1}{(2\pi f_O)^2 L}$$

Step 6: Perform dc analysis. Based on the calculated values of the inductor and capacitor, the program performs a dc analysis for the given design. The program calculates various circuit parameters, such as those of the peak inductor current, peak capacitor voltage, operating frequency, and the transistor's switching current, corresponding to the design specifications. The dc characteristic curves are provided to study the behavior of the converter. The graphs give the user a complete view of the SRC operation and, therefore, enhance insight into the design.

Step 7: Reiterate the design. If the results are not satisfactory, for example, the peak capacitor voltage is too high, the user can reiterate the design process starting with step 2 to improve the existing design.

In summary, step 1 provides the basic data for the design. Step 2 through step 4 guide and design by choosing the user-specified parameter values. Step 5 calculates values of the tank inductor and capacitor according to the information and data provided in the previous four steps. Step 6 checks the design and points out the direction of improvement to the user.

3.2 Design Examples Of The SRC

In this section, various design examples will be shown. The design of SRCs with infinite Q and finite Q will be performed. The design of SRCs operating below and above resonance will also be demonstrated.

3.2.1 Design Of An SRC Below Resonance With Infinite Q

In this section, a design example of an ideal SRC below resonant frequency is shown. For this operating condition, switches are turned off at zero current (natural commutation). In this example, the design procedure and the effect of choosing different user-specified parameter values are demonstrated. Intermediate steps and some information are omitted. The design procedure is shown below in a step-by-step manner.

Step 1:

Design specifications are as follows:

Input voltage range = 50-70 volts

Output current range = 3-8 amps

Output voltage = 110 volts

Step 2:

The program calculates the required turns ratio and prompts the following message:

The maximum primary-to-secondary turns ratio = 0.455

The recommended turns ratio = 0.273, at which average V_{ON} equals 0.5. Following the discussion in step 2 and the observations from Fig. 3.4, n is selected such that $V_{ON} > 0.5$. The chosen turns ratio n = **0.3**

Step 3:

Assuming the SRC is to work at a frequency below 100 kHz, the resonant frequency is set at 100 kHz.

Step 4:

Following the discussion in step 4 and the observations from Fig. 3.4, the minimum switching frequency is selected such that the peak inductor current and peak capacitor voltage are not too high. In the first iteration, selected minimum ω_N = **0.7**, which corresponds to f_{MIN} = **70** kHz.

Step 5:

The calculated values of the tank are as follows:

Tank inductor = 12.36694 μH

Tank capacitor = 0.2048226 μF

Step 6:

DC analysis is performed and the results are printed.

Vs(V)	Io(A)	F(kHz)	ILAV(A)	IQAV(A)	ILP(A)	VCP(V)
50.00	3.00	79.87	10.0	4.15	17.48	152.83
50.00	8.00	92.59	26.7	11.1	43.05	351.52
70.00	3.00	70.00	10.0	3.68	17.68	174.37
70.00	8.00	88.24	26.7	9.81	42.71	368.87

Certain circuit parameter ranges are listed below.

	F(kHz)	ISW(A)	VCO(V)	IQR(A)	IDR(A)	ILR(A)	ILP(A)	VCP(V)
Min	**70.00**	8.69	82.20	7.29	2.34	11.25	17.48	152.83
Max	**92.59**	32.98	232.01	19.93	9.26	29.76	43.05	**368.87**

Definitions of the variables are listed in Appendix A. Figure 3.6 shows the curves of the peak inductor current and peak capacitor voltage as a function of the switching frequency.

The SRC in the first design iteration is simulated by the SPICE program. Figures 3.7 and 3.8 are the simulation results at the minimum and maximum switching frequencies, respectively. The peak values are matched with those calculated by the package.

Assuming the peak capacitor voltage is too high in the first design iteration, the design can be improved by changing the user-specified parameters in step 2 to those in step 4. The study of Fig. 3.6(b) shows that if the converter operates at a lower frequency, the peak capacitor voltage will be lower. Following this observation and the discussion in step 4, the minimum switching frequency in the second design iteration is reduced. The other parameters remain the same as in the first design.

Step 2:

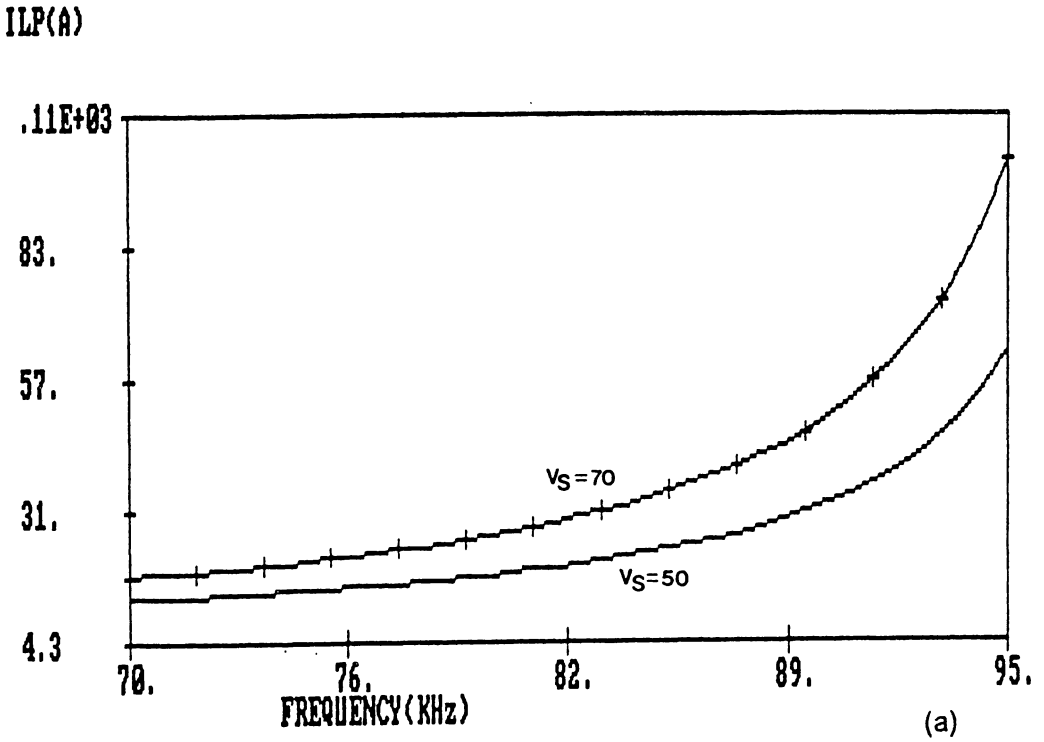
The transformer's turns ratio = 0.3

Step 3:

The tank's resonant frequency = 100 kHz

Step 4:

In the second iteration, selected minimum ω_N = **0.6**, which corresponds to f_{MIN} = **60** kHz.



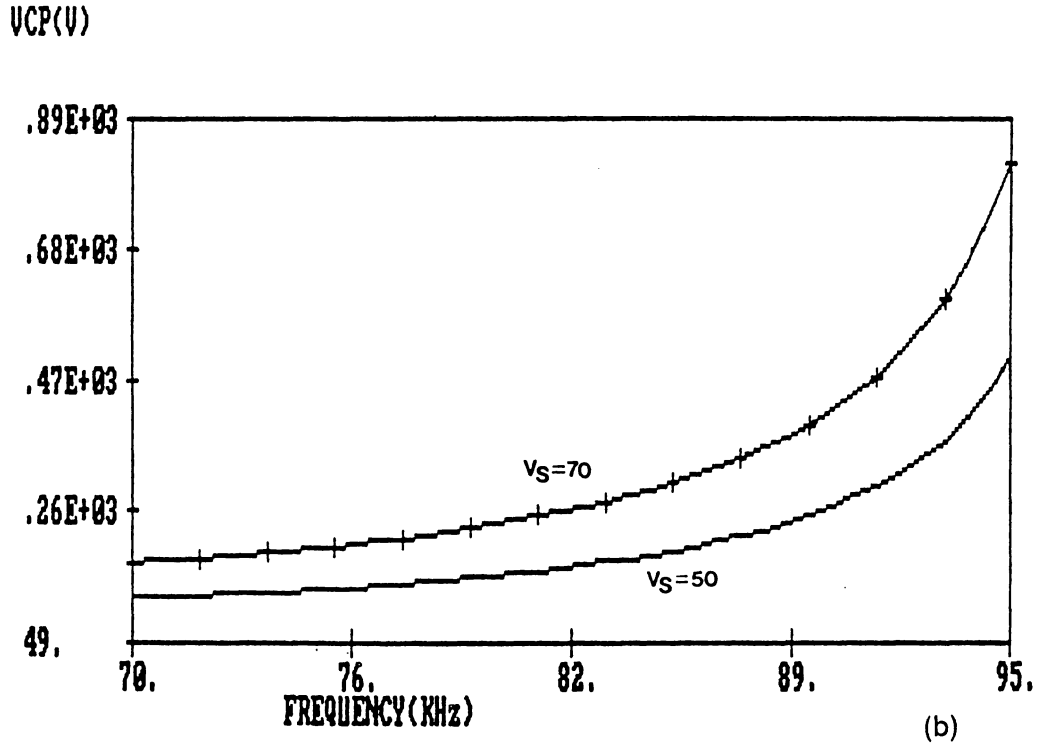


Fig. 3.6 DC characteristic curves in the first design iteration
(a) Peak inductor current
(b) Peak capacitor voltage

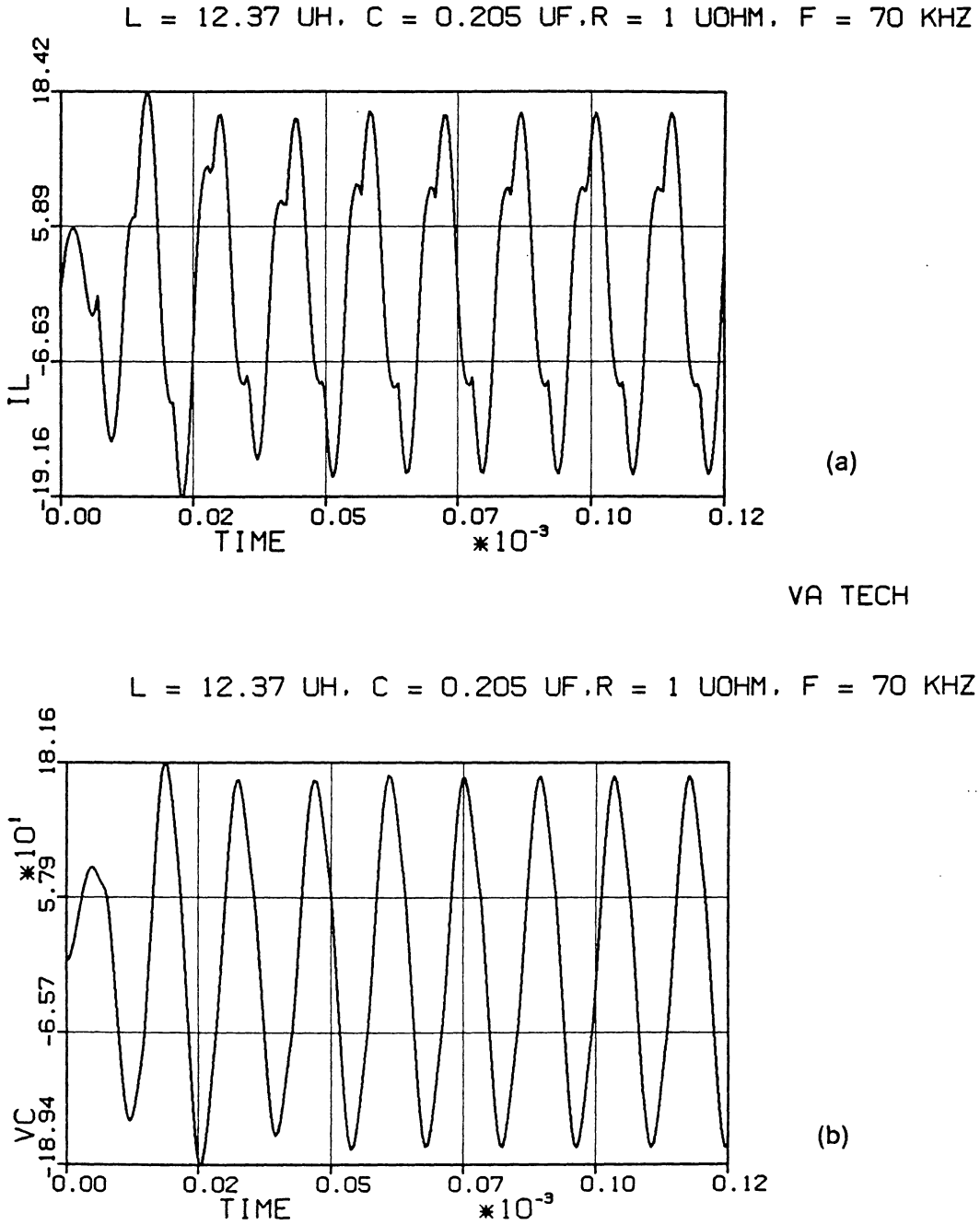
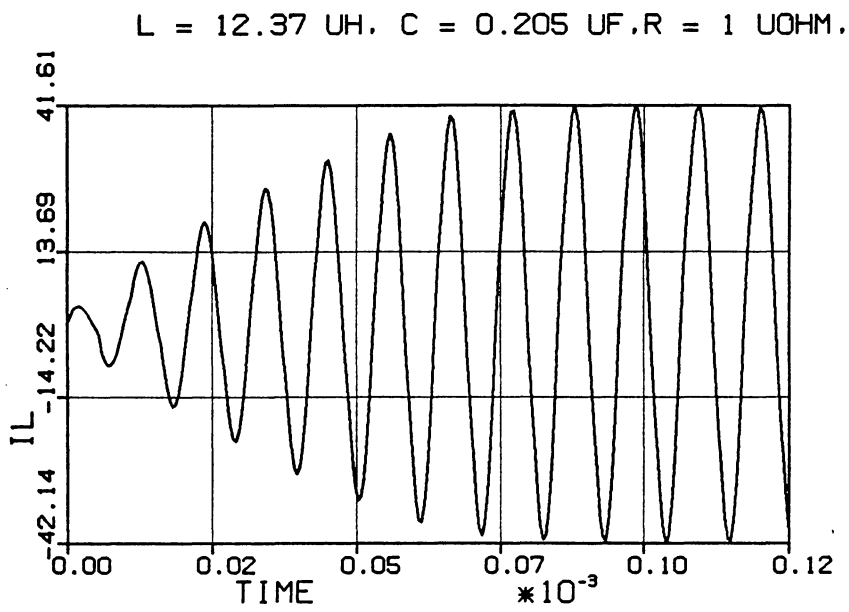
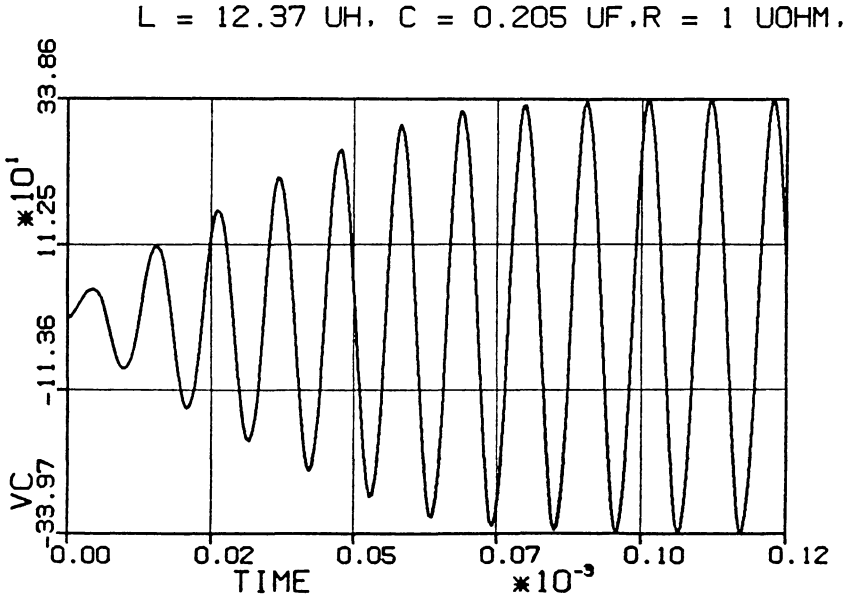


Fig. 3.7 SPICE simulation in the first design iteration ($f = f_{MIN}$)
(a) Inductor current waveform
(b) Capacitor voltage waveform



(a)



(b)

Fig. 3.8 SPICE simulation in the first design iteration ($f = f_{MAX}$)
(a) Inductor current waveform
(b) Capacitor voltage waveform

Step 5:

The calculated values of the tank are as follows:

Tank inductor = 9.030848 μH

Tank capacitor = 0.2804863 μF

Step 6:

DC analysis is performed and the results are printed below.

Vs(V)	Io(A)	F(kHz)	ILAV(A)	IQAV(A)	ILP(A)	VCP(V)
50.00	3.00	72.11	10.0	4.15	18.79	123.61
50.00	8.00	89.82	26.7	11.1	43.64	264.63
70.00	3.00	60.00	10.0	3.68	19.66	148.55
70.00	8.00	84.05	26.7	9.81	43.32	282.78

Certain circuit parameter ranges are listed below.

	F(kHz)	ISW(A)	VCO(V)	IQR(A)	IDR(A)	ILR(A)	ILP(A)	VCP(V)
Min	**60.00**	5.54	70.03	7.59	2.20	11.54	18.79	123.61
Max	**89.82**	31.23	174.65	20.03	9.11	29.85	43.64	**282.78**

The major analysis results in the two design iterations are listed below for comparison.

Iteration	f_{MIN} (kHz)	f_{MAX} (kHz)	I_{LRMAX} (A)	I_{LPMAX} (A)	V_{CPMAX} (V)
1	70.00	92.59	29.76	43.05	368.87
2	60.00	89.92	29.85	43.64	282.78

In the above table, I_{LRMAX}, I_{LPMAX}, and V_{CPMAX} refer to the absolute maximum values which can occur for all possible input and output variations. Figure 3.9 shows the curves of the peak inductor current and peak capacitor voltage as a function of the switching frequency for the second design iteration. As seen from the results, the peak capacitor voltage is reduced from **368.87** volts to **282.78** volts by reducing the lower bound of the switching frequency as discussed in step 4. However, the range of the switching frequency, Δfs , is increased from **22.59** kHz to **29.82** kHz in the second iteration. This is the trade-off the designer must make to reduce the stress on the resonant capacitor.

3.2.2 Design Of An SRC Above Resonance With Infinite Q

In this section, a design example of an SRC above resonant frequency is shown. For this operating condition, switches are turned off at nonzero current (forced commutation) and turned on at zero current and zero voltage. In this example, the design procedure and the trade-offs are demonstrated. The design specifications are the same as those in the previous example. Thus, design step 1 one is omitted. The design procedure is shown below in a step-by-step manner.

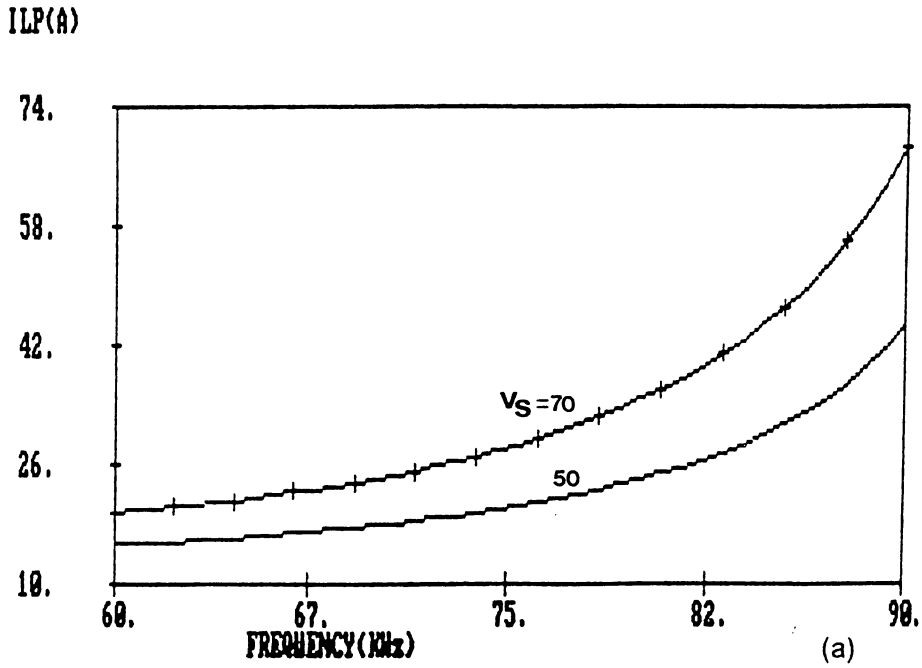
Step 2:

The program calculates the required turns ratio and prompts the following message:

The maximum primary-to-secondary turns ratio = 0.455

The recommended turns ratio = 0.273, at which average V_{ON} equals 0.5. Following the discussion in step 2 and the observations from Fig. 3.5, n is selected such that $V_{ON} > 0.5$. The chosen turns ratio n = **0.3**

Step 3:



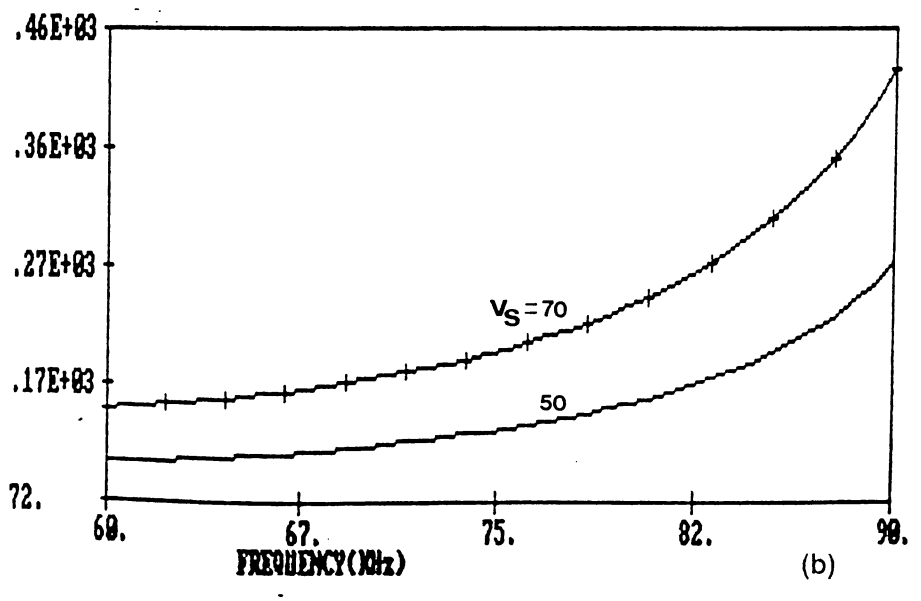


Fig. 3.9 DC characteristic curves in the second design iteration
(a) Peak inductor current
(b) Peak capacitor voltage

Assuming the SRC is to work in the frequency range between 100 and 150 kHz, the resonant frequency is set at 100 kHz.

Step 4:

Following the discussion in step 4 and the observations from Fig. 3.5, the minimum switching frequency is selected such that the peak inductor current and peak capacitor voltage are not too high. In the first iteration, selected minimum ω_N = **1.05**, which corresponds to f_{MIN} = **105** kHz.

Step 5:

The calculated values of the tank are as follows:

Tank inductor = 18.10179 μH

Tank capacitor = 0.1399325 μF

Step 6:

DC analysis is performed and the results are printed.

Vs(V)	Io(A)	F(kHz)	ILAV(A)	IQAV(A)	ILP(A)	VCP(V)
50.00	3.00	113.29	10.00	4.15	15.36	157.71
50.00	8.00	105.00	26.67	11.07	41.39	453.73
70.00	3.00	123.09	10.00	3.68	16.02	145.15
70.00	8.00	108.40	26.67	9.81	41.90	439.50

Certain circuit parameter ranges are listed below.

	F(kHz)	ISW(A)	VCO(V)	IQR(A)	IDR(A)	ILR(A)	ILP(A)	VCP(V)
Min	**105.0**	13.32	68.43	6.93	2.78	11.09	15.36	145.15
Max	**123.1**	39.13	299.46	19.64	9.84	29.68	41.90	**453.73**

Figure 3.10 shows the curves of the peak inductor current and peak capacitor voltage as a function of the switching frequency. Assuming the peak capacitor voltage is too high in the first design iteration, the design can be improved by changing the user-specified parameters in step 2 to those in step 4. The study of Fig. 3.10(b) finds that if the converter operates at a higher frequency, the peak capacitor voltage will be lower. Following this observation and the discussion in step 4, the maximum switching frequency in the second design iteration is increased. The other parameters remain the same as in the first design. Design step 1 is omitted.

Step 2:

The transformer's turns ratio = 0.3

Step 3:

The tank's resonant frequency = 100 kHz

Step 4:

In the second iteration, selected maximum $\omega_N = 1.5$, which corresponds to $f_{MAX} = 150$ kHz.

Step 5:

The calculated values of the tank are as follows:

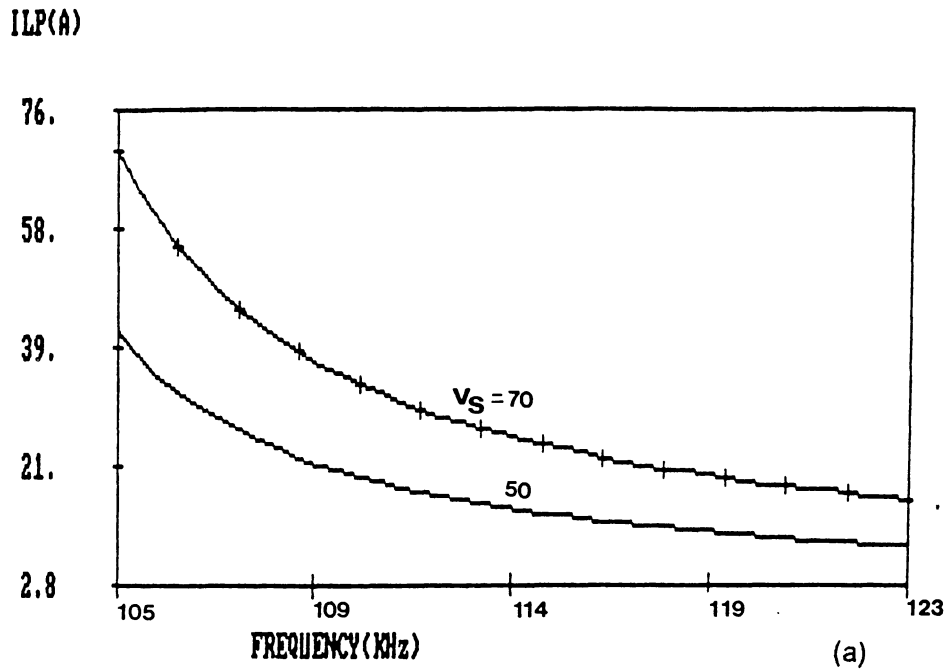
Tank inductor = 8.784644 μH

Tank capacitor = 0.2883474 μF

Step 6:

DC analysis is performed and the results are printed below.

Vs(V)	Io(A)	F(kHz)	ILAV(A)	IQAV(A)	ILP(A)	VCP(V)
50.00	3.00	127.40	10.00	4.15	15.41	68.06
50.00	8.00	110.28	26.67	11.07	41.07	209.66
70.00	3.00	150.00	10.00	3.68	17.08	57.80
70.00	8.00	117.65	26.67	9.81	42.31	196.53



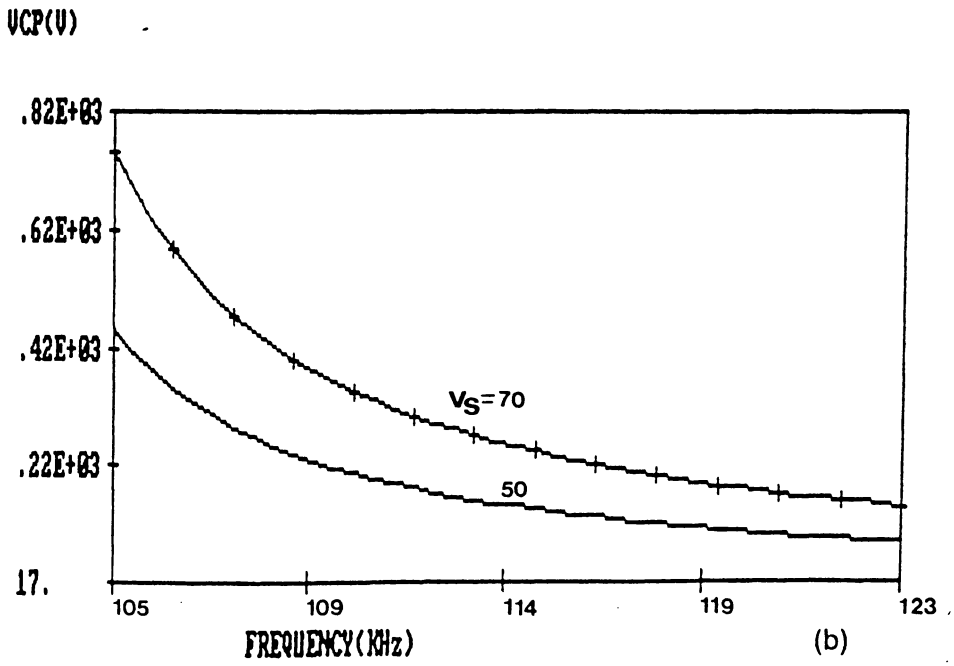


Fig. 3.10 DC characteristic curves in the first design iteration
(a) Peak inductor current
(b) Peak capacitor voltage

Certain circuit parameter ranges are listed below.

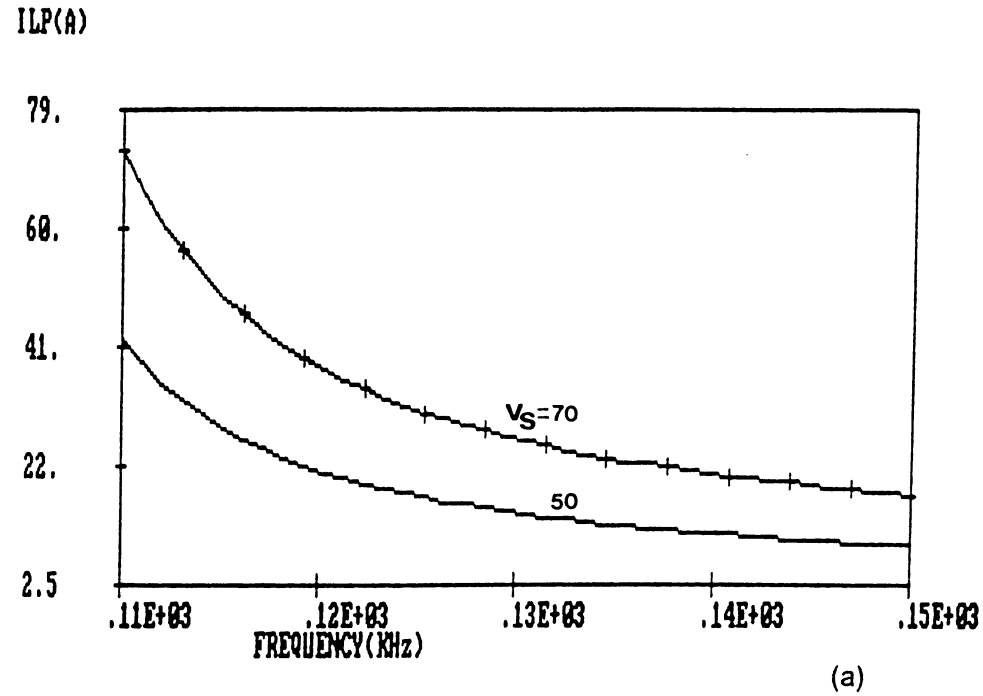
	F(kHz)	ISW(A)	VCO(V)	IQR(A)	IDR(A)	ILR(A)	ILP(A)	VCP(V)
Min	**110.28**	14.56	27.25	6.93	2.90	11.11	15.41	57.80
Max	**150.0**	41.09	138.38	19.57	10.0	29.76	42.31	**209.66**

The major analysis results in the two design iterations are listed below for comparison.

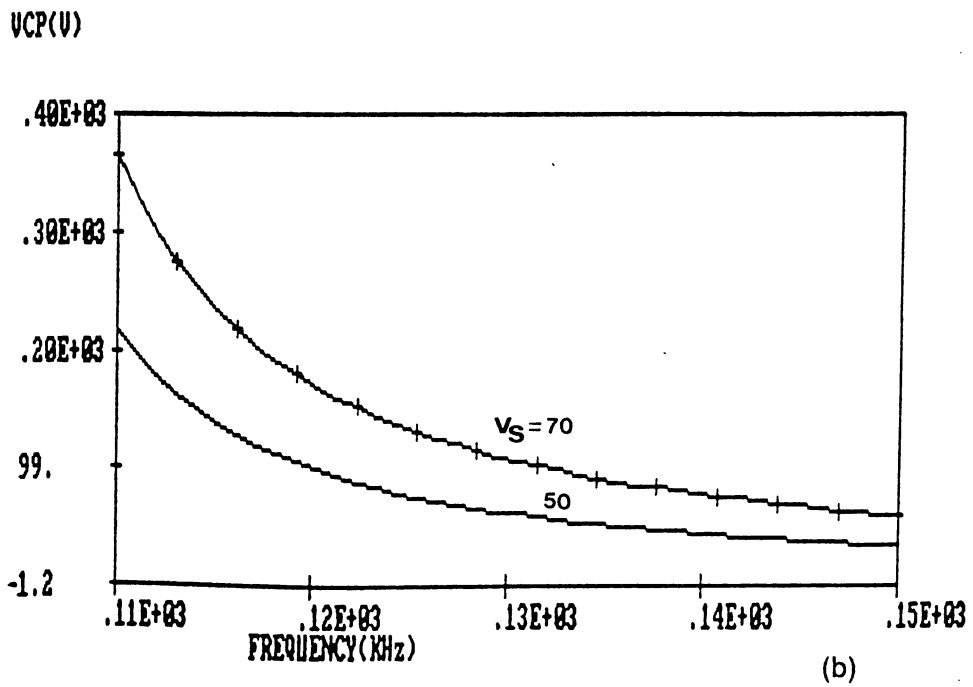
Iteration	f_{MIN} (*kHz*)	f_{MAX} (*kHz*)	I_{LRMAX} (*A*)	I_{LPMAX} (*A*)	V_{CPMAX} (*V*)
1	105.00	123.09	29.68	41.90	453.73
2	110.28	150.00	29.76	42.31	209.66

Figure 3.11 shows the curves of the peak inductor and peak capacitor voltage as a function of the switching frequency for the second design iteration. As seen from the results, the peak capacitor voltage is reduced from **453.73** volts to **209.66** volts by increasing the upper bound of the switching frequency as discussed in step 4. However, the range of the switching frequency, Δfs , is increased from **18.09** kHz to **39.72** kHz in the second iteration. Once again, it is seen that the design of an SRC is an iterative process and involves trade-offs.

The SRC in the second design iteration is simulated by the SPICE program. Figures 3.12 and 3.13 are the simulation results at the minimum and maximum switching fre-

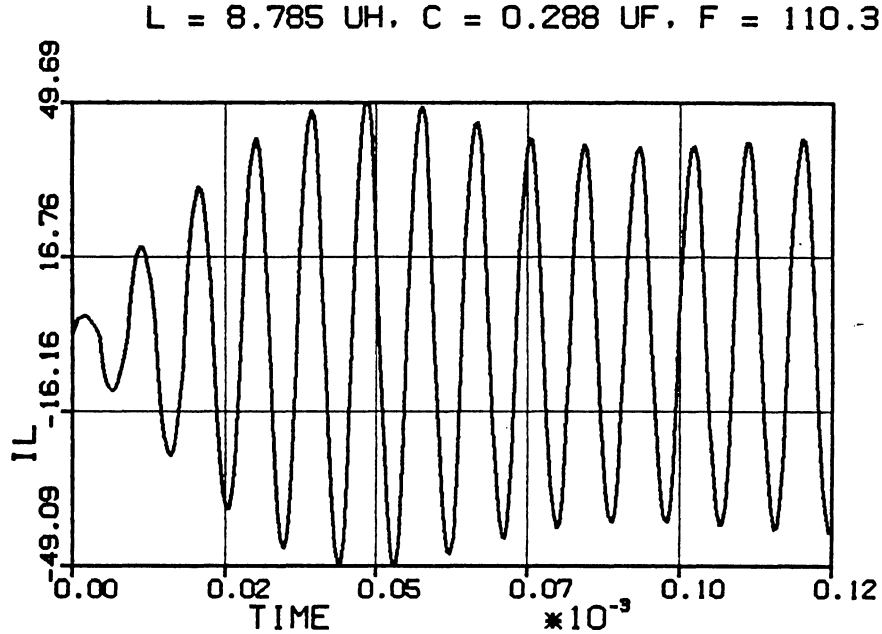


(a)



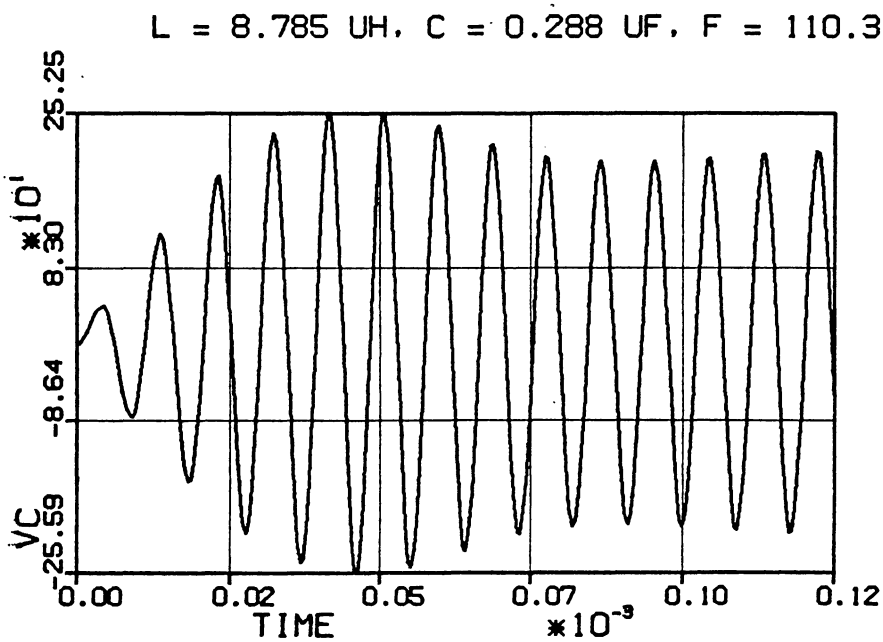
(b)

Fig. 3.11 DC characteristic curves in the second design iteration
(a) Peak inductor current
(b) Peak capacitor voltage



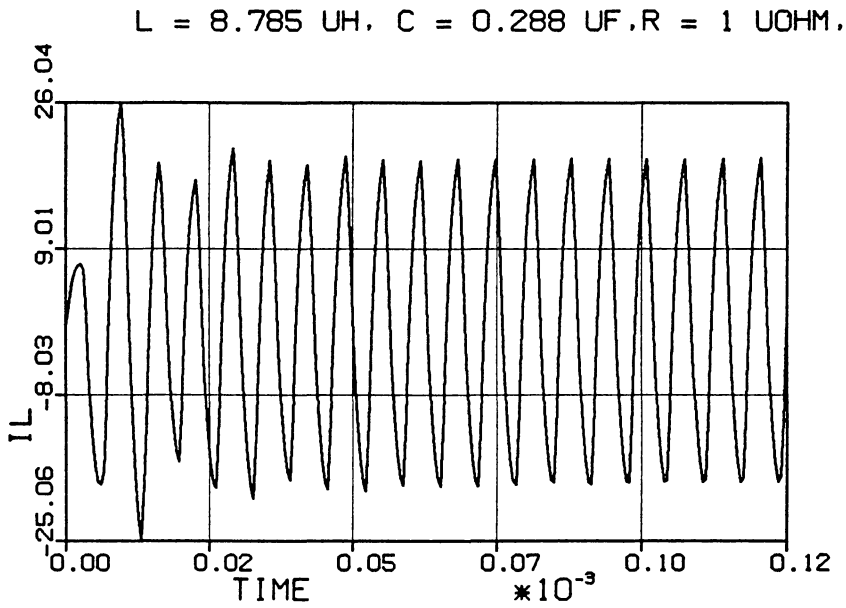
(a)

VA TECH



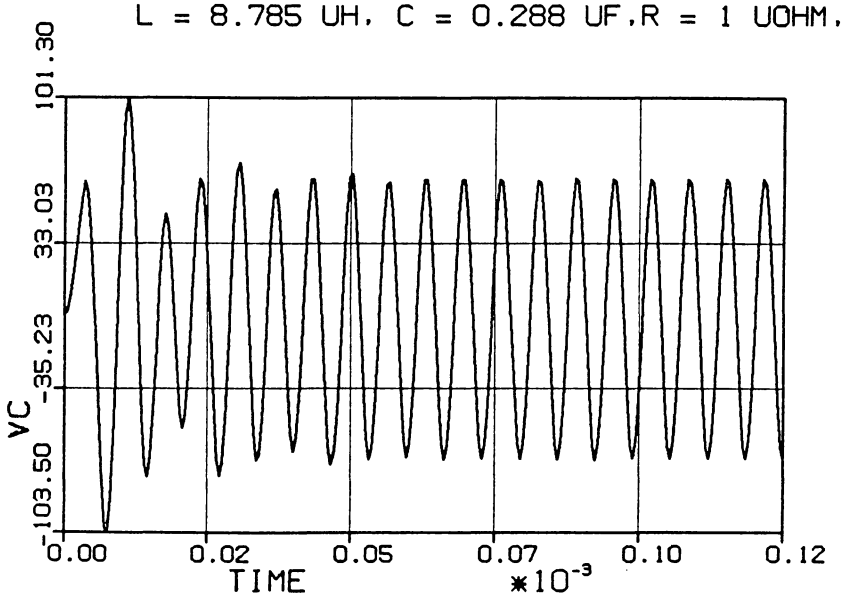
(b)

Fig. 3.12 SPICE simulation in the second design iteration ($f = f_{MIN}$)
(a) Inductor current waveform
(b) Capacitor voltage waveform



(a)

VA TECH



(b)

Fig. 3.13 SPICE simulation in the second design iteration ($f = f_{MAX}$)
(a) Inductor current waveform
(b) Capacitor voltage waveform

quencies, respectively. The peak values are matched with those calculated by the package.

3.2.3 Validity Of The Design With Infinite Q

In practice, parasitic losses in the tank circuit always exist and Q is finite. Therefore, the validity of an SRC designed for the lossless case should be checked. The program provides this function as an option after the design is finished. Assuming an ideal SRC (Fig. 1.1) has already been designed, the behavior of the designed converter when parasitic losses considered is now investigated (Fig. 2.2). For the fixed output voltage, V_o , when Q decreases, the converter's maximum output current will decrease. The minimum quality factor, Q_{MIN}, is defined when the maximum output current of the converter equals the required maximum load current. In other words, if Q is less than Q_{MIN} , the converter cannot provide the required load current. For each SRC, Q_{MIN} exists and is determined by the program. To demonstrate, the design example in Sec. 3.2.1 is used. In the example, the user-specified parameters were given as follows:

Step 2: The transformer's turns ratio = 0.3

Step 3: The tank's resonant frequency = 100 kHz

Step 4: The minimum switching frequency = 70 kHz

Step 5: The calculated values of the tank are as follows:

Tank inductor = 12.36694 μH

Tank capacitor = 0.2048226 μF

Q_{MIN} = **15.03202**

Now this converter is analyzed with losses considered.

Case 1: Q = **40,**

DC analysis is performed and the results are listed below.

Vs(V)	Io(A)	F(kHz)	ISW(A)	VCO(V)	ILAV(A)	IQAV(A)	VCP(V)
50.00	3.00	80.87	8.06	107.3	10.0	4.28	150.91
50.00	8.00	93.88	23.25	273.88	26.66	11.9	346.67
70.00	3.00	70.50	8.58	87.75	10.0	3.77	173.12
70.00	8.00	88.93	30.76	206.15	26.67	10.4	365.99

Case 2: Q = **14,**

DC analysis is performed and the results are listed below.

Vs(V)	Io(A)	F(kHz)	ISW(A)	VCO(V)	ILAV(A)	IQAV(A)	VCP(V)
50.00	3.00	83.31	6.60	118.21	9.99	4.52	146.41
50.00	**7.446**	99.94	0.00	303.16	24.82	12.4	303.16
70.00	3.00	71.60	8.11	97.92	9.99	3.93	170.36
70.00	8.00	90.81	24.85	264.24	26.65	11.6	358.22

As shown in the first case where Q equals 40, if Q is greater than Q_{MIN}, the design of an ideal SRC is still valid. This means that if a practical SRC can have a Q factor greater than Q_{MIN}, then the values of L and C and the transformer's turns ratio found in the design of an ideal SRC can be used to build a practical SRC. If the analysis results are compared with the lossless case in Sec. 3.2.1, it can be seen that for the

same load current, the switching frequency is increased slightly in the case with losses. This is so because the increasing switching frequency will compensate the parasitic losses in the converter to some extent.

In the second case where Q equals 14, it is seen that when the input voltage equals 50 volts, the maximum output current is **7.446** amperes which is less than the required maximum output current. Therefore, when Q is less than Q_{MIN}, design specifications will not be met. Since the parasitic losses are difficult to account for, quantitatively, before a converter is built, it is quite useful to know Q_{MIN} for a given design.

The next question which is of interest is how to minimize the effect of parasitic loss in a design. Because the effect of parasitic losses is more profound at higher switching frequencies and higher V_{ON} as shown in Figs. 3.1 and 3.2, one can minimize the effect of parasitic losses by reducing the SRC's operating frequency and reducing the transformer's turns ratio. This can be verified by using the design example in Sec. 3.2.1 again. In the second design iteration, the user-specified parameter values were as follows.

Step 2: The transformer's turns ratio = 0.3.

Step 3: The tank resonant frequency = 100 kHz.

Step 4: The minimum switching frequency = 60 kHz.

Step 5: The calculated tank element values are as follows.

Tank inductor = 9.030848 μH

Tank capacitor = 0.2804863 μF

Q_{MIN} = **10.97357**

When Q = **14**, the converter operating condition is as follows.

Vs(V)	Io(A)	F(kHz)	ISW(A)	VCO(V)	ILAV(A)	IQAV(A)	VCP(V)
50.00	3.00	74.99	5.86	91.84	9.99	4.43	118.78
50.00	8.00	94.86	12.57	234.06	26.65	12.89	250.41
70.00	3.00	61.34	5.51	80.06	9.99	3.88	145.21
70.00	8.00	86.26	26.03	183.52	26.65	11.10	275.38

The comparison between the two design iterations is listed below.

Iteration	n	L (μH)	C (μF)	Q_{MIN}
1	0.3	12.36694	0.2048226	15.03202
2	0.3	9.030848	0.2804863	10.97357

As we see from the example, the design specification is met when Q equals 14 by reducing the minimum switching frequency to 60 kHz. Thus, the user can design an SRC to meet given design specifications while minimizing the effect of parasitic losses by properly choosing the user-specified parameter values following the design guidelines.

Figure 3.14 shows a detailed flow chart of the design program of an SRC with infinite Q. This flow chart shows the major features of the design program. The design guidelines appear in the design process as comments.

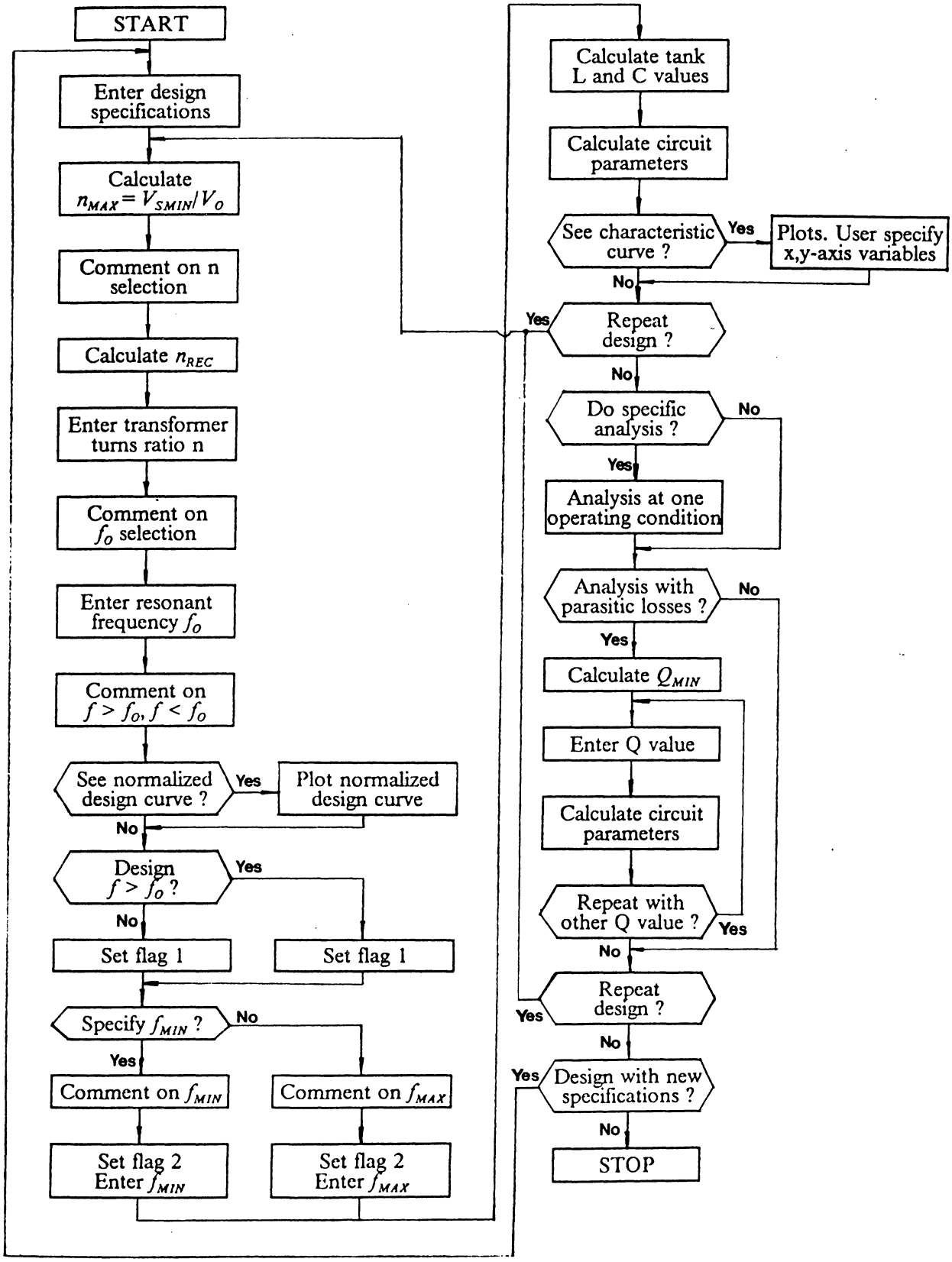


Fig. 3.14 Flow chart of the ideal SRC design program

3.2.4 Design Of An SRC With Finite Q

The design example in Sec.3.2.1. is used again, except that Q is finite. The design procedure is the same as that of an ideal SRC. The same user-specified parameter values are used and the design process is shown.

Step 1:

Design specifications are as follows:

Input voltage range = 50-70 volts

Output current range = 3-8 amps

Output voltage = 110 volts

Resonant tank quality factor = **40**

Step 2:

The program calculates the required turns ratio and prompts the following message:

The maximum primary-to-secondary turns ratio = 0.455.

The recommended turns ratio = 0.273, at which average V_{ON} equals 0.5.

The value of k = 0.96149 when Q = 40.

Following the discussion in step 2, n is selected such that the maximum $V_{ON} < k$.

The chosen turns ratio n = **0.3**, at which the maximum $V_{ON} = nV_O/V_{SMIN} = 0.66$.

Step 3:

Assuming the SRC is to work at a frequency below 100 kHz, the tank's resonant frequency is set at 100 kHz.

Step 4:

In reference to Figs. 3.1 and 3.2, the minimum switching frequency f_{MIN} = 70 kHz is selected such that the loss effect is not pronounced when compared with an ideal SRC.

Step 5:

The calculated values of the tank are as follows:

Tank inductor = 12.15086 μH

Tank capacitor = 0.208465 μF

Step 6:

DC analysis is performed and the results are printed below.

Vs(V)	Io(A)	F(kHz)	ISW(A)	VCO(V)	ILAV(A)	IQAV(A)	VCP(V)
50.00	3.00	80.50	8.01	105.8	10.0	4.28	148.97
50.00	8.00	93.74	23.31	268.74	26.67	11.9	341.13
70.00	3.00	70.00	8.46	86.74	10.0	3.77	171.31
70.00	8.00	88.72	30.73	202.44	26.66	10.4	**360.4**

Figure 3.15 shows the peak capacitor voltage as a function of the switching frequency. If the peak capacitor voltage is too high, the designer can iterate the design by changing the user-specified parameters in step 2 through step 4. A study of Fig. 3.15 shows that if the converter operates at a lower frequency, the peak capacitor voltage will be lower. A lower minimum switching frequency is selected in the second design iteration. The other parameters remain the same as in the first design.

Step 2:

The transformer's turns ratio = 0.3

Step 3:

The tank's resonant frequency = 100 kHz

Step 4:

The minimum switching frequency = **60** kHz

Step 5:

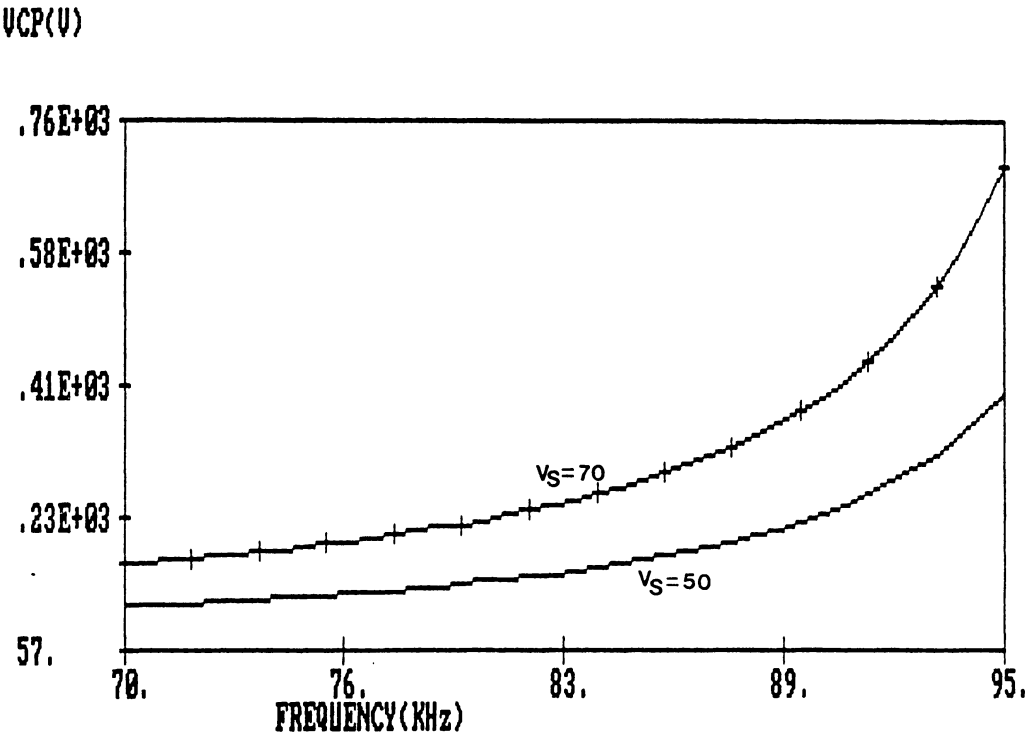


Fig. 3.15 Curve of the capacitor's peak voltage in the first design iteration

The calculated values of the tank are as follows:

Tank inductor = 8.924744 μH

Tank capacitor = 0.283821 μF

Step 6:

DC analysis is performed and the results are printed out below.

Vs(V)	Io(A)	F(kHz)	ISW(A)	VCO(V)	ILAV(A)	IQAV(A)	VCP(V)
50.00	3.00	72.64	6.69	84.70	10.0	4.25	121.26
50.00	8.00	90.89	23.89	194.97	26.67	11.7	258.43
70.00	3.00	60.00	5.34	73.18	10.0	3.75	146.80
70.00	8.00	84.50	29.65	149.50	26.66	10.3	**277.95**

The major analysis results in the two design iterations are listed below for comparison.

Iteration	f_{MIN} (kHz)	f_{MAX} (kHz)	V_{CPMAX} (V)
1	70.00	93.74	360.4
2	60.00	90.89	277.95

Figure 3.16 illustrates the peak capacitor voltage as a function of the switching frequency for the second design iteration.

The SRC in the second design iteration is verified by the SPICE simulation. Figures 3.17 and 3.18 are the simulation results at the minimum and maximum switching frequencies, respectively. The peak values are matched with those calculated by the package.

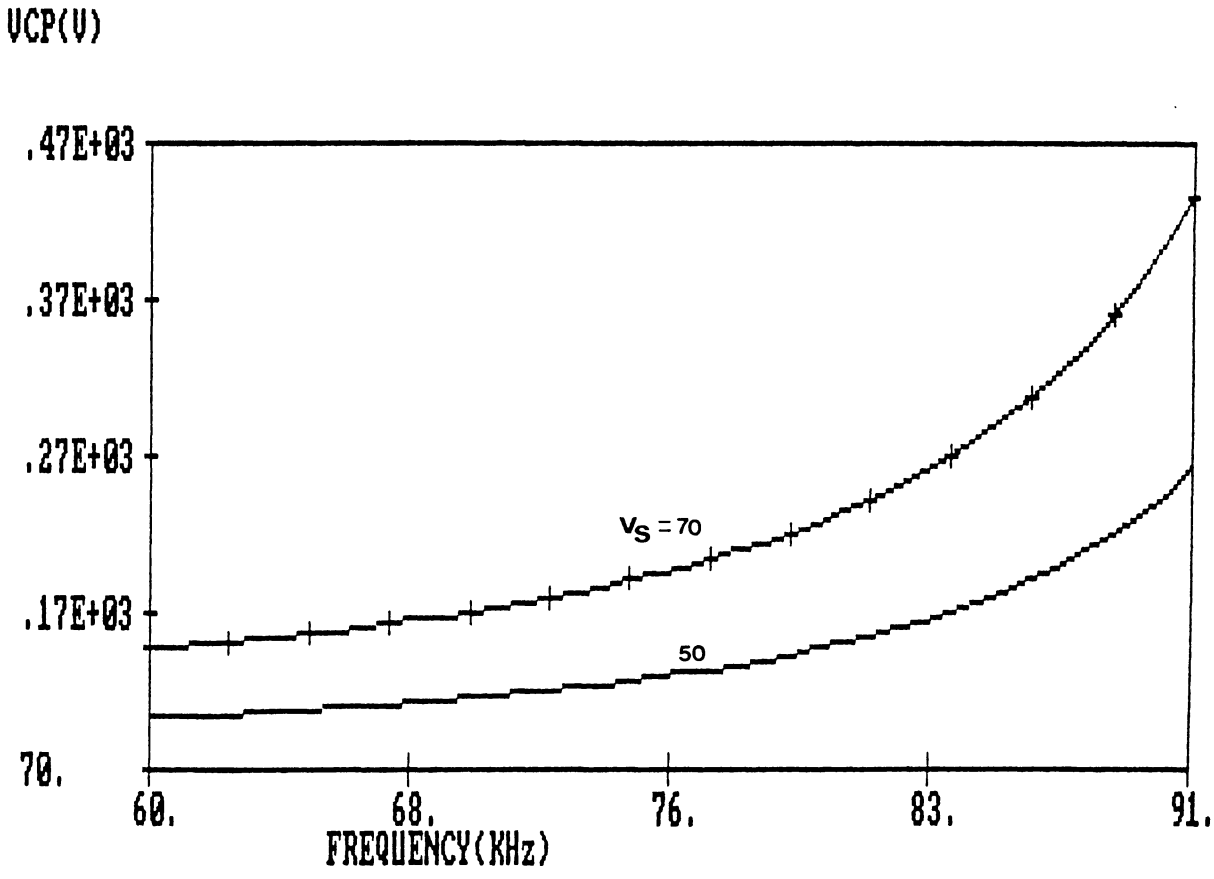


Fig. 3.16 Curve of the capacitor's peak voltage in the second design iteration

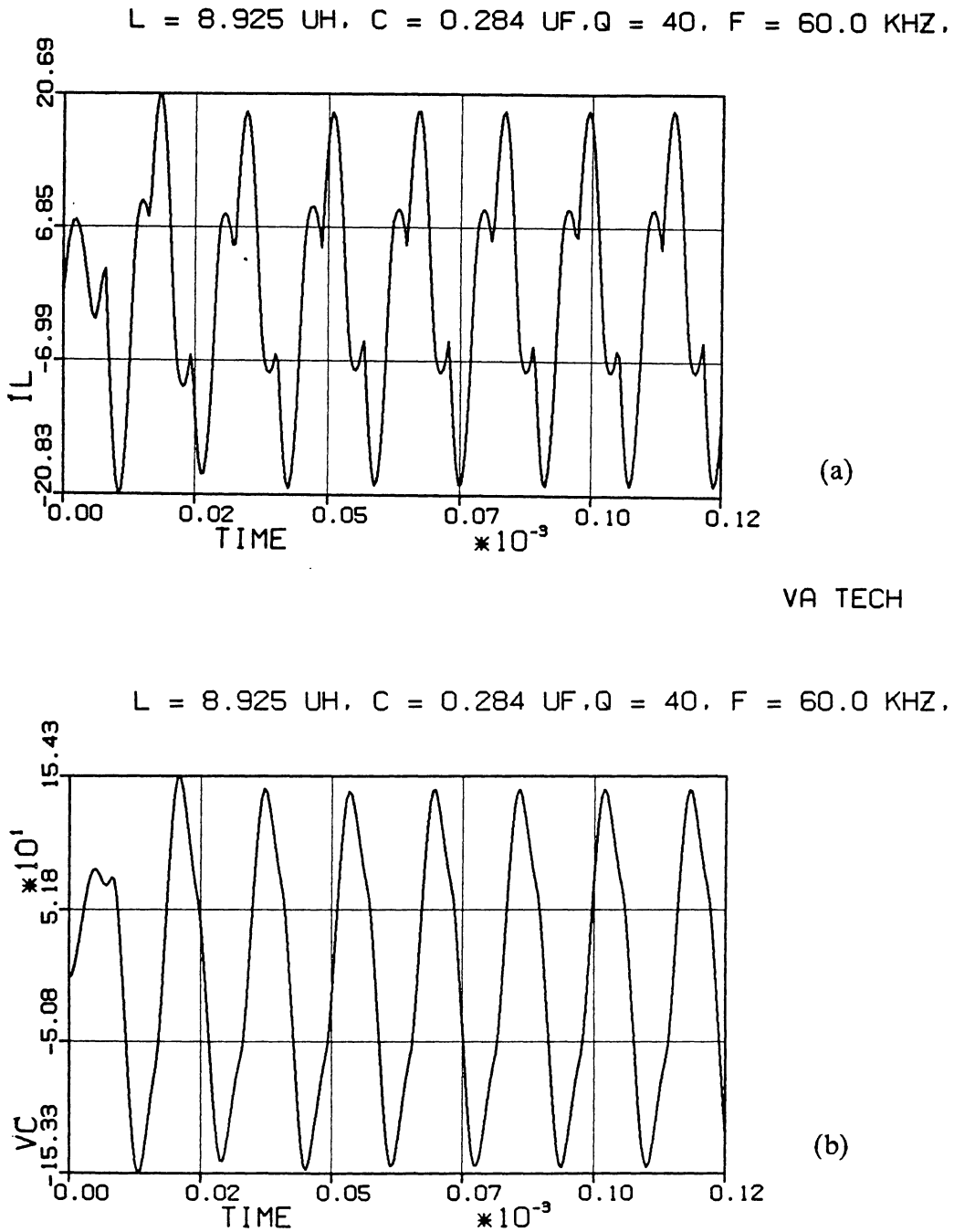


Fig. 3.17 SPICE simulation results in the second design iteration ($f = f_{MIN}$)
(a) Inductor current waveform
(b) Capacitor voltage waveform

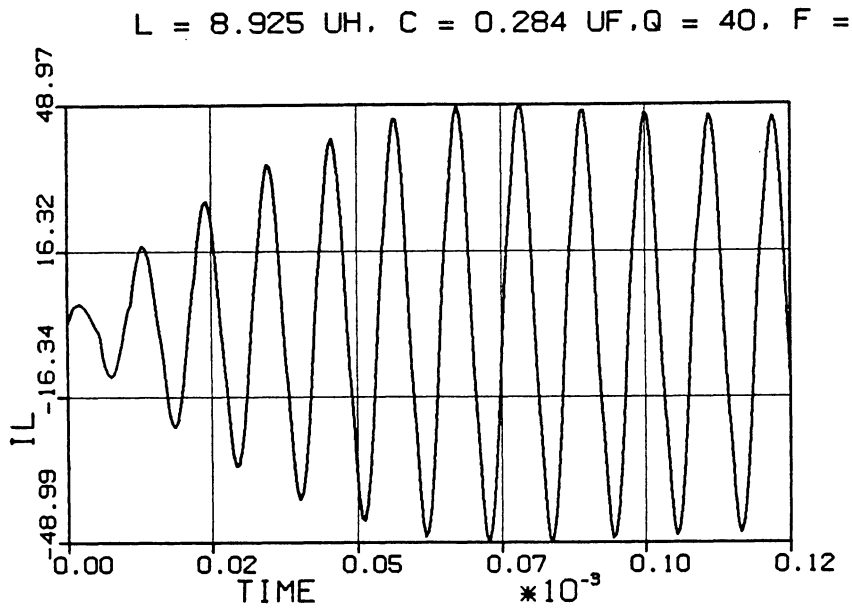


Fig. 3.18 SPICE simulation in the second design iteration ($f = f_{MAX}$)
(a) Inductor current waveform
(b) Capacitor voltage waveform

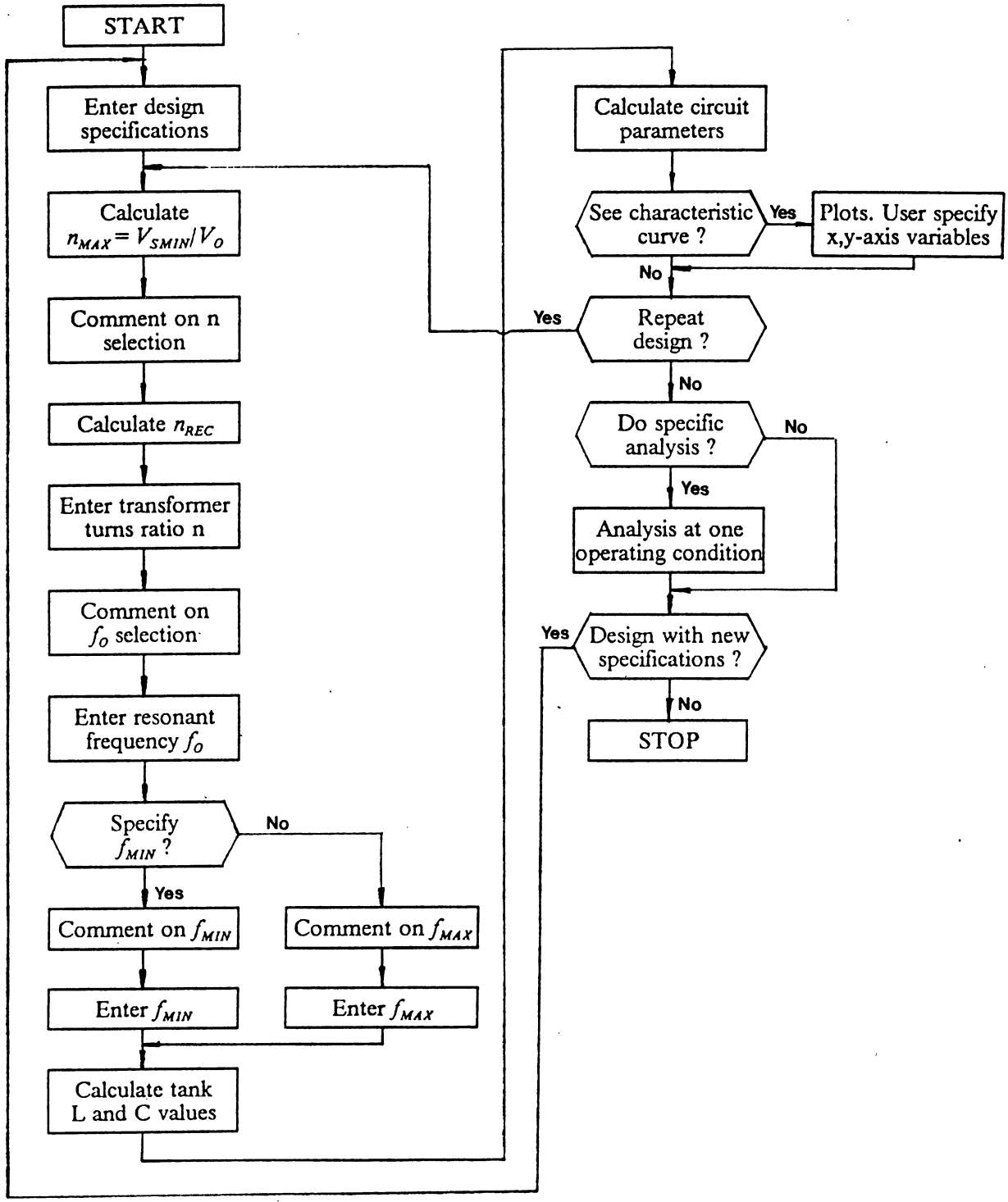


Fig. 3.19 Flow chart of the nonideal SRC design program

Figure 3.19 shows a detailed flow chart of the design program of an SRC with finite Q. The structure of the program is similar to that of an ideal SRC design program.

The design examples with finite and infinite Q are compared below.

Q	L (μH)	C (μF)	f_{MIN} (*kHz*)	f_{MAX} (*kHz*)	V_{CPMAX} (*V*)
∞	12.36694	0.2048226	70.0	92.59	368.87
∞	9.030848	0.2804863	60.0	89.82	282.78
40	12.15086	0.208465	70.0	93.74	360.4
40	8.924744	0.283821	60.0	90.89	277.95

As can be seen from the above table and the simulated tank waveforms, the designs of an SRC with a high Q are close. Therefore, the design of an ideal SRC can be used to simplify the design process when Q is large.

4. SUMMARY

A computer software package was developed to facilitate the design and analysis of an SRC. The package consists of an analysis program and a design program. The package can design and analyze an SRC operating above or below resonant frequency and can incorporate the effect of parasitic losses in the tank circuit. This work describes, in detail, the development of this software program and provides useful information on designing a series resonant converter.

In Chapter 2, the design oriented analysis of an SRC is presented. The analytical results derived from the state-plane analysis are incorporated into the analysis program. The flow chart of the analysis program is shown. The inputs to the analysis program are input voltage, output voltage, values of the tank circuit elements, transformer's turns ratio, and switching frequency or load current. The operating mode of the SRC at the given operating condition is first determined by testing all boundary conditions. The steady-state trajectory radius corresponding to the given operating condition is found next by a numerical method. This enables a quick calculation of all salient parameters, such as peak inductor current and peak capacitor voltage. The

results are plotted for the entire operating range to give the user a complete view of converter operation.

In Chapter 3, the design program of an SRC is presented. Again the analytical results derived from the state-plane analysis are utilized in the design program. In the design program, the user designs an SRC by choosing the user-specified parameter values. These parameters are the transformer's turns ratio, tank resonant frequency, and the upper or lower bound of the switching frequency. The design is carried out in a user friendly step-by-step manner. Design examples are presented first assuming an ideal SRC where the resonant tank is lossless. The validity of this design is discussed. The design of a nonideal SRC where a finite tank quality factor is assumed is also presented. The desired operating region of an SRC is in CCM. Graphical capability is provided in the package to enhance the analysis as well as to facilitate the design of an SRC.

DC analysis is performed at the end of each design iteration to validate the design. The design of an SRC is often conducted in an iterative process. Design curves are provided to facilitate this iterative design process.

The results of various examples are verified by SPICE simulations. Using the package, the design and analysis of a series resonant converter is conducted in a straight forward manner. The program is user-friendly with graphic capabilities and is written for the IBM-PC.

Appendix A. Symbols Of Variables

The definitions of variables used in the paper are listed below. If N is added to the variable, the variable is normalized.

f	Switching frequency
fo	Resonant frequency
n	Transformer's primary-to-secondary turns ratio
Vs	Input voltage
Vo	Output voltage
Io	Output (load) current
ISW	Transistor current at switching point
VCO	Capacitor voltage at switching point
IQAV	Average current of the transistor
IQR	RMS current of the transistor
IDAV	Average current of the diode
IDR	RMS current of the diode
ILR	RMS current of the inductor
ILAV	(Half-Cycle) Average current of the inductor
ILP	Peak inductor current
VCP	Peak capacitor voltage

Appendix B. SPICE Simulation Program

The SPICE program which is used for the circuit model in Fig. 2.35 is listed below.

```
SRC SIMULATION FOR VERIFICATION
VS1    2   1  DC  50
VS2    1   0  DC  50
RTANK  3   1  1M
LTANK  4   3  9.03U IC=0
CTANK  6   5  0.28U IC=0
VZ1    5   4  DC  0
D1     2   8  DS
D2     7   9  DS
V1     8   7  PULSE(250,0,0.1U,0.1U,0.1U,6.105U,12.61U)
V2     9   0  PULSE(0,250,0.1U,0.1U,0.1U,6.105U,12.61U)
DS1    7   2  DIODE
DS2    0   7  DIODE
RS1    19  2  5
RS2    20  7  5
CS1    7   19 5N IC=0
CS2    0   20 5N IC=0
DO1    11  13 DIODE
DO2    16  11 DIODE
DO3    10  13 DIODE
DO4    16  10 DIODE
RO1    14  13 5
RO2    15  11 5
RO3    17  13 5
RO4    18  10 5
CO1    11  14 5N IC=0
CO2    16  15 5N IC=0
CO3    10  17 5N IC=0
CO4    16  18 5N IC=0
```

```
EF      12   6   (11,10) 0 0.3
VZ2     7    12  DC  0
FF      10   11  VZ2 0 0.3
RG      10   6   10MEG
VO      13   16  DC 110
.MODEL DIODE D(PB=0.7V)
.MODEL DS    D(PB=1.OV)
.TRAN  0.5U  250U  UIC
.PRINT TRAN V(6,5) I(VZ1)
.OPTIONS ITL5=500000 ACCT
.OPTIONS LIMPTS=50002 LVLTIM=2
.END
```

The Fortran program which takes the discrete data from SPICE simulation and calculates the average and rms value is listed below.

```
      REAL RIL(250),Y(250),Y2(250)
C  READ IN ALL VALUES OF IL AS RIL
      N=0
   10 N=N+1
      READ(8,*)A,B,C
      RIL(N)=ABS(C)
      IF(N.GE.250)GOTO 20
      GOTO 10
C  DECIDE THE NUMBER OF POINT (NP) IN ONE HALF-CYCLE.
C  PER IS THE TIME INTERVAL OF THE HALF-CYCLE IN MICRO SECOND.
C  THE SETP IN SIMULATION IS 0.5 MICRO SECOND
   20 READ(5,*)PER
      XN=PER/0.5
      NP=INT(XN)
C  CHOSE NP POINT AFTER 5 CYCLE OF OPERATION AS STEADY-STATE VALUE
      NSTART=10*NP
      NEND=11*NP
      N=0
      DO 30 L=NSTART,NEND
      N=N+1
      Y(N)=RIL(L)
      Y2(N)=RIL(L)**2
   30 CONTINUE
C  USE SIMPSON'S RULE TO FIND AREA
      DELTAX=PER/NP
      SUM1=Y(1)+Y(N)
      SUMM1=Y2(1)+Y2(N)
      SUM2=0.
      SUMM2=0.
      J=N-1
      DO 60 I=2,J,2
      SUM2=SUM2+Y(I)
      SUMM2=SUMM2+Y2(I)
   60 CONTINUE
```

```
      SUM3 = 0.
      SUMM3 = 0.
      K = N-2
      DO 70 I = 3,K,2
      SUM3 = SUM3 + Y(I)
      SUMM3 = SUMM3 + Y2(I)
   70 CONTINUE
      AREA1 = (SUM1 + 4.*SUM2 + 2.*SUM3)*(DELTAX/3.)
      AREA2 = (SUMM1 + 4.*SUMM2 + 2.*SUMM3)*(DELTAX/3.)
      AVE = AREA1/PER
      RMS = (AREA2/PER)**0.5
      WRITE(6,75)AVE,RMS
   75 FORMAT(/,1X,'AVERAGE CURRENT = ',1PE14.7,2X,'RMS CURRENT = ',1PE14.7)
      STOP
      END
```

Appendix C. Program Listing

```
      PROGRAM SRC
      CHARACTER * 1 ANS
C
C THIS IS THE MAIN PROGRAM. USERS SELECT SPECIFIC TASK THEY WANT TO
C CARRY OUT.
C
      WRITE(*,100)
 100  FORMAT(1X,'THIS PROGRAM PERFORMS ANALYSIS AND DESIGN OF
     #SERIES RESONANT CONVERTER',/,
     #' UNDER DIFFERENT CONDITIONS. IF YOU ANSWER THE FOLLOWING',/,
     #' QUESTIONS AND ENTER THE CORRESPONDING DATA, THIS',/,
     #' PROGRAM WILL BE HAPPY TO SERVE YOU',/)
      WRITE(*,*)'DEFINE THE CIRCUIT PARAMETRES'
      WRITE(*,*)'VS  - THE INPUT VOLTAGE'
      WRITE(*,*)'VO  - THE OUTPUT VOLTAGE'
      WRITE(*,*)'IO  - THE OUTPUT CURRENT'
      WRITE(*,*)'OMEGAN - NORMALIZED OPERATING FREQUENCY'
      WRITE(*,*)'VCO,ILO - SWITCHING POINT STATE VARIABLE'
      WRITE(*,*)'VCP,ILP - PEAK CAP VOLTAGE AND PEAK IND CURRENT'
      WRITE(*,*)'ALPHA,BETA - DIODE AND TRANSISTOR CONDUCTION ANGLE'
      WRITE(*,*)'IDAV,IDR - DIODE AVERAGE AND RMS CURRENT'
      WRITE(*,*)'IQAV,IQR - TRANSISTOR AVERAGE AND RMS CURRENT'
      WRITE(*,*)'ILAV,ILR - INDUCTOR (HALF-CYCLE) AVERAGE AND RMS CURR
     #ENT'
      WRITE(*,99)
  99  FORMAT(/,1X,'IMPORTANT NOTE : ',
     #/,' LETTER N IN EACH VARIABLE INDICATES IT IS AN
     #NORMALIZED VARIABLE.')
 501  WRITE(*,111)
 111  FORMAT(/,1X,'IS THIS A LOSSLESS CASE STUDY ? THIS MEANS AN ',
     #/,' IDEAL SERIES RESONANT CONVERTER WITHOUT PARASITIC
```

```
   #LOSS. (Y/N) ?')
    READ(*,101)ANS
101  FORMAT(A)
    IF(ANS.EQ.'Y') THEN
    GOTO 20
    ELSE
    KLOSS=3
    CALL SUB3(KLOSS)
    WRITE(*,*)'JOB IN SUBROUTINE SUB3 HAS BEEN DONE'
    GOTO 104
    ENDIF
 20  WRITE(*,102)
102  FORMAT(/,' THIS PART OF PROGRAM PERFORMS DC ANALYSIS AND DESIGN',
   #/,' OF SRC WITHOUT PARASITIC LOSS. THIS IS AN IDEAL CASE STUDY'/)
    KLOSS=0
    WRITE(*,113)
113  FORMAT(/,1X,'WOULD YOU LIKE TO DO A CIRCUIT ANALYSIS WHEN
   #OPERATING',/,' FREQUENCY IS A GIVEN VARYING PARAMETER ? (Y/N)')
    READ(*,101) ANS
    IF(ANS.EQ.'Y') THEN
    CALL SUB1(KLOSS)
    WRITE(*,*)'JOB IN SUBROUTINE SUB1 HAS BEEN DONE'
    ENDIF
    WRITE(*,114)
114  FORMAT(/,1X,'WOULD YOU LIKE TO DO A CIRCUIT ANALYSIS WHEN OUTPUT',
   #/,' CURRENT (LOAD) IS A GIVEN VARYING PARAMETER ? (Y/N)')
    READ(*,101)ANS
    IF(ANS.EQ.'Y') THEN
    CALL SUB2(KLOSS)
    WRITE(*,*)'JOB IN SUBROUTINE SUB2 HAS BEEN DONE'
    ENDIF
    WRITE(*,115)
115  FORMAT(/,1X,'WOULD YOU LIKE TO DO A SERIES RESONANT CONVERTER',
   #/,' DESIGN ? (Y/N)')
    READ(*,101)ANS
    IF(ANS.EQ.'Y') THEN
    CALL DESIGN(KLOSS)
    WRITE(*,*)'JOB IN SUBROUTINE DESIGN HAS BEEN DONE'
    ENDIF
104  WRITE(*,103)
103  FORMAT(/,1X,'DO YOU WISH TO REPEAT FROM BEGINNING ? (Y/N)',/)
    READ(*,101) ANS
    IF (ANS.EQ.'Y') GOTO 501
    STOP
    END


    SUBROUTINE SER1 (R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
   #     IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG)
C
C   FOR AN IDEAL LOSLESS SRC, CALCULATE THE CIRCUIT PARAMETERS GIVEN
```

```
C  RADIUS R AND OUTPUT VOLTAGE Von.
C  KFLAG = 1 : INDICATE OMEGAN > 1.0 CASE
C  KFLAG = 0 : INDICATE OMEGAN < 1.0 CASE
C  L = 1 : INDICATE R = 1.0 + Von, WHICH IS THE BOUNDARY BETWEEN CCM
C  AND DCM.
C  FOR CCM CASE ONLY.
C
      IMPLICIT REAL (A-H,I,O-Z)
      PI = 4.0*ATAN(1.0)
      IF(KFLAG.EQ.0) THEN
      RP = R-2.0*VON
      ILPN = R
      VCPN = R + 1.-VON
      IF(L.EQ.1) THEN
      ALPHA = PI
      BETA = PI
      ILON = 0.
      ELSE
      ALPHA = PI-ACOS((1.-R*VON + VON**2)/(R-2.*VON))
      BETA = PI-ACOS((1. + R*VON-VON**2)/R)
      ILON = R*SIN(BETA)
      ENDIF
      ELSE
      RP = R + 2.*VON
      ALPHA = ACOS((1. + R*VON + VON**2)/(R + 2.*VON))
      BETA = ACOS((1.-R*VON-VON**2)/R)
      VCPN = R-1. + VON
      ILON = R*SIN(BETA)
      IF(BETA.GE.(PI/2.)) THEN
      ILPN = R
      ELSE
      ILPN = ILON
      ENDIF
      ENDIF
      TN = 2.*(ALPHA + BETA)
      OMEGAN = PI/(ALPHA + BETA)
      VCON = VON*VCPN
      ILAVN = 2.*VCPN/(ALPHA + BETA)
      IQAVN = (VCPN + VCON)/(2.*(ALPHA + BETA))
      IDAVN = (VCPN-VCON)/(2.*(ALPHA + BETA))
      IQRN = R/2.*SQRT((BETA-0.5*SIN(2.*BETA))/(ALPHA + BETA))
      IDRN = RP/2.*SQRT((ALPHA-0.5*SIN(2.*ALPHA))/(ALPHA + BETA))
      ILRN = SQRT(2.*(IDRN**2 + IQRN**2))
      RETURN
      END


      SUBROUTINE STAPLN(KTOL,KSIG,CNF,VNF,FO,RATIO,VONO)
C
C  THIS SUBROUTINE GENERATES ONE EQUILIBRIUM TRAJECTORY FOR STATE
C  PLANE ANALYSIS AT A PARTICULAR OUTPUT VOLTAGE(Vo) AND TRAJECTORY
```

```
C  RADIUS R, WHICH CORRESPONDS TO A PARTICULAR OPERATING FREQUENCY,
C  AND OUTPUT CURRENT.
C  COVER BOTH CCM AND DCM CASES.
C  IN CCM, COVER OMEGAN > 1.AND < 1. CASES.
C  KSIG=0: NORMALIZED PLOT WILL BE SHOWN.
C        USER SPECIFY Von, AND Wn OR IIAVN.
C  KSIG=1: UNNORMALIZED PLOT WILL BE SHOWN.
C        USER SPECIFY FREQUENCY OR Io.
C        Vo IS SUPPLIED BY CALLING PROGRAM.
C  IT WILL CALL FIND1 OR FIND2 TO FIND CORRESPONDING RADIUS R.
C
      IMPLICIT REAL(A-H,I,O-Z)
      REAL XDAT(121),YDAT(121,2)
      INTEGER*4 LINTYP(2)
      CHARACTER*20 XLABLE,YLABLE,TEMP,ANS
      PI=4.*ATAN(1.)
      JY=121
      N=121
      M=2
      LINTYP(1)=0
      LINTYP(2)=0
      LINFRQ=0
      JGRAPH=1
      IF(KSIG.EQ.0)THEN
      CNF=1.
      VNF=1.
      XLABLE='VCN'
      YLABLE='ILN'
      ELSE
      XLABLE='VC(V)'
      YLABLE='IL(A)'
      VON=VONO
      ENDIF
      KTOL=1
      IF(KSIG.EQ.0)THEN
      WRITE(*,8)
 8    FORMAT(/,' ONE EQUILIBRIUM TRAJECTORY WILL BE GENERATED, WHICH',
     #/,' CORRESPONDS TO ONE PARTICULAR NORMALIZED OUTPUT VOLTAGE Von',
     #/,' AND NORMALIZED OPERATING FREQUENCY OMEGAN.',
     #//,' YOU HAVE TWO OPTIONS :',
     #/,' (1) : SPECIFY Von AND OMEGAN',
     #/,' (2) : SPECIFY Von AND ILAVN',/)
      ELSE
      WRITE(*,5)
 5    FORMAT(/,' ONE EQUILIBUM TRAJECTORY WILL BE GENERATED, WHICH',
     #/,' CORRESPONDS TO ONE PARTICULAR OUTPUT VOLTAGE, OPERATING',
     #/,' FREQUENCY, AND OUTPUT CURRENT.',
     #//,' YOU HAVE TWO OPTIONS :',
     #/,' (1): SPECIFY OPERATING FREQUENCY f',
     #/,' (2): SPECIFY OUTPUT CURRENT Io')
      ENDIF
```

```
501  IF(KSIG.EQ.0)THEN
     WRITE(*,4)
 4   FORMAT(/,' DO YOU WISH TO SPECIFY VON AND OMEGAN ? (Y/N)')
     READ(*,101)ANS
     IF(ANS.EQ.'Y')THEN
     WRITE(*,*)'ENTER THE VALUE OF Von. IT IS < 1.0'
     READ(*,*)VON
     WRITE(*,*)'ENTER THE VALUE OF OMEGAN.'
     READ(*,*)OMEGAR
     CALL FIND1(OMEGAR,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
    #   IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
     GOTO 9
     ENDIF
     ELSE
     WRITE(*,51)
 51  FORMAT(/,' DO YOU WISH TO SPECIFY OPERATING FREQUENCY ? (Y/N)')
     READ(*,101)ANS
     IF(ANS.EQ.'Y')THEN
     WRITE(*,*)'ENTER OPERATING FREQUENCY IN KHz'
     READ(*,*)FREQ
     OMEGAR = FREQ*10.**3/FO
     CALL FIND1(OMEGAR,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
    #   IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
     GOTO 9
     ENDIF
     ENDIF
     IF(KSIG.EQ.0)THEN
     WRITE(*,*)'ENTER THE VALUE OF Von. IT IS < 1.0'
     READ(*,*)VON
     WRITE(*,*)'ENTER THE VALUE OF ILAVN.'
     READ(*,*)ION
     ELSE
     WRITE(*,*)'ENTER THE VALUE OF OUTPUT CURRENT'
     READ(*,*)IO
     ION = IO/(CNF*RATIO)
     ENDIF
     WRITE(*,7)
 7   FORMAT(/,' DO YOU WISH TO CONSIDER OMEGAN > 1. CASE ? (Y/N)')
     KFLAG = 0
     READ(*,101)ANS
     IF(ANS.EQ.'Y') KFLAG = 1
     CALL FIND2(ION,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
    #   IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
 9   VCSTEP = 2.*VCPN/120.0
     IF(KFLAG.EQ.0)THEN
     RP = R-2.*VON
     XN = (VCPN-VCON)/VCSTEP
C  DECIDE NUMBER OF STEP K TO REACH ANOTHER TOPLOGICAL MODE
     K = INT(XN)
     XDAT(1) = -VCPN
     YDAT(1,1) = 0.
```

```
      ADJS = RP-VCSTEP
C  ADJS IS THE ADJACENT SIDE OF ANGLE
      DO 10 J = 1,K
      VALUE = ABS(ADJS/RP)
C  CHECK WETHER ARGUMENT OF ARCCOS IS > 1. IF IT IS > 1., SET ANGLE = PI
C  TO PREVENT RUN TIME ERROR
      IF(VALUE.GE.1.)THEN
      ANGLE = PI
      ELSE
      ANGLE = ACOS(ADJS/RP)
      ENDIF
      XDAT(J + 1) = -VCPN + FLOAT(J)*VCSTEP
      YDAT(J + 1,1) = RP*SIN(ANGLE)
      ADJS = ADJS-VCSTEP
   10 CONTINUE
      ADJS = ABS(1.-VON-VCSTEP-XDAT(K + 1))
      DO 15 J = K + 2,121
      VALUE = ABS(ADJS/R)
      IF(VALUE.GE.1.)THEN
      ANGLE = PI
      ELSE
      ANGLE = ACOS(ADJS/R)
      ENDIF
      XDAT(J) = -VCPN + FLOAT(J)*VCSTEP
      YDAT(J,1) = R*SIN(ANGLE)
      ADJS = ADJS-VCSTEP
   15 CONTINUE
      GOTO 20
      ENDIF
      IF (KFLAG.EQ.1) THEN
      RP = R + 2.*VON
      XN = (2.*VCPN-VCON)/VCSTEP
C  DECIDE NUMBER OF STEPS TO REACH ANOTHER TOPLOGICAL MODE
      K = INT(XN)
      XDAT(1) = -VCPN
      YDAT(1,1) = 0.
      ADJS = R-VCSTEP
      DO 11 J = 1,K
      VALUE = ABS(ADJS/R)
      IF(VALUE.GE.1.0)THEN
      ANGLE = PI
      ELSE
      ANGLE = ACOS(ADJS/R)
      ENDIF
      XDAT(J + 1) = -VCPN + FLOAT(J)*VCSTEP
      YDAT(J + 1,1) = R*SIN(ANGLE)
      ADJS = ADJS-VCSTEP
   11 CONTINUE
      ADJS = ABS(1. + VON + VCSTEP + XDAT(K + 1))
      DO 16 J = K + 2,121
      VALUE = ABS(ADJS/RP)
```

```
      IF(VALUE.GE.1.)THEN
      ANGLE = PI
      ELSE
      ANGLE = ACOS(ADJS/RP)
      ENDIF
      XDAT(J) = -VCPN + FLOAT(J)*VCSTEP
      YDAT(J,1) = RP*SIN(ANGLE)
      ADJS = ADJS + VCSTEP
   16 CONTINUE
      ENDIF
C  TO UNNORMALIZE VARIABLE
   20 CONTINUE
      DO 17 J = 1,121
      XDAT(J) = XDAT(J)*VNF
      YDAT(J,1) = YDAT(J,1)*CNF
   17 CONTINUE
C  TO FIND LOWER PART OF CURVE. IT IS SYMMETRIC TO THE UPPER PART
      DO 25 J = 1,121
      YDAT(J,2) = -YDAT(122-J,1)
   25 CONTINUE
      CALL PLOTS(XDAT,YDAT,JY,N,M,LINTYP,LINFRQ,JGRAPG,XLABLE,YLABLE,
     #                    JER)
      READ(*,30)TEMP
   30 FORMAT(A4)
      CALL SCRNQQ(3)
      WRITE(*,40)
   40 FORMAT(///,' DO YOU WISH TO PLOT ANOTHER CURVE ? (Y/N)')
      READ(*,101)ANS
  101 FORMAT(A)
      IF(ANS.EQ.'Y') GOTO 501
      RETURN
      END


      SUBROUTINE SUB1(KLOSS)
      IMPLICIT REAL (A-H,I,O-Z)
      COMMON ANS
C
C  DC ANALYSIS OF SERIES RESONANT CONVRTER WITH OR WITHOUT LOSS.
C  SUB2 IS USED TO COMPUTE DC CHARACTERISTICS WHEN :
C  (1) : Von AND OPERATING FREQUENCY OMEGAN ARE GIVEN IN LOSSLESS CASE
C  (2) : Von,OMEGAN, AND DAMPING FACTOR ZETA ARE GIVEN IN LOSS CASE
C  COVER BOTH THE CCM AND DCM MODES OF OPERATION
C  IN CCM MODE, CONSIDER OMEGAN > 1.0 AND OMEGAN < 1.0 TWO CASES
C  FOR NO LOSS CASE; CONSIDER OMEGAN < 1.0 CASE ONLY IN LOSS CASE.
C  KSIG = 0 : INDICATE NORMALIZED CASE STUDY
C  KSIG = 1 : INDICATE UNNORMALIZED (ACTUAL) CASE STUDY
C  KLOSS = 0 : INDICATE NO LOSS CASE
C  KLOSS = 1 : INDICATE DCM-1 MODE IN LOSS CASE
C  KLOSS = 2 : INDICATE DCM-2 MODE IN LOSS CASE
C  KLOSS = 3 : INDICATE CCM MODE IN LOSS CASE
```

```
C  IT CAN GENERATE DESIGN CURVE Von vs Ion FOR DIFFERENT OMEGAN
C
      PI=4.0*ATAN(1.0)
  101  FORMAT(A)
  501  KSIG=0
      WRITE(*,11)
   11  FORMAT(/,1X,'DO YOU WISH TO DO AN ACTUAL (UNNORMALIZED) CASE ',
     #/,' ANALYSIS ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y') THEN
      KSIG=1
      WRITE(*,*)'ENTER THE VALUE OF INPUT VOLTAGE, Vs'
      READ(*,*)VS
      WRITE(*,*)'ENTER THE VALUE OF OUTPUT VOLTAGE, Vo'
      READ(*,*)VO
      WRITE(*,*)'ENTER INDUCTOR VALUE IND, IN MICRO HENRY'
      READ(*,*)IND
      WRITE(*,*)'ENTER CAPACITOR VALUE CAP, IN MICRO FARAD'
      READ(*,*)CAP
      WRITE(*,*)'ENTER OPERATING FREQUENCY FREQ, IN kHz'
      READ(*,*)FREQ
      WRITE(*,12)
   12  FORMAT(/,1X,'ENTER TRANSFORMER PRIMARY TO SECONDARY TURNS RATIO',
     #/,' IF THERE IS NO TRANSFORMER, ENTER 1.0')
      READ(*,*)RATIO
      ZO=SQRT(IND/CAP)
      WO=10.0**6/SQRT(IND*CAP)
      FO=WO/(2.0*PI)
      VON=VO*RATIO/VS
C  VON IS THE NORMALIZED OUTPUT VOLTAGE REFLECTED TO RESONANT TANK SIDE
      VONO=VON
      OMEGAR=10.0**3*FREQ/FO
      CNF=VS/ZO
      VNF=VS
C  CNF AND VNF ARE CURRENT AND VOLTAGE NORMALIZING FACTORS,RESPECTIVLY.
      IF(KLOSS.NE.0)THEN
      WRITE(*,21)
   21  FORMAT(/,' ENTER THE RESONANT TANK QUALITY FACTOR Q. IT IS RELATED
     #',/,' TO RESONANT TANK DAMPING FACTOR ZETA BY : Q=1/(2*ZETA)',/)
      READ(*,*)Q
      ZETA=1./(2.*Q)
      FD=FO*SQRT(1.-ZETA**2)
C  FD = DAMPED NATURAL FREQUENCY
      OMEGAR=10.**3*FREQ/FD
      IF(OMEGAR.EQ.1.)THEN
      WRITE(*,22)
   22 FORMAT(/,' THIS IS THE MAXIMUM LOAD CASE')
      ENDIF
      IF(OMEGAR.GT.1.)THEN
      WRITE(*,23)
   23  FORMAT(/,' OPERATING FREQUENCY HAS EXCEDED DAMPED NATURAL FREQUENC
```

```
#Y',/)
 GOTO 25
 ENDIF
 ENDIF
 GOTO 13
 ENDIF
 WRITE(*,*)'ENTER THE VALUE OF Von. IT IS REAL AND LESS THAN 1.0'
 READ(*,*)VON
 IF(KLOSS.EQ.0)THEN
 WRITE(*,*)'ENTER THE VALUE OF OMEGAN, IT IS A REAL VALUE '
 READ(*,*)OMEGAR
 ELSE
 WRITE(*,*)'ENTER THE VALUE OF OMEGAN, IT IS REAL AND NO GREATER
#THAN 1.'
 READ(*,*)OMEGAR
 IF(OMEGAR.EQ.1.)THEN
 WRITE(*,22)
 ENDIF
 WRITE(*,21)
 READ(*,*)Q
 ZETA=1./(2.*Q)
 ENDIF
13 KTOL=1
 IF(KLOSS.EQ.0)THEN
 CALL FIND1(OMEGAR,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
#  IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
 ELSE
 CALL FIND3(OMEGAR,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,
#  R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
 ENDIF
 IF(KSIG.EQ.0)THEN
 CALL PRINT(R,RPR,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
#DAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,KLOSS)
 ENDIF
 IF(KSIG.EQ.1) THEN
 WRITE(*,31)VS,FREQ
31 FORMAT(/,' WHEN INPUT VOLTAGE ='',1PE14.7,1X,'V,',2X,'OPERATING
#FREQUENCY ='',1PE14.7,1X,'KHz')
 IO=ILAVN*CNF*RATIO
 WRITE(*,32)IO
32 FORMAT(' THE OUTPUT CURRENT ='',1PE14.7,1X,'A')
 IF(KLOSS.EQ.0)THEN
 FOKHZ=FO/10.**3
 WRITE(*,43)FOKHZ
43 FORMAT(' RESONANT FREQUENCY ='',1PE14.7,1X,'KHz')
 ELSE
 FDKHZ=FD/10.**3
 WRITE(*,44)FDKHZ
44 FORMAT(' DAMPED NATURAL FREQUENCY ='',1PE14.7,1X,'KHz')
 ENDIF
 CALL RESULT(VCON,ILON,ILPN,VCPN,OMEGAN,IDAVN,IDRN,IQAVN,IQRN,
```

```
     #    ILRN,ILAVN,CNF,VNF,FO,FD,KLOSS)
      ENDIF
      IF(KSIG.EQ.1)THEN
      WRITE(*,15)
   15  FORMAT(/,' DO YOU WISH TO SEE A SET OF DESIGN CURVE ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      CALL GRAPH(KLOSS,KTOL,ZETA,KSIG,CNF,VNF,FO,RATIO,VONO,FDKHZ)
      ENDIF
      ELSE
      WRITE(*,16)
   16  FORMAT(/,1X,'DO YOU WISH TO SEE A SET OF NORMALIZED DESIGN CURVE ?
     # (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y') THEN
      KTOL=0
      CALL GRAPH(KLOSS,KTOL,ZETA,KSIG,CNF,VNF,FO,RATIO,VONO,FDKHZ)
      ENDIF
      ENDIF
      IF(KLOSS.EQ.0)THEN
      WRITE(*,17)
   17  FORMAT(/,' DO YOU WISH TO SEE A STATE PLANE DIAGRAM ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      CALL STAPLN(KTOL,KSIG,CNF,VNF,FO,RATIO,VONO)
      ENDIF
      ENDIF
   25  WRITE(*,120)
  120  FORMAT(/,1X,'DO YOU WISH TO REPEAT SAME ANALYSIS ? (Y/N)',/)
      READ(*,101) ANS
      IF(ANS.EQ.'Y') THEN
      GOTO 501
      ENDIF
      RETURN
      END


      SUBROUTINE GRAPH(KLOSS,KTOL,ZETA,KSIG,CNF,VNF,FO,RATIO,VONO,FDKHZ)
C
C   SUBROUTINE GRAPH IS USED TO GENERATE A SET OF DESIGN CURVES.
C   BOTH X-AXIS AND Y-AXIS VARIABLES ARE SPECIFIED BY THE USER.
C   COVER BOTH CCM AND DCM OPERATION.
C   IN CCM, CONSIDER (1): OMEGAN > 1. AND < 1. IN LOSSLESS CASE
C                    (2): OMEGAN < 1. CASE ONLY IN LOSS CASE.
C   KSIG=0: FIVE NORMALIZED DESIGN CURVES WILL BE PLOTED.
C   THESE FIVE CURVES ARE EVENLY DISTRIBUTED ON AN NORMALIZED FREQUENCY
C   OR OUTPUT VOLTAGE RANGE WHICH IS ALSO SPECIFIED BY THE USER.
C   KSIG=1: ONE ACTUAL DESIGN CURVE WILL BE PLOTED.
C
      IMPLICIT REAL(A-H,I,O-Z)
      REAL XDAT(40),YDAT(40,5)
```

```
      INTEGER*4 LINTYP(5)
      CHARACTER*35 XLABLE,YLABLE,TEMP,ANS
      PI=4.*ATAN(1.)
      JY=40
      N=40
      IF(KSIG.EQ.1)THEN
      M=1
      FOKHZ=FO/10.**3
C     WRITE(*,*)'CNF=',CNF,'VNF=',VNF,'FOKHZ=',FOKHZ
C     WRITE(*,*)'RATIO=',RATIO,'VON=',VONO,'KSIG=',KSIG
      ELSE
      CNF=1.
      VNF=1.
      FOKHZ=1.
      FDKHZ=1.
      RATIO=1.
      M=5
      ENDIF
      DO 10 K=1,M
      LINTYP(K)=0
   10 CONTINUE
      LINFRQ=0
      JGRAPH=1
      IF(KSIG.EQ.0)THEN
      WRITE(*,11)
   11 FORMAT(/,1X,'FIVE DESIGN CURVES WILL BE GENERATED. X-AXIS VARIABLE
     #',/,' AND Y-AXIS VARIABLE ARE SPECIFIED BY THE USER. THESE FIVE CU
     #RVES',/,' ARE EVENLY DISTRIBUTED ON A FREQUENCY RANGE OR OUTPUT VO
     #LTAGE',/,' RANGE WHICH IS ALSO SPECIFIED BY THE USER',//,
     #' IMPORTANT NOTE :'
     #/,' FOR FREQUENCY < 1.0 CASE, LOWER CURVE CORRESPOND TO LOWER
     #FREQUENCY',/,' OR HIGHER OUTPUT VOLTAGE.'
     #/,' FOR FREQUENCY > 1.0 CASE. LOWER CURVE CORRESPOND TO HIGHER
     #FREQUENCY',/,' OR LOWER OUTPUT VOLTAGE.'
     #//,' YOU HAVE TWO OPTIONS :',
     #/,' (1) : SPECIFY AN NORMALIZED OPERATING REQUENCY RANGE',
     #/,'       X-AXIS VARIABLE IS Von',
     #/,' (2) : SPECIFY AN NORMALIZED OUTPUT VOLTAGE RANGE',
     #/,'       X-AXIS VARIABLE IS Wn',/)
      ELSE
      WRITE(*,9)
    9 FORMAT(/,' ONE ACTUAL DESIGN CURVE WILL BE GENERATED. X-AXIS
     #VARIABLE',/,' AND Y-AXIS VARIABLE ARE SPECIFIED BY THE USER.',
     #/,' YOU HAVE TWO OPTIONS :',
     #/,' (1): CHOOSE X-AXIS VARIABLE TO BE OUTPUT VOLTAGE Vo',
     #/,' (2): CHOOSE X-AXIS VARIABLE TO BE OPERATING FREQUENCY')
      ENDIF
  101 FORMAT(A)
  501 IF(KSIG.EQ.0)THEN
      WRITE(*,12)
   12 FORMAT(/,1X,'DO YOU WISH Von TO BE YOUR X-AXIS VARIABLE ? (Y/N)')
```

```
      READ(*,101)ANS
      IF(ANS.EQ.'Y') THEN
      WRITE(*,*)'ENTER THE UPPER BOUND OF NORMALIZED FREQUENCY, Wnmax'
      READ(*,*)WMAX
      WRITE(*,*)'ENTER THE LOWER BOUND OF NORMALIZED FREQUENCY, Wnmin'
      READ(*,*)WMIN
      XLABLE='VON'
      VONMIN=0.
      VONMAX=0.999
      STEP1=(WMAX-WMIN)/4.
      STEP2=(VONMAX-VONMIN)/39.
      NX=1
C  NX=1 INDICATE X-AXIS VARIABLE IS Von
      GOTO 502
      ENDIF
      ENDIF
      IF(KSIG.EQ.1)THEN
      WRITE(*,22)
   22 FORMAT(/,' DO YOU WISH Vo TO BE YOUR X-AXIS VARIABLE ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      WRITE(*,*)'ENTER THE OPERATING FREQUENCY IN KHz'
      READ(*,*)FREQ
      IF(KLOSS.EQ.0)THEN
      WMIN=FREQ/FOKHZ
      ELSE
      WMIN=FREQ/FDKHZ
      ENDIF
      XLABLE='VO(V)'
      VONMIN=0.
      VONMAX=0.999
      STEP1=0.
      STEP2=(VONMAX-VONMIN)/39.
      NX=1
      GOTO 502
      ENDIF
      ENDIF
      IF(KSIG.EQ.0)THEN
      WRITE(*,15)
   15 FORMAT(/,' X-AXIS VARIABLE IS Wn',/)
      WRITE(*,*)'ENTER THE UPPER BOUND OF NORMALIZED OUTPUT VOLTAGE,
     #Vonmax'
      READ(*,*)VONMAX
      WRITE(*,*)'ENTER THE LOWER BOUND OF NORMALIZED OUTPUT VOLTAGE,
     #Vonmin'
      READ(*,*)VONMIN
      XLABLE='WN'
      WMAX=0.995
      WMIN=0.5
      STEP1=(VONMAX-VONMIN)/4.
      STEP2=(WMAX-WMIN)/39.
```

```
      NX=2
C  NX=2 INDICATE X-AXIS VARIABLE IS Wn
      ENDIF
      IF(KSIG.EQ.1)THEN
      WRITE(*,23)
   23  FORMAT(/,' X-AXIS VARIABLE IS FREQUENCY IN KHz')
      WRITE(*,*)'ENTER THE UPPER BOUND OF OPERATING FREQUENCY IN KHz'
      READ(*,*)FMAX
      WRITE(*,*)'ENTER THE LOWER BOUND OF OPERATING FREQUENCY IN KHz'
      READ(*,*)FMIN
      IF(KLOSS.EQ.0)THEN
      WMAX=FMAX/FOKHZ
      WMIN=FMIN/FOKHZ
      ELSE
      WMAX=FMAX/FDKHZ
      WMIN=FMIN/FDKHZ
      ENDIF
      VONMIN=VONO
      XLABLE='FREQUENCY(KHz)'
      STEP1=0.
      STEP2=(WMAX-WMIN)/39.
      NX=2
      ENDIF
  502  CONTINUE
      IF(KSIG.EQ.0)THEN
      IF(KLOSS.EQ.0)THEN
      WRITE(*,13)
   13  FORMAT(/,' THE FOLLOWING STEPS ALLOW YOU TO SELECT Y-AXIS VARIABLE
     #',/,' YOUR CHOICES ARE : ILAVN,ILPN,IQAVN,IDAVN,VCPN',/)
      ELSE
      WRITE(*,113)
  113  FORMAT(/,' THE FOLLOWING STEPS ALLOW YOU TO SELECT Y-AXIS VARIABLE
     #',/,' YOUR CHOICES ARE : ILAVN,IQAVN,IDAVN,VCPN',/)
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE ILAVN CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=1
      YLABLE='ILAVN'
      GOTO 21
      ENDIF
      IF(KLOSS.EQ.0)THEN
      WRITE(*,*)'DO YOU WISH TO SEE ILPN CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=2
      YLABLE='ILPN'
      GOTO 21
      ENDIF
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE IQAVN CURVE ? (Y/N)'
```

```
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=3
      YLABLE='IQAVN'
      GOTO 21
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE IDAVN CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=4
      YLABLE='IDAVN'
      GOTO 21
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE VCPN CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=5
      YLABLE='VCPN'
      GOTO 21
      ENDIF
      WRITE(*,14)
   14 FORMAT(/,' YOU HAVE NOT SELECTED A Y-AXIS VARIABLE. DO YOU WANT
     #',/,' TO SELECT A Y-AXIS VARIABLE TO BE PLOTED ? (Y/N)',/)
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      GOTO 502
      ELSE
      GOTO 71
      ENDIF
      ENDIF
      IF(KSIG.EQ.1)THEN
  503 IF(KLOSS.EQ.0)THEN
      WRITE(*,24)
   24 FORMAT(/,' THE FOLLOWING STEPS ALLOW YOU TO SELECT Y-AXIS
     #VARIABLE',/,' YOUR CHOICES ARE : ILAV,ILP,IQAV,IDAV,VCP',/)
      ELSE
      WRITE(*,124)
  124 FORMAT(/,' THE FOLLOWING STEPS ALLOW YOU TO SELECT Y-AXIS
     #VARIABLE',/,' YOUR CHOICES ARE : ILAV,IQAV,IDAV,VCP',/)
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE ILAV CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=1
      YLABLE='ILAV(A)'
      GOTO 21
      ENDIF
      IF(KLOSS.EQ.0)THEN
      WRITE(*,*)'DO YOU WISH TO SEE ILP CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
```

```
      NY=2
      YLABLE='ILP(A)'
      GOTO 21
      ENDIF
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE IQAV CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=3
      YLABLE='IQAV(A)'
      GOTO 21
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE IDAV CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=4
      YLABLE='IDAV(A)'
      GOTO 21
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE VCP CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=5
      YLABLE='VCP(V)'
      GOTO 21
      ENDIF
      WRITE(*,14)
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      GOTO 503
      ELSE
      GOTO 71
      ENDIF
      ENDIF
C   THE X-AXIS VARIABLE = Von OR Vo CASE IS CONSIDERED BELLOW
   21 IF(NX.EQ.1)THEN
      OMEGAR=WMIN
      DO 51 K=1,M
      VON=VONMIN
      DO 41 J=1,40
      IF(KLOSS.EQ.0)THEN
      CALL FIND1(OMEGAR,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #   IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
      ELSE
      CALL FIND3(OMEGAR,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,
     #   R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
      ENDIF
      XDAT(J)=VON*VNF/RATIO
      IF(NY.EQ.1) YDAT(J,K)=ILAVN*CNF
      IF(NY.EQ.2) YDAT(J,K)=ILPN*CNF
      IF(NY.EQ.3) YDAT(J,K)=IQAVN*CNF
```

```
      IF(NY.EQ.4) YDAT(J,K) = IDAVN*CNF
      IF(NY.EQ.5) YDAT(J,K) = VCPN*VNF
      VON = VON + STEP2
   41 CONTINUE
      OMEGAR = OMEGAR + STEP1
   51 CONTINUE
      ELSE
C  X-AXIS VARIABLE = Wn OR FREQ IS CONSIDERED BELLOW
      VON = VONMIN
      DO 52 K = 1,M
      OMEGAR = WMIN
      DO 42 J = 1,40
      IF(KLOSS.EQ.0)THEN
      CALL FIND1(OMEGAR,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #   IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
      XDAT(J) = OMEGAR*FOKHZ
      ELSE
      CALL FIND3(OMEGAR,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,
     #   R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
      XDAT(J) = OMEGAR*FDKHZ
      ENDIF
      IF(NY.EQ.1) YDAT(J,K) = ILAVN*CNF
      IF(NY.EQ.2) YDAT(J,K) = ILPN*CNF
      IF(NY.EQ.3) YDAT(J,K) = IQAVN*CNF
      IF(NY.EQ.4) YDAT(J,K) = IDAVN*CNF
      IF(NY.EQ.5) YDAT(J,K) = VCPN*VNF
      OMEGAR = OMEGAR + STEP2
   42 CONTINUE
      VON = VON + STEP1
   52 CONTINUE
      ENDIF
      CALL PLOTS(XDAT,YDAT,JY,N,M,LINTYP,LINFRQ,JGRAPH,XLABLE,YLABLE,
     #   JER)
      READ(*,60)TEMP
   60 FORMAT(A4)
      CALL SCRNQQ(3)
      WRITE(*,70)
   70 FORMAT(///,1X,'DO YOU WISH TO PLOT ANOTHER SET OF CURVE ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y') GOTO 501
   71 RETURN
      END


      SUBROUTINE FIND1(OMEGAR,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,
     #      OMEGAN,IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
C
C  THIS SUBROUTINE IS USED TO FIND R AND OTHER CIRCUIT PARAMETERS
C  WHEN Von AND NORMALIZED OPERATING FREQUENCY,OMEGAR, ARE KNOWN
C  FOR A GIVEN Von, TRY DIFFERENT R's SUCH THAT SPECIFED OMEGAR
C  IS REACHED.
```

```
C  KTOL=1 MEANS HIGHER ACCURACY IN NUMERICAL CALCULATION.
C  KTOL=0 MEANS LOWER ACCURACY IN CALCULATION.
C
      IMPLICIT REAL (A-H,I,O-Z)
      IF(KTOL.EQ.1)THEN
      TOL=1.E-06
      ELSE
      TOL=1.E-04
      ENDIF
      IF(OMEGAR.GT.1.0) THEN
      KFLAG=1
      RMIN=1.-VON +0.001
      ELSE
      KFLAG=0
      RMIN=1.+VON
      ENDIF
      IF(OMEGAR.LE.0.5) THEN
      OMEGAN=OMEGAR
      CALL DCM (R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     # IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN)
      GO TO 15
      ENDIF
      RMAX=25.
      R=RMIN
      STEP3=(RMAX-RMIN)/2.
C     R=(RMAX+RMIN)/2.
      DO 10 L=1,100
      CALL SER1 (R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #      IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG)
      ERROR=OMEGAR-OMEGAN
      IF(KFLAG.EQ.1) ERROR=-ERROR
      IF(ABS(ERROR).LT.TOL) GOTO 15
      CALL AGAIN1 (ERROR,RMIN,RMAX,R,STEP3)
   10 CONTINUE
   15 RETURN
      END


      SUBROUTINE AGAIN1(E,AMIN,AMAX,A,STEP)
C
C  THIS SUBROUTINE IS USED TO COMPUTE AN NEW INDEPENDENT VARIABLE A,
C  SUCH THAT A DEPENDENT VARIABLE IS CONVERGED TO THE DESIRED VALUE.
C  VARING R UNTIL SPECIFIED CIRCUIT PARAMETER IS MATCHED
C
      IF(E.LT.0.) GO TO 50
      H=(AMAX-A)/2.
      IF(H.GT.STEP) H=STEP
      AMIN=A
      A=A+H
      GOTO 100
   50 H=(A-AMIN)/2.
```

```
      IF(H.GT.STEP) H=STEP
      AMAX=A
      A=A-H
  100 CONTINUE
      RETURN
      END


      SUBROUTINE DCM(R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #      IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN)
C
C   SUBROUTINE DCM IS USED TO CALCULATE CIRCUIT PARAMETERS FOR SRC
C   IN DCM MODE WHEN THERE IS NO PARASITIC LOSS.
C
      IMPLICIT REAL (A-H,I,O-Z)
      PI=4.0*ATAN(1.0)
      R=1.0+VON
      RP=1.-VON
      ALPHA=PI
      BETA=PI
      VCPN=2.
      ILPN=1.+VON
      VCON=2.*VON
      ILON=0.
      ILAVN=4.*OMEGAN/PI
      IQAVN=R*OMEGAN/PI
      IDAVN=RP*OMEGAN/PI
      IQRN=SQRT(OMEGAN)*R/2.
      IDRN=SQRT(OMEGAN)*RP/2.
      ILRN=SQRT(2.*(IDRN**2+IQRN**2))
      RETURN
      END


      SUBROUTINE PRINT (R,RPR,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #   IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,KLOSS)
C
C    THIS SUBROUTINE IS USED TO PRINT THE NORMALIZED RESULTS.
C
      IMPLICIT REAL (A-H,I,O-Z)
      ALPHA=ALPHA*57.29578
      BETA=BETA*57.29578
      WRITE(*,101)
  101 FORMAT(/,1X,'THE NORMALIZED RESULTS ARE LISTED BELLOW :',/)
      WRITE(*,102) VON
  102 FORMAT(1X,'VON=',1PE14.7)
      WRITE(*,104) OMEGAN
  103 FORMAT(1X,'OMEGAN=',1PE14.7)
      WRITE(*,107) ILAVN
  107 FORMAT(1X,'ILAVN=',1PE14.7)
      IF(KLOSS.EQ.0)THEN
```

```
      WRITE(*,103) R
  103 FORMAT(1X,'RADIUS R = ',1PE14.7)
      WRITE(*,105) ALPHA
  105 FORMAT(1X,'ALPHA = ',1PE14.7)
      WRITE(*,106) BETA
  106 FORMAT(1X,'BETA = ',1PE14.7)
      WRITE(*,108) ILRN
  108 FORMAT(1X,'ILRN = ',1PE14.7)
      WRITE(*,109) ILPN
  109 FORMAT(1X,'ILPN = ',1PE14.7)
      WRITE(*,110) VCPN
  110 FORMAT(1X,'VCPN = ',1PE14.7)
      WRITE(*,111) VCON
  111 FORMAT(1X,'VCON = ',1PE14.7)
      WRITE(*,112) ILON
  112 FORMAT(1X,'ILON = ',1PE14.7)
      WRITE(*,113) IQAVN
  113 FORMAT(1X,'IQAVN = ',1PE14.7)
      WRITE(*,114) IDAVN
  114 FORMAT(1X,'IDAVN = ',1PE14.7)
      WRITE(*,115) IQRN
  115 FORMAT(1X,'IQRN = ',1PE14.7)
      WRITE(*,116) IDRN
  116 FORMAT(1X,'IDRN = ',1PE14.7)
      IF(OMEGAN.LE.0.5)THEN
      WRITE(*,117)
  117 FORMAT(/,' THE CONVERTER IS IN DCM',/)
      ENDIF
      GOTO 15
      ENDIF
      IF(KLOSS.EQ.3)THEN
      WRITE(*,124)RPR
  124 FORMAT(1X,'RADIUS RPR = ',1PE14.7)
      WRITE(*,105)ALPHA
      WRITE(*,106)BETA
      WRITE(*,110)VCPN
      WRITE(*,111)VCON
      WRITE(*,112)ILON
      WRITE(*,113)IQAVN
      WRITE(*,114)IDAVN
      GOTO 15
      ENDIF
      IF(KLOSS.EQ.1) THEN
      WRITE(*,11)
   11 FORMAT(/,' THE CONVERTER IS IN DCM-1 MODE',/)
      ENDIF
      IF(KLOSS.EQ.2) THEN
      WRITE(*,12)
   12 FORMAT(/,' THE CONVERTER IS IN DCM-2 MODE',/)
      ENDIF
   15 RETURN
```

```
      END


      SUBROUTINE SUB2(KLOSS)
      IMPLICIT REAL(A-H,I,O-Z)
      COMMON ANS
C
C  DC ANALYSIS OF SERIES RESONANT CONVERTER WITH OR WITHOUT PARASITIC
C  LOSS. SUB3 IS USED TO COMPUTE CIRCUIT PARAMETERS WHEN :
C  (1) : Von AND OUTPUT CURRENT Ion (LOAD) ARE GIVEN IN NO LOSS CASE.
C  (2) : Von,Ion,AND DAMPING FACTOR ZETA ARE GIVEN IN LOSS CASE
C  COVER BOTH CCM AND DCM OPERATION
C  IN CCM: (1) COVER OMEGAN > 1.0 AND < 1.0 CASES FOR NO LOSS CASE
C          (2) COVER OMEGAN < 1. CASE ONLY IN LOSS CASE
C  KSIG=0 : NORMALIZED CASE
C  KSIG=1 : UNNORMALIZED CASE
C
      PI=4.0*ATAN(1.0)
 501  KSIG=0
      WRITE(*,41)
  41  FORMAT(/,1X,'DO YOU WISH TO DO AN ACTUAL (UNNORMALIZED) CASE',
     #/,' ANALYSIS ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y') THEN
      KSIG=1
      WRITE(*,*)'ENTER THE VALUE OF INPUT VOLTAGE, Vs'
      READ(*,*)VS
      WRITE(*,*)'ENTER THE VALUE OF OUTPUT VOLTAGE, Vo'
      READ(*,*)VO
      WRITE(*,*)'ENTER THE VALUE OF OUTPUT CURRENT, Io'
      READ(*,*)IO
      WRITE(*,*)'ENTER THE INDUCTOR VALUE IND, IN MICRO HENRY'
      READ(*,*)IND
      WRITE(*,*)'ENTER THE CAPACITOR VALUE CAP, IN MICRO FARAD'
      READ(*,*)CAP
      WRITE(*,11)
  11  FORMAT(/,1X,'ENTER TRANSFORMER PRIMARY TO SECONDARY TURNS RATIO',
     #/,' IF THERE IS NO TRANSFORMER, ENTER 1.0')
      READ(*,*)RATIO
      ZO=SQRT(IND/CAP)
      WO=10.0**6/SQRT(IND*CAP)
      FO=WO/(2.*PI)
      VON=VO*RATIO/VS
      VONO=VON
      ION=(IO*ZO)/(VS*RATIO)
C   ION IS THE LOAD CURRENT WHICH IS REFLECTED TO PRIMARY SIDE,
     ION=ILAVN.
      CNF=VS/ZO
      VNF=VS
C  CNF AND VNF ARE CURRENT AND VOLTAGE NORMALIZING FACTORS RESPECTIVELY
      IF(KLOSS.NE.0)THEN
```

```
      WRITE(*,23)
   23 FORMAT(/,' ENTER THE RESONANT TANK QUALITY FACTOR Q. IT IS RELATED
     #',/,' TO RESONANT TANK DAMPING FACTOR ZETA BY : Q=1/(2*ZETA)',/)
      READ(*,*)Q
      ZETA=1./(2.*Q)
      FD=FO*SQRT(1.-ZETA**2)
      S=EXP(-ZETA*PI/SQRT(1.-ZETA**2))
      S1=SQRT(1.-ZETA**2)
      ILNMAX=2.*(1.-VON)*(1.+S)/(PI*(1.-S))
      IOMAX=ILNMAX*CNF*RATIO*S1
      IF(ION.EQ.ILNMAX)THEN
      WRITE(*,24)
   24 FORMAT(/,' THIS IS THE MAXIMUM LOAD CURRENT CASE')
      ENDIF
      IF(ION.GT.ILNMAX) THEN
      WRITE(*,25)IOMAX
   25 FORMAT(/,' THE MAXIMUM LOAD CURRENT =',1PE14.7,' A')
      WRITE(*,26)
   26 FORMAT(/,' LOAD CURRENT HAS EXCEDED THE UPPER LIMIT. THE CONVERTER
     #',/,' CAN NOT PROVIDE IT',/)
      GOTO 17
      ENDIF
      ENDIF
      ELSE
      WRITE(*,*)'ENTER THE VALUE OF Von. IT IS REAL AND LESS THAN 1.0'
      READ (*,*)VON
      WRITE(*,*)'ENTER THE VALUE OF Ion. IT IS A REAL VALUE.'
      READ(*,*)ION
      IF(KLOSS.NE.0)THEN
      WRITE(*,23)
      READ(*,*)Q
      ZETA=1./(2.*Q)
      S=EXP(-ZETA*PI/SQRT(1.-ZETA**2))
      S1=SQRT(1.-ZETA**2)
      ILNMAX=2.*(1.-VON)*(1.+S)/(PI*(1.-S))*S1
      IF(ION.EQ.ILNMAX)THEN
      WRITE(*,24)
      ENDIF
      IF(ION.GT.ILNMAX)THEN
      WRITE(*,27)ILNMAX
   27 FORMAT(/,' THE MAXIMUM NORMALIZED LOAD CURRENT =',1PE14.7)
      WRITE(*,26)
      GOTO 17
      ENDIF
      ENDIF
      ENDIF
      KTOL=1
      IF(KLOSS.EQ.0)THEN
      WRITE(*,31)
   31 FORMAT(/,1X,'DO YOU WISH TO CONSIDER OPERATING FREQUENCY GREATER T
     #HAN',/,' RESONANT FREQUENCY CASE (F > Fo) ? (Y/N)')
```

```
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      KFLAG=1
      ELSE
      KFLAG=0
      ENDIF
      CALL FIND2(ION,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #   IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
      ELSE
      CALL FIND4(ION,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,
     #   R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
      ENDIF
      IF(KSIG.EQ.0)THEN
      CALL PRINT(R,RPR,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #       IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,KLOSS)
      GOTO 18
      ENDIF
      WRITE(*,21)VS,IO
   21 FORMAT(/,' WHEN INPUT VOLTAGE=',1PE14.7,1X,'V,',2X,'OUTPUT CURRENT
     #=',1PE14.7,' A')
      IF(KLOSS.EQ.0)THEN
      FOKHZ=FO/10.**3
      FREQ=OMEGAN*FOKHZ
      WRITE(*,12)FREQ
   12 FORMAT(1X,'THE OPERATING FREQUENCY =',1PE14.7,1X,'KHz')
      WRITE(*,13)FOKHZ
   13 FORMAT(1X,'THE RESONANT FREQUENCY =',1PE14.7,1X,'KHz')
      ELSE
      FDKHZ=FD/10.**3
      FREQ=OMEGAN*FDKHZ
      WRITE(*,12)FREQ
      WRITE(*,14)FDKHZ
   14 FORMAT(/,' THE DAMPED NATURAL FREQUENCY =',1PE14.7,1X,'KHz')
      ENDIF
      CALL RESULT(VCON,ILON,ILPN,VCPN,OMEGAN,IDAVN,IDRN,IQAVN,IQRN,
     #   ILRN,ILAVN,CNF,VNF,FO,FD,KLOSS)
   18 CONTINUE
      IF(KSIG.EQ.1)THEN
      WRITE(*,19)
   19 FORMAT(/,1X,'DO YOU WISH TO SEE A SET OF DESIGN CURVES ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y') THEN
      CALL GRAPH(KLOSS,KTOL,ZETA,KSIG,CNF,VNF,FO,RATIO,VONO,FDKHZ)
      ENDIF
      ELSE
      WRITE(*,20)
   20 FORMAT(/,1X,'DO YOU WISH TO SEE A SET OF NORMALIZED DESIGN CURVES
     #? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y') THEN
      KTOL=0
```

```
      CALL GRAPH(KLOSS,KTOL,ZETA,KSIG,CNF,VNF,FO,RATIO,VONO,FDKHZ)
      ENDIF
      ENDIF
      IF(KLOSS.EQ.0)THEN
      WRITE(*,51)
   51  FORMAT(/,' DO YOU WISH TO SEE A STATE PLANE DIAGRAM ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      CALL STAPLN(KTOL,KSIG,CNF,VNF,FO,RATIO,VONO)
      ENDIF
      ENDIF
   17  WRITE(*,16)
   16  FORMAT(/,1X,'DO YOU WISH TO REPEAT THIS ANALYSIS ? (Y/N)')
      READ(*,101)ANS
  101  FORMAT(A)
      IF(ANS.EQ.'Y') GOTO 501
      RETURN
      END


      SUBROUTINE FIND2(ION,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #        IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
C
C  FIND2 IS USED TO FIND R AND OTHER CIRCUIT PARAMETERS WHEN Von
C  AND OUTPUT CURRENT Ion ARE KNOWN
C  FOR A GIVEN VON, TRY DIFFERENT R's SUCH THAT SPECIFIED Ion IS REACHED
C
      IMPLICIT REAL(A-H,I,O-Z)
      PI=4.*ATAN(1.)
      IF(KTOL.EQ.1)THEN
      TOL=1.E-06
      ELSE
      TOL=1.E-04
      ENDIF
      IF(KFLAG.EQ.1) THEN
      RMIN=1.0-VON+0.001
      ELSE
      RMIN=1.+VON
      IF(ION.LT.(2./PI)) THEN
      OMEGAN=ION*PI/4.0
      CALL DCM(R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #        IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN)
      GOTO 25
      ENDIF
      ENDIF
      RMAX=25.
      R=RMIN
      STEP3=(RMAX-RMIN)/2.
      DO 20 L=1,100
      CALL SER1(R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #     IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG)
```

```
      ERROR=ION-ILAVN
      IF(ABS(ERROR).LT.TOL) GOTO 25
      CALL AGAIN1(ERROR,RMIN,RMAX,R,STEP3)
   20 CONTINUE
   25 RETURN
      END


      SUBROUTINE RESULT(VCON,ILON,ILPN,VCPN,OMEGAN,IDAVN,IDRN,IQAVN,
     #  IQRN,ILRN,ILAVN,CNF,VNF,FO,FD,KLOSS)
C
C  THIS SUBROUTINE IS USED TO CALCULATE AND PRINT ACTUAL CIRCUIT PARA-
C  METERS WHEN NORMALIZED PARAMETERS AND NORMALIZING FACTORS ARE KNOWN
C
      IMPLICIT REAL(A-H,I,O-Z)
      FRE=OMEGAN*FO/(10.**3)
      WRITE(*,11)
   11 FORMAT(/,1X,'THE ACTUAL RESULTS ARE LISTED BELLOW :',/)
      IF(KLOSS.EQ.0)THEN
      WRITE(*,12)FRE
   12 FORMAT(1X,'FRE =',1PE14.7,' KHz',5X,'FRE=OPERATING FREQUENCY')
      ILAV=ILAVN*CNF
      WRITE(*,13)ILAV
   13 FORMAT(1X,'ILAV =',1PE14.7,' A',6X,'ILAV=AVERAGE INDUCTOR CURRENT'
     #)
      ILR=ILRN*CNF
      WRITE(*,14)ILR
   14 FORMAT(1X,'ILR =',1PE14.7,' A',7X,'ILR=INDUCTOR RMS CURRENT')
      ILP=ILPN*CNF
      WRITE(*,15) ILP
   15 FORMAT(1X,'ILP =',1PE14.7,' A',7X,'ILP=PEAK INDUCTOR CURRENT')
      VCP=VCPN*VNF
      WRITE(*,16)VCP
   16 FORMAT(1X,'VCP =',1PE14.7,' V',7X,'VCP=PEAK CAPACITOR VOLTAGE')
      VCO=VCON*VNF
      WRITE(*,17)VCO
   17 FORMAT(1X,'VCO =',1PE14.7,' V',7X,'VCO=CAPACITOR VOLTAGE AT SWITCH
     #ING')
      ILO=ILON*CNF
      WRITE(*,18)ILO
   18 FORMAT(1X,'ISW =',1PE14.7,' A',7X,'ISW=SWITCH CURRENT AT SWITCHING
     #')
      IQAV=IQAVN*CNF
      WRITE(*,19)IQAV
   19 FORMAT(1X,'IQAV =',1PE14.7,' A',6X,'IQAV=AVERAGE TRANSISTOR CURREN
     #T')
      IDAV=IDAVN*CNF
      WRITE(*,20)IDAV
   20 FORMAT(1X,'IDAV =',1PE14.7,' A',6X,'IDAV=AVERAGE DIODE CURRENT')
      IQR=IQRN*CNF
      WRITE(*,21)IQR
```

```
21   FORMAT(1X,'IQR  =',1PE14.7,' A',7X,'IQR = TRANSISTOR RMS CURRENT')
     IDR = IDRN*CNF
     WRITE(*,22) IDR
22   FORMAT(1X,'IDR  =',1PE14.7,' A',7X,'IDR = DIODE RMS CURRENT')
     GOTO 25
     ENDIF
     FRE = OMEGAN*FD/(10.**3)
     ILAV = ILAVN*CNF
     IF(KLOSS.EQ.3)THEN
     WRITE(*,12)FRE
     WRITE(*,13)ILAV
     VCP = VCPN*VNF
     IQAV = IQAVN*CNF
     IDAV = IDAVN*CNF
     ILO = ILON*CNF
     VCO = ABS(VCON)*VNF
     WRITE(*,16)VCP
     WRITE(*,17)VCO
     WRITE(*,18)ILO
     WRITE(*,19)IQAV
     WRITE(*,20)IDAV
     GOTO 25
     ENDIF
     WRITE(*,12)FRE
     WRITE(*,13)ILAV
  25 RETURN
     END


     SUBROUTINE DESIGN(KLOSS)
     IMPLICIT REAL (A-H,I,O-Z)
     REAL ILAV(4),IQAV(4),IDAV(4),ILO(4),VCO(4),IQR(4),IDR(4),ILR(4)
     REAL VCP(4),ILP(4),XILAV(4),XIQAV(4),XIDAV(4),XILO(4),XVCO(4),B(4)
     REAL XIQR(4),XIDR(4),XILR(4),XVCP(4),XILP(4),F(4),XF(4),FRE(4),X(4
    #)
     COMMON ANS
C
C  THIS SUBROUTINE TAKES DESIGN SPECIFICATIONS AND FIND THE VALUES OF
C  THE RESONANT TANK. DC ANALYSIS IS PERFORMED AT THE END OF THE DESIGN
C
     PI = 4.*ATAN(1.)
     KD = 0
C  KD = 0 INDICATE A LOSSLESS DESIGN
     WRITE(*,21)
  21  FORMAT(/,' THE DESIGN SPECIFICATIONS ARE INPUT VOLTAGE RANGE,',
    #/,' OUTPUT CURRENT RANGE, AND OUTPUT VOLTAGE.'//)
 501  WRITE(*,*)'ENTER UPPER BOUND OF INPUT VOLTAGE, Vsmax'
     READ(*,*)VSH
     WRITE(*,*)'ENTER LOWER BOUND OF INPUT VOLTAGE, Vsmin'
     READ(*,*)VSL
     WRITE(*,*)'ENTER OUTPUT VOLTAGE, Vo'
```

```
      READ(*,*)VO
      WRITE(*,*)'ENTER MAXIMUM OUTPUT CURRENT, Iomax'
      READ(*,*)IOMAX
      WRITE(*,*)'ENTER MINIMUM OUTPUT CURRENT, Iomin'
      READ(*,*)IOMIN
      VSAVE=(VSL+VSH)/2.
      VONREC=0.5
      RECN=VONREC*VSAVE/VO
C  VONREC=0.5 IS THE RECOMMENDED Von VALUE. RECN IS THE CORRESPONDING
C  TRANSFORMER PRIMARY TO SECONDARY TURNS RATIO N SUCH THAT Von=0.5
   10 XN=VSL/VO
      IF(XN.LT.1.)THEN
      WRITE(*,11)
   11  FORMAT(/,' TRANSFORMER IS REQUIRED TO STEP UP INPUT VOLTAGE ')
      ENDIF
      WRITE(*,45)
   45  FORMAT(/,' THE USER SPECIFIED PARAMETERS ARE TRANSFORMER TURNS',
     #/,' RATIO, RESONANT FREQUENCY, AND OPERATING FREQUENCY.')
      WRITE(*,12)XN
   12  FORMAT(/,' TRANSFORMER PRIMARY TO SECONDARY TURNS RATIO N (=Vsmin/
     #Vo)',/,' MUST BE LESS THAN',F5.3)
      WRITE(*,13)
   13  FORMAT(/,' ENTER A VALUE FOR TURNS RATIO AND WRITE IT DOWN')
      WRITE(*,22)
   22  FORMAT(/,' NOTE ON CHOOSING TRANSFORMER TURNS RATIO:',
     #/,' IF YOU CHOOSE RATIO TO BE MUCH LESS THAN N, THEN',
     #/,' (1): TANK CURRENT AND SWITCHING CURRENT WILL BE HIGH. THUS IN'
     #,/,'     THE DESIGN LARGER COMPONENTS THAN NECESSARY WILL BE USED
     #',/,' (2): PEAK CAPACITOR VOLTAGE, VCP IS HIGH.',
     #//,' IF YOU CHOOSE RATIO TOO CLOSE TO N, THEN',
     #/,' (1): REQUIRED OUTPUT VOLTAGE Vo MAY NOT BE REACHED AT HEAVY',
     #/,'     LOADS WITH CIRCUIT LOSSES.',
     #/,' (2): CIRCUIT RESPONSE IS SLOW.')
      WRITE(*,14)RECN
   14  FORMAT(/,' THE RECOMMENDED TURNS RATIO N =',F5.3)
      READ(*,*)RATIO
      VONMIN=VO*RATIO/VSH
      VONMAX=VO*RATIO/VSL
      XNN=RATIO
      WRITE(*,49)
   49  FORMAT(/,' ENTER THE VALUE OF RESONANT FREQUENCY, Fo, IN KHz')
      WRITE(*,40)
   40  FORMAT(/,' NOTE ON CHOOSING RESONANT FREQUENCY:',
     #/,' (1): HIGHER RESONANT FREQUENCY WILL ALLOW SMALLER TANK INDUCTO
     #R,',/,'     CAPACITOR, AND OUTPUT FILTER CAPACITOR VALUES.',
     #/,' (2): IF RESONANT FREQUENCY IS TOO HIGH, THEN',
     #/,'     (a): PARASITIC LOSS WILL HAVE MORE AFFECT ON CONVERTER OP
     #ERATION',/,'     (b): POWER LOSS WILL INCREASE.',
     #/,' (3): Fo, MAXIMUM OPERATING FREQUENCY SHOULD < 85
     #/,'     DESIGN OPERATING FREQUENCY RANGE BELLOW Fo')
      READ(*,*)FO
```

```
      IF(KLOSS.NE.0)THEN
      KD=1
C  KD=1 INDICATE LOSS CASE DESIGN
      WRITE(*,310)
 310  FORMAT(/,' ENTER THE RESONANT TANK QUALITY FACTOR Q, IT IS RELATED
     #',/,' TO RESONANT TANK DAMPING FACTOR ZETA BY : Q=1/(2.*ZETA)',/)
      READ(*,*)Q
      ZETA=1./(2.*Q)
      FD=FO*SQRT(1.-ZETA**2)
      S=EXP(-ZETA*PI/SQRT(1.-ZETA**2))
      S1=SQRT(1.-ZETA**2)
      KTOL=1
      KX=0
      WRITE(*,311)
 311  FORMAT(/,' OPERATING FREQUENCY RANGE IS LIMITED BELOW RESONANT FRE
     #QUENCY')
      GOTO 280
      ENDIF
      WRITE(*,31)
  31  FORMAT(/,' YOU HAVE TWO OPTIONS:',
     #/,' (1): DESIGN OPERATING FREQUENCY RANGE BELLOW Fo',
     #/,' (2): DESIGN OPERATING FREQUENCY RANGE ABOVE Fo')
      WRITE(*,41)
  41  FORMAT(/,' NOTE ON CHOOSING OPERATING FREQUENCY RANGE :
     #/,' (1): IF OPERATING FREQUENCY RANGE IS BELLOW Fo, THEN',
     #/,'      SWITCH IS TURNED OFF AT ZERO CURRENT',
     #/,' (2): IF OPERATING FREQUENCY RANGE IS ABOVE Fo, THEN',
     #/,'      SWITCH IS TURNED ON AT ZERO CURRENT',)
      WRITE(*,20)
  20  FORMAT(/,' DO YOU WISH TO SEE A SET OF NORMALIZED DESIGN CURVE BEF
     #ORE',/,' YOU CHOOSE OPERATING FREQUENCY ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      WRITE(*,*)'THE MINIMUM NORMALIZED OUTPUT VOLTAGE =',VONMIN
      WRITE(*,*)'THE MAXIMUM NORMALIZED OUTPUT VOLTAGE =',VONMAX
      KTOL=0
      KSIG=0
      CALL GRAPH(KLOSS,KTOL,ZETA,KSIG,CNF,VNF,FO,RATIO,VONO,FDKHZ)
      ENDIF
      KTOL=1
      RATIO=XNN
      WRITE(*,24)
  24  FORMAT(/,' DO YOU WISH TO DESIGN OPERATING FREQUENCY RANGE ABOVE F
     #o ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      KX=1
      ELSE
      KX=0
      WRITE(*,46)
  46  FORMAT(/,' NOTE FOR FREQUENCY RANGE < Fo CASE :',
```

```
   #/,' (1): MAXIMUM FREQUENCY SHOULD NOT > 85
   #/,' (2): MINIMUM FREQUENCY SHOULD NOT < 50
    ENDIF
280  WRITE(*,28)
 28  FORMAT(/,' YOU HAVE ANOTHER TWO OPTIONS:',
   #/,' (1): SPECIFY MINIMUM FREQUENCY IN THE OPERATING FREQUENCY RANG
   #E',/,' (2): SPECIFY MAXIMUM FREQUENCY IN THE OPERATING FREQUENCY R
   #ANGE')
    WRITE(*,25)
 25  FORMAT(/,' DO YOU WISH TO SPECIFY MINIMUM OPERATING FREQUENCY ? (Y
   #/N)')
    READ(*,101)ANS
    IF(ANS.EQ.'Y')THEN
    NX=1
    WRITE(*,50)
 50  FORMAT(/,' ENTER MINIMUM OPERATING FREQUENCY Fmin, IN KHz')
    WRITE(*,27)
 27  FORMAT(/,' NOTE ON CHOOSING Fmin :',
   #/,' (1): WHEN F < Fo, INCREASE Fmin WILL INCREASE L, Zo, AND DECRE
   #ASE',/,'      C VALUES. VCP WILL INCREASE SIGNIFICANTLY.'
   #,/,' (2): WHEN F > Fo, IF Fmin IS CHOSEN TOO HIGH, CONVERTER OPERA
   #TING',/,'      FREQUENCY RANGE WILL BE WIDE. Zo AND VCP WILL DECRE
   #ASE.')
    READ(*,*)FREQ
    ELSE
    NX=2
    WRITE(*,51)
 51  FORMAT(/,' ENTER MAXIMUM OPERATING FREQUENCY Fmax, IN KHz')
    WRITE(*,35)
 35  FORMAT(/,' NOTE ON CHOOSING Fmax :',
   #/,' (1): WHEN F < Fo, IF Fmax IS CHOSEN TOO LOW, CONVERTER WILL',
   #/,'      GO INTO DCM. Zo DECREASE AND ILP WILL BE VERY HIGH.',
   #/,' (2): WHEN F > Fo, INCREASE Fmax WILL INCREASE C, DECREASE L AN
   #D',/,'      Zo VALUES. VCP WILL DECREASE SIGNIFICANTLY.')
    READ(*,*)FREQ
    ENDIF
    OMEGAR=FREQ/FO
    IF(KLOSS.NE.0)THEN
    OMEGAR=FREQ/FD
    ENDIF
    IF(KX.EQ.0.AND.NX.EQ.1)THEN
    VON=VONMIN
    GOTO 29
    ENDIF
    IF(KX.EQ.0.AND.NX.EQ.2)THEN
    VON=VONMAX
    GOTO 29
    ENDIF
    IF(KX.EQ.1.AND.NX.EQ.1)THEN
    VON=VONMAX
    GOTO 29
```

```
      ENDIF
      IF(KX.EQ.1.AND.NX.EQ.2)THEN
      VON=VONMIN
      ENDIF
   29 IF(KD.EQ.0)THEN
      CALL FIND1(OMEGAR,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     # IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
      ELSE
      CALL FIND3(OMEGAR,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,
     # IDAVN,R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
      ENDIF
      ZO1=ILAVN*RATIO*VSH/IOMIN
      ZO2=ILAVN*RATIO*VSL/IOMAX
      IF(KX.EQ.0.AND.NX.EQ.1)THEN
      ZO=ZO1
      GOTO 32
      ENDIF
      IF(KX.EQ.0.AND.NX.EQ.2)THEN
      ZO=ZO2
      GOTO 32
      ENDIF
      IF(KX.EQ.1.AND.NX.EQ.1)THEN
      ZO=ZO2
      GOTO 32
      ENDIF
      IF(KX.EQ.1.AND.NX.EQ.2)THEN
      ZO=ZO1
      ENDIF
   32 IND=(ZO*10.0**3)/(2.*PI*FO)
      CAP=10.0**6/(((2.*PI*FO)**2)*IND)
      WRITE(*,15)IND
   15 FORMAT(/,' INDUCTOR =',1PE14.7,2X,'MICRO HENRY')
      WRITE(*,16)CAP
   16 FORMAT(' CAPACITOR =',1PE14.7,2X,'MICRO FARAD')
      WRITE(*,26)ZO
   26 FORMAT(' CHARACTERISTIC IMPEDENCE =',1PE14.7,2X,'OHM',/)
      IF(KD.EQ.1)THEN
      CALL SUB4(VSH,VSL,VO,FO,ZO,RATIO,IOMAX,IOMIN,Q,KD)
      GOTO 360
      ENDIF
      WRITE(*,81)
   81 FORMAT(' A SET OF CIRCUIT PARAMETERS WITH ABOVE ELEMENT VALUES IS
     #SHOWN BELLOW :')
      WRITE(*,33)
   33 FORMAT(/,4X,'VS(V)',5X,'IO(A)',3X,'F(KHz)',2X,'ILAV(A)',2X,'IQAV(A
     #)',3X,'ILP(A)',3X,'VCP(V)',/)
      DO 34 J=1,4
      IF(J.EQ.1.OR.J.EQ.2)THEN
      VS=VSL
      ELSE
      VS=VSH
```

```
      ENDIF
      IF(J.EQ.1.OR.J.EQ.3)THEN
      IO=IOMIN
      ELSE
      IO=IOMAX
      ENDIF
      VON=VO*RATIO/VS
      ION=(IO*ZO)/(VS*RATIO)
      CNF=VS/ZO
      VNF=VS
      CALL FIND2(ION,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #  IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
      F(J)=OMEGAN*FO
      ILAV(J)=ILAVN*CNF
      IQAV(J)=IQAVN*CNF
      ILP(J)=ILPN*CNF
      VCP(J)=VCPN*VNF
      ILO(J)=ILON*CNF
      VCO(J)=VCON*VNF
      IQR(J)=IQRN*CNF
      IDR(J)=IDRN*CNF
      ILR(J)=ILRN*CNF
      IDAV(J)=IDAVN*CNF
      WRITE(*,43)VS,IO,F(J),ILAV(J),IQAV(J),ILP(J),VCP(J)
   43 FORMAT(1X,7F9.3)
   34 CONTINUE
      DO 90 J=1,4
      FRE(J)=F(J)
   90 CONTINUE
C  TO ARRANGE CIRCUIT PARAMETERS IN DECENDING ORDER FOR FINDING RANGE
      DO 71 K=1,8
      DO 61 J=1,4
      IF(K.EQ.1)B(J)=ILO(J)
      IF(K.EQ.2)B(J)=VCO(J)
      IF(K.EQ.3)B(J)=IQR(J)
      IF(K.EQ.4)B(J)=IDR(J)
      IF(K.EQ.5)B(J)=ILR(J)
      IF(K.EQ.6)B(J)=ILP(J)
      IF(K.EQ.7)B(J)=VCP(J)
      IF(K.EQ.8)B(J)=F(J)
   61 CONTINUE
      CALL ARANGE(B,X,4)
      DO 62 J=1,4
      IF(K.EQ.1)XILO(J)=X(J)
      IF(K.EQ.2)XVCO(J)=X(J)
      IF(K.EQ.3)XIQR(J)=X(J)
      IF(K.EQ.4)XIDR(J)=X(J)
      IF(K.EQ.5)XILR(J)=X(J)
      IF(K.EQ.6)XILP(J)=X(J)
      IF(K.EQ.7)XVCP(J)=X(J)
      IF(K.EQ.8)XF(J)=X(J)
```

```
 62  CONTINUE
 71  CONTINUE
     WRITE(*,17)
 17  FORMAT(/,' THE RANGE OF CERTAIN CIRCUIT PARAMETERS IS SHOWN BELLOW
    #:')
     WRITE(*,69)
 69  FORMAT(/,7X,'F(KHz)',3X,'ISW(A)',3X,'VCO(V)',1X,'IQRMS(A)',1X,'IDR
    #MS(A)',1X,'ILRMS(A)',1X,'ILPEAK(A)',1X,'VCPEAK(V)',/)
     WRITE(*,70)XF(4),XILO(4),XVCO(4),XIQR(4),XIDR(4),XILR(4),XILP(4),X
    #VCP(4)
 70  FORMAT(' MIN',8F9.3)
     WRITE(*,73)XF(1),XILO(1),XVCO(1),XIQR(1),XIDR(1),XILR(1),XILP(1),X
    #VCP(1)
 73  FORMAT(' MAX',8F9.3)
C    CHECK WHETHER FO<>FMAX<>FMIN CASE
     IF(KX.EQ.0)THEN
     FBH=.85*FO
     FBL=.5*FO
     IF(XF(1).GT.FBH)THEN
     WRITE(*,83)
 83  FORMAT(/,' FMAX IS TOO HIGH,MAY CAUSE EXCEEDING')
     ENDIF
     IF(XF(4).LT.FBL)THEN
     WRITE(*,82)
 82  FORMAT(/,' FMIN IS TOO LOW,MAY CAUSE LOOSE LOCK DURI
    #ING',/,' OPERATION. YOU MAY CONSIDER REDESIGN')
     ENDIF
     ENDIF
360  WRITE(*,84)
 84  FORMAT(/' DO YOU WISH TO SEE DESIGN CURVES AT THIS SET OF CIRCUIT
    #ELEMENT VALUE ? (Y/N)')
     READ(*,101)ANS
     IF(ANS.EQ.'Y')THEN
     CALL GRAPH2(VSH,VSL,VO,FO,ZO,RATIO,FRE,KD,ZETA,FD)
     ENDIF
     WRITE(*,36)
 36  FORMAT(/,' DO YOU WISH TO REPEAT DESIGN AT SAME DESIGN SPECIFICATI
    #ON ? (Y/N)')
     READ(*,101)ANS
     IF(ANS.EQ.'Y')GOTO 10
     WRITE(*,18)
 18  FORMAT(/,' DO YOU WISH TO INVESTIGATE CIRCUIT BEHAVIOR AT A PARTIC
    #ULAR',/,' OPERATING CONDITION ? (Y/N)')
     READ(*,101)ANS
101  FORMAT(A)
     IF(ANS.EQ.'Y') THEN
     CALL SUB2(KLOSS)
     ENDIF
     IF(KD.EQ.0)THEN
     WRITE(*,102)
102  FORMAT(/,' DO YOU WISH TO INVESTIGATE CIRCUIT BEHAVIOR WHEN LOSS',
```

```
     #/,' IS CONSIDERED ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      CALL SUB4(VSH,VSL,VO,FO,ZO,RATIO,IOMAX,IOMIN,Q,KD)
      WRITE(*,37)
   37 FORMAT(/,' NOTE ON REDUCING Qmin :',
     #/,' (1): REDUCE RESONANT FREQUENCY Fo.',
     #/,' (2): REDUCE OPERATING FREQUENCY.',
     #/,' (3): REDUCE TRANSFORMER TURNS RATIO.')
      ENDIF
      WRITE(*,36)
      READ(*,101)ANS
      IF(ANS.EQ.'Y')GOTO 10
      ENDIF
      WRITE(*,19)
   19 FORMAT(/,' DO YOU WISH TO DO ANOTHER DESIGN ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y') GOTO 501
      RETURN
      END


      SUBROUTINE ARANGE(B,X,M)
      IMPLICIT REAL(A-H,I,O-Z)
      REAL B(M),X(M)
C
C   THIS SUBROUTINE IS USED TO ARRANGE M VALUES IN DECENDING ORDER. IT
C   TAKES ARRAY B CONTAINING THE ORIGINAL M VALUES TO BE ARRANGED. IT
C   RETURNS ARRAY X WHICH CONTAINS M VALUES IN DECENDING ORDER.
C
      DO 21 K=1,M
      BIG=B(1)
      N=1
      DO 11 L=2,M
      IF(BIG.GT.B(L))GOTO 11
      BIG=B(L)
      N=L
   11 CONTINUE
      B(N)=0.
      X(K)=BIG
   21 CONTINUE
      RETURN
      END


      SUBROUTINE GRAPH2(VSH,VSL,VO,FO,ZO,RATIO,FRE,KD,ZETA,FD)
C
C  THIS SUB IS SPECIFICALLY WRITTERN FOR DESIGN PART. THE STRUCTURE IS
C  SIMILAR TO SUBROUTINE GRAPH, BUT SIMPLIER.
C
      IMPLICIT REAL(A-H,I,O-Z)
```

```
      REAL XDAT(40),YDAT(40,6),FRE(4)
      INTEGER*4 LINTYP(6)
      CHARACTER*35 XLABLE,YLABLE,TEMP,ANS
      PI=4.*ATAN(1.)
      JY=40
      N=40
      M=2
      LINTYP(1)=0
      LINTYP(2)=2
      LINFRQ=3
      JGRAPH=1
      XLABLE='FREQUENCY(KHz)'
      KTOL=0
      CNFL=VSL/ZO
      CNFH=VSH/ZO
      VNFL=VSL
      VNFH=VSH
      VONMIN=VO*RATIO/VSH
      VONMAX=VO*RATIO/VSL
  101 FORMAT(A)
  501 WRITE(*,11)
   11 FORMAT(/,' THE CURVE WITH "+" IS Vs=Vsmax CURVE',
     #/,' THE CURVE WITHOUT "+" IS Vs=Vsmin CURVE',
     #//,' YOU HAVE TWO OPTIONS:',
     #/,' (1): SPECIFY A FREQUENCY RANGE AT WHICH YOU WANT TO LOOK CURVE
     # IN MORE DETAIL',/,' (2): USE DEFAULT FREQUENCY RANGE 0.5*Fo-0.99*
     #Fo',/)
      WRITE(*,*)'DO YOU WISH TO SPECIFY YOUR FREQUENCY RANGE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      WRITE(*,*)'ENTER UPPER BOUND OF FREQUENCY IN kHz'
      READ(*,*)FMAX
      WRITE(*,*)'ENTER LOWER BOUND OF FREQUENCY IN kHz'
      READ(*,*)FMIN
      IF(KD.EQ.0)THEN
      WMAX=FMAX/FO
      WMIN=FMIN/FO
      ELSE
      WMAX=FMAX/FD
      WMIN=FMIN/FD
      ENDIF
      ELSE
      WMAX=0.99
      WMIN=0.5
      ENDIF
      STEP2=(WMAX-WMIN)/39.
  502 IF(KD.EQ.0)THEN
      WRITE(*,12)
   12 FORMAT(/,' THE FOLLOWING STEPS ALLOW YOU TO SELECT Y-AXIS VARIABLE
     #',/,' YOUR CHOICES ARE : ILAV,ILP,ISW,IQAV,IDAV,VCP',/)
      ELSE
```

```
      WRITE(*,112)
  112 FORMAT(/,' THE FOLLOWING STEPS ALLOW YOU TO SELECT Y-AXIS VARIABLE
     #',/,' YOUR CHOICES ARE : ILAV,ISW,IQAV,IDAV,VCP',/)
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE ILAV CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=1
      YLABLE='ILAV(A)'
      GOTO 21
      ENDIF
      IF(KD.EQ.0)THEN
      WRITE(*,*)'DO YOU WISH TO SEE ILP CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=2
      YLABLE='ILP(A)'
      GOTO 21
      ENDIF
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE ISW CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=6
      YLABLE='ISW(A)'
      GOTO 21
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE IQAV CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=3
      YLABLE='IQAV(A)'
      GOTO 21
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE IDAV CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=4
      YLABLE='IDAV(A)'
      GOTO 21
      ENDIF
      WRITE(*,*)'DO YOU WISH TO SEE VCP CURVE ? (Y/N)'
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      NY=5
      YLABLE='VCP(V)'
      GOTO 21
      ENDIF
      WRITE(*,14)
   14 FORMAT(/,' YOU HAVE NOT SELECTED A Y-AXIS VARIABLE. DO YOU WANT TO
     #',/,' SELECT A Y-AXIS VARIABLE TO BE PLOTED ? (Y/N)',/)
```

```
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      GOTO 502
      ELSE
      GOTO 71
      ENDIF
   21 VON=VONMAX
      CNF=CNFL
      VNF=VNFL
      DO 52 K=1,2
      OMEGAR=WMIN
      DO 42 J=1,40
      IF(KD.EQ.0)THEN
      CALL FIND1(OMEGAR,R,VON,VCON,ILON,ILPN,VCPN,ALPHA,BETA,OMEGAN,
     #  IDAVN,IDRN,IQAVN,IQRN,ILRN,ILAVN,L,KFLAG,KTOL)
      XDAT(J)=OMEGAR*FO
      ELSE
      CALL FIND3(OMEGAR,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,
     #  IDAVN,R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
      XDAT(J)=OMEGAR*FD
      ENDIF
      IF(NY.EQ.1) YDAT(J,K)=ILAVN*CNF
      IF(NY.EQ.2) YDAT(J,K)=ILPN*CNF
      IF(NY.EQ.3) YDAT(J,K)=IQAVN*CNF
      IF(NY.EQ.4) YDAT(J,K)=IDAVN*CNF
      IF(NY.EQ.5) YDAT(J,K)=VCPN*VNF
      IF(NY.EQ.6) YDAT(J,K)=ILON*CNF
      OMEGAR=OMEGAR+STEP2
   42 CONTINUE
      VON=VONMIN
      CNF=CNFH
      VNF=VNFH
   52 CONTINUE
      CALL PLOTS(XDAT,YDAT,JY,N,M,LINTYP,LINFRQ,JGRAPH,XLABLE,YLABLE,
     #  JER)
      READ(*,60)TEMP
   60 FORMAT(A4)
      CALL SCRNQQ(3)
      WRITE(*,70)
   70 FORMAT(///,1X,'DO YOU WISH TO PLOT ANOTHER SET OF CURVE ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y') GOTO 501
   71 RETURN
      END


      SUBROUTINE SUB4(VSH,VSL,VO,FO,ZO,RATIO,IOMAX,IOMIN,Q,KD)
C
C  THIS SUBRIUTINE IS USED TO CHECK THE RESULT IN DESIGN WHEN LOSS IS
C  CONSIDERED. IT GIVES THE MINIMUM Q VALUE OF RESONANT TANK WHICH MEET
```

```
C  THE DESIGN SPECIFICATION. IT CALCULATE CIRCUIT PARAMETERS AT GIVEN Q
C
      IMPLICIT REAL(A-H,I,O-Z)
      REAL ILAV(4),IQAV(4),F(4),VCP(4),ILO(4),VCO(4)
      COMMON ANS
      PI=4.*ATAN(1.)
      KTOL=1
      IF(KD.EQ.1)GO TO 31
      IONMAX=(IOMAX*ZO)/(VSL*RATIO)
      VON=VO*RATIO/VSL
      QMIN=1.
      QMAX=500.
      Q=QMIN
      STEP3=(QMAX-QMIN)/2.
      DO 5 L=1,100
      ZETA=1./(2.*Q)
      S=EXP(-ZETA*PI/SQRT(1.-ZETA**2))
      ILNMAX=2.*(1.-VON)*(1.+S)/(PI*(1.-S))
      ERROR=IONMAX-ILNMAX
      IF(ABS(ERROR).LT.1.E-05)GOTO 6
      CALL AGAIN1(ERROR,QMIN,QMAX,Q,STEP3)
 5    CONTINUE
 6    QX=Q
501   WRITE(*,7)QX
 7    FORMAT(/,' THE MINIMUM Q VALUE WHICH CAN MEET DESIGN SPECIFICATION
     #=',1PE14.7)
      WRITE(*,10)
 10   FORMAT(/,' ENTER THE RESONANT TANK QUALITY FACTOR Q. IT IS RELATED
     #',/,' TO RESONANT TANK DAMPING FACTOR ZETA BY : Q=1/(2*ZETA)',/)
      READ(*,*)Q
 31   ZETA=1./(2.*Q)
      FD=FO*SQRT(1.-ZETA**2)
      S=EXP(-ZETA*PI/SQRT(1.-ZETA**2))
      S1=SQRT(1.-ZETA**2)
      WRITE(*,21)
 21   FORMAT(' A SET OF CIRCUIT PARAMETERS WITH ABOVE ELEMENT VALUES IS
     #SHOWN BELLOW :')
      WRITE(*,20)Q,FD
 20   FORMAT(/,' WHEN Q=',1PE14.7,2X,'DAMPED NATURAL FREQUENCY=',1PE14.7
     #,1X,'KHz')
      WRITE(*,22)
 22   FORMAT(/,4X,'VS(V)',5X,'IO(A)',3X,'F(KHz)',3X,'ISW(A)',3X,'VCO(V)'
     #,2X,'ILAV(A)',2X,'IQAV(A)',3X,'VCP(V)',/)
      KS=0
      KS2=0
      DO 11 J=1,4
      IF(J.EQ.1.OR.J.EQ.2)THEN
      VS=VSL
      ELSE
      VS=VSH
      ENDIF
```

```
      IF(J.EQ.1.OR.J.EQ.3)THEN
      IO=IOMIN
      ELSE
      IO=IOMAX
      ENDIF
      VON=VO*RATIO/VS
      ION=(IO*ZO)/(VS*RATIO)
      CNF=VS/ZO
      VNF=VS
      ILNMAX=2.*(1.-VON)*(1.+S)/(PI*(1.-S))
      IF(ION.GT.ILNMAX)THEN
      ION=ILNMAX
      IO=ION*CNF*RATIO*S1
      KS=1
C  KS=1 INDICATE THAT CONVERTER CAN NOT PROVIDE REQUIRED LOAD CURRENT
      ENDIF
      CALL FIND4(ION,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,
     #   R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
      F(J)=OMEGAN*FD
      ILAV(J)=ILAVN*CNF
      IF(KLOSS.EQ.3)THEN
      IQAV(J)=IQAVN*CNF
      VCP(J)=VCPN*VNF
      ILO(J)=ILON*CNF
      VCO(J)=ABS(VCON)*VNF
      WRITE(*,12)VS,IO,F(J),ILO(J),VCO(J),ILAV(J),IQAV(J),VCP(J)
   12 FORMAT(1X,8F9.3)
      ELSE
      KS2=1
C  KS2=1 INDICATE THAT CONVERTER GOES INTO DCM DURING OPERATION
      WRITE(*,13)VS,IO,F(J),ILAV(J)
   13 FORMAT(1X,4F9.3)
      ENDIF
   11 CONTINUE
      IF(KS.EQ.1)THEN
      WRITE(*,14)
   14 FORMAT(/,' LOAD CURRENT HAS EXCEEDED THE UPPER LIMIT. CONVERTER',
     #/,' CAN NOT PROVIDE IT')
      ENDIF
      IF(KS2.EQ.1)THEN
      WRITE(*,15)
   15 FORMAT(/,' CONVERTER GOES INTO DCM DURING OPERATION')
      ENDIF
      IF(KD.EQ.1)GOTO 32
      WRITE(*,16)
   16 FORMAT(/,' DO YOU WISH TO REPEAT ANALYSIS AT ANOTHER Q VALUE ? (Y/
     #N)')
      READ(*,101)ANS
  101 FORMAT(A)
      IF(ANS.EQ.'Y')GOTO 501
   32 RETURN
```

```
      END


      SUBROUTINE SUB3(KLOSS)
      IMPLICIT REAL(A-H,I,O-Z)
      COMMON ANS
C
C THIS IS THE SUBPROGRAM THAT DEALS WITH NONIDEAL SRC ANALYSIS AND
C DESIGN USERS SELECT SPECIFIC TASK TO BE DONE
C
      WRITE(*,100)
 100  FORMAT(/,' THIS PART OF PROGRAM PERFORMS DC ANALYSIS AND DESIGN OF
     # SRC WITH',
     #/,' LOSS. THE VARIOUS PARASITIC LOSSES ARE MODELED BY A SINGLE',
     #/,' LOSS RESISTOR IN SERIES WITH THE RESONANT INDUCTOR',/)
 501  WRITE(*,102)
 102  FORMAT(/,' WOULD YOU LIKE TO DO A CIRCUIT ANALYSIS WHEN OPERATING
     #',/,' FREQUENCY IS A GIVEN VARYING PARAMETER ? (Y/N)')
      READ(*,101)ANS
 101  FORMAT(A)
      IF(ANS.EQ.'Y')THEN
      CALL SUB1(KLOSS)
      WRITE(*,*)'JOB IN SUBROUTINE SUB1 HAS BEEN DONE'
      ENDIF
      WRITE(*,103)
 103  FORMAT(/,' WOULD YOU LIKE TO DO A CIRCUIT ANALYSIS WHEN OUTPUT',
     #/,' CURRENT (LOAD) IS A GIVEN VARYING PARAMETER ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      CALL SUB2(KLOSS)
      WRITE(*,*)'JOB IN SUBROUTINE SUB2 HAS BEEN DONE'
      ENDIF
      WRITE(*,105)
 105  FORMAT(/,' WOULD YOU LIKE TO DO A SERIES RESONANT CONVERTER',
     #/,' DESIGN ? (Y/N)')
      READ(*,101)ANS
      IF(ANS.EQ.'Y')THEN
      CALL DESIGN(KLOSS)
      WRITE(*,*)' JOB IN SUBROUTINE DESIGN HAS BEEN DONE.'
      ENDIF
      WRITE(*,104)
 104  FORMAT(/,' DO YOU WISH TO REPEAT ANALYSIS OR DESIGN WITH LOSS ? (Y
     #/N)',/)
      READ(*,101)ANS
      IF(ANS.EQ.'Y')GOTO 501
      RETURN
      END


      SUBROUTINE FIND3(OMEGAR,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,
```

```
     #        IDAVN,R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
C
C  THIS SUBROUTINE IS USED TO FIND RPR AND OTHER CIRCUIT PARAMETERS
C  WHEN Von, NORMALIZED OPERATING FREQUENCY OMEGAR,AND DAMPING
C  FACTOR ZETA ARE KNOWN
C  FOR A GIVEN Von AND ZETA, TRY DIFFERENT RPR's SUCH THAT SPECIFIED
C  OMEGAR IS REACHED
C  COVER CCM, DCM-1, AND DCM-2 CASE
C
      IMPLICIT REAL(A-H,I,O-Z)
      PI=4.*ATAN(1.)
      KLOSS=3
      S=EXP(-ZETA*PI/SQRT(1.-ZETA**2))
      S1=SQRT(1.-ZETA**2)
      IF(VON.GE.S)THEN
C
C  CONVERTER IS IN DCM-1 MODE
C
      KLOSS=1
      OMEGAN=OMEGAR
      R1PR=2.*S*(1.-VON)/(1.-S)
      ILAVN=2.*(1.-VON)*(1.+S)*OMEGAR/(PI*(1.-S))*S1
      VCPN=1.-VON+R1PR
      IDAVN=0.
      IQAVN=ILAVN
      ILON=0.
      VCON=VCPN
      GOTO 22
      ENDIF
      IF(OMEGAR.LE.0.5)THEN
C
C  CONVERTER IS IN DCM-2 MODE
C
      KLOSS=2
      OMEGAN=OMEGAR
      R1PR=2.*S*(1.+S*VON)/(1.+S**2)
      ILAVN=2.*OMEGAR*(1.-VON+2.*S+S**2+S**2*VON)/(PI*(1.+S**2))*S1
      VCPN=1.-VON+R1PR
      ILON=0.
      GOTO 22
      ENDIF
      IF(OMEGAR.EQ.1.)THEN
      OMEGAN=1.
      ALPHA=0.
      BETA=PI
      R1PRO=2.*(1.-VON)/(1.-S)
      RPR=R1PRO*S
      VCPN=(1.-VON)*(1.+S)/(1.-S)
      ILAVN=2.*(1.-VON)*(1.+S)/(PI*(1.-S))*S1
      IQAVN=VCPN/PI*S1
      IDAVN=0.
```

```
      VCON=VCPN
      ILON=0.
      GOTO 22
      ENDIF
      CALL RANGE(ZETA,VON,RPRMIN,RPRMAX)
      RPR=RPRMIN
      STEP3=(RPRMAX-RPRMIN)/2.
      DO 20 K=1,500
      CALL SER2(RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,R1PRO,
     #  VCON,ILON,ALPHA,BETA,KTOL)
      ERROR=OMEGAR-OMEGAN
      IF(ABS(ERROR).LT.1.E-04) GOTO 22
      CALL AGAIN1(ERROR,RPRMIN,RPRMAX,RPR,STEP3)
   20 CONTINUE
   22 RETURN
      END


      SUBROUTINE RANGE(ZETA,VON,RPRMIN,RPRMAX)
C
C  SUBROUTINE RANGE DETERMINES THE RANGE OF THE RADIUS RPR FOR CCM
C  WHEN THE DAMPING FACTOR ZETA AND NORMALIZED OUTPUT VOLTAGE Von
C  ARE KNOWN.
C  RPRMAX IS THE MAXIMUM RADIUS WHEN WN=1.
C  RPRMIN IS THE MINIMUM RADIUS WHEN WN=0.5, BOUNDARY BETWEEN CCM
C  AND DCM-2.
C
      PI=4.*ATAN(1.)
      S=EXP(-ZETA*PI/SQRT(1.-ZETA**2))
      RPRMIN=2.*S*(1.+S*VON)/(1.+S**2)
      RPRMAX=2.*S*(1.-VON)/(1.-S)
      RETURN
      END


      SUBROUTINE SER2(RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,
     #       R1PRO,VCON,ILON,ALPHA,BETA,KTOL)
C
C  THIS SUBROUTINE CALCULATES THE VARIOUS CIRCUIT PARAMETERS OF A CCM
C  EQUILIBRIUM TRAJECTORY OF SRC WHEN RADIUS RPR,OUTPUT VOLTAGE Von,
C  AND DAMPING FACTOR ZETA ARE GIVEN.
C  IT USES SUBROUTINES AGAIN1,RECT AND FUNCTION SUBPROGRAM A.
C
      IMPLICIT REAL(A-H,I,O-Z)
      PI=4.*ATAN(1.)
      IF(KTOL.EQ.1)THEN
      TOL=1.E-06
      ELSE
      TOL=1.E-04
      ENDIF
      APRMIN=0.
```

```
      APRMAX = PI
      ALPHPR = APRMIN
      STEP = PI/2.
      S1 = SQRT(1.-ZETA**2)
      S = -ZETA/SQRT(1.-ZETA**2)
      R2PRO = RPR-2.*VON
      DO 100 K = 1,100
      R2PR = (R2PRO/SQRT(1.-ZETA*SIN(2.*ALPHPR)))*
     #     EXP(S*(A(ALPHPR,ZETA)-A(0.,ZETA)))
      R1PRO = SQRT(R2PR**2 + 4. + 4.*R2PR*COS(ALPHPR))
      ABPR = (R2PR**2-R1PRO**2-4.)/(4.*R1PRO)
      IF(ABPR.LE.-1.) GOTO 70
      IF(ABPR.GE.1.) GO TO 80
      BPR = ACOS(ABPR)
      GOTO 90
   70 BPR = + 1.*PI
      GO TO 90
   80 BPR = 0.
   90 BPRO = PI-BPR
      R1PR = (R1PRO*SQRT(1.-ZETA*SIN(2.*BPRO)))*
     #     EXP(S*(A(PI,ZETA)-A(BPRO,ZETA)))
      ERROR = R1PR-RPR
      IF(ABS(ERROR).LT.TOL)GOTO 200
      CALL AGAIN1(ERROR,APRMIN,APRMAX,ALPHPR,STEP)
C     CALL AGAIN2(APRMIN,APRMAX,R1,R2,ALPHPR,W1,R1PR,RPR,K)
  100 CONTINUE
  200 ALPHA = A(ALPHPR,ZETA)-A(0.,ZETA)
      BETA = A(PI,ZETA)-A(BPRO,ZETA)
      OMEGAN = PI/(ALPHA + BETA)
      VCPN = 1.-VON + R1PR
      ILAVN = 2.*VCPN/(ALPHA + BETA)*S1
      XC = 1.-VON
      B1PRO = PI + BPRO
      CALL RECT(VCON,ILON,XC,0.,R1PRO,B1PRO,S1)
      IQAVN = (VCPN-VCON)/(2.*(ALPHA + BETA))*S1
      IDAVN = (VCPN + VCON)/(2.*(ALPHA + BETA))*S1
      RETURN
      END


      SUBROUTINE RECT(X,Y,XC,YC,R,A,S1)
      IMPLICIT REAL(A-H,I,O-Z)
      X = XC + R*COS(A)
      Y = (YC-R*SIN(A))*S1
      RETURN
      END


      FUNCTION A(APR,ZETA)
      PI = 4.*ATAN(1.)
      IF(ABS(APR-PI/2.).LT.1.E-03) GOTO 10
```

```
      A=ATAN(-ZETA/SQRT(1.-ZETA**2)+TAN(APR)/SQRT(1.-ZETA**2))
      IF(A.LT.0..AND.APR.GT.(PI/4.)) A=PI+A
      RETURN
   10 A=APR
      RETURN
      END


      SUBROUTINE AGAIN2(RMIN,RMAX,R1,R2,R,W1,W2,WN,K)
C
C  THIS SUBROUTINE ATTEMPTS TO IMPROVE CONVERGENCY BY CHOOSING R BY
C  LINEAR INTERPOLATION TECHNIQUE.
C
      IF(K.EQ.1) GOTO 11
      IF(ABS(W1-W2).GT.1.E-09) GOTO 10
      J=99999
      WRITE(*,*)RMIN,RMAX,R,W1,W2,J
      STOP
   10 R=R2+(R1-R2)*(WN-W2)/(W1-W2)
      STEP=(RMAX-RMIN)/5.
      RX=R2+STEP
      RY=R2-STEP
      IF(R.GT.RX) R=RX
      IF(R.LT.RY) R=RY
      IF(R.GT.RMAX) R=RMAX
      IF(R.LT.RMIN) R=RMIN
      R1=R2
      R2=R
      W1=W2
      RETURN
   11 R1=R
      R=RMIN+(RMAX-RMIN)/5.
      R2=R
      W1=W2
      RETURN
      END


      SUBROUTINE FIND4(ION,RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,
     #        R1PRO,VCON,ILON,ALPHA,BETA,KLOSS,KTOL)
C
C THIS SUBROUTINE IS USED TO FIND RPR AND OTHER CIRCUIT PARAMETERS WHEN
C Von, NORMALIZEDD OUTPUT CURRENT Ion, AND DAMPING FACTOR ZETA ARE GIVEN
C FOR A GIVEN Von AND ZETA, TRY DIFFERENT RPR's SUCH THAT SPECIFIED Ion
C IS REACHED.
C
      IMPLICIT REAL(A-H,I,O-Z)
      PI=4.*ATAN(1.)
      KLOSS=3
      S=EXP(-ZETA*PI/SQRT(1.-ZETA**2))
      S1=SQRT(1.-ZETA**2)
```

```
      ION = ION*S1
      IF(VON.GE.S)THEN
C
C   CONVERTER IS IN DCM-1 MODE
C
      KLOSS = 1
      OMEGAN = ION*PI*(1.-S)/(2.*(1.-VON)*(1. + S))
      ILAVN = ION
      R1PR = 2.*S*(1.-VON)/(1.-S)
      VCPN = 1.-VON + R1PR
      VCON = VCPN
      ILON = 0.
      IDAVN = 0.
      GOTO 24
      ENDIF
      IONDC2 = (1.-VON + 2.*S + S**2 + S**2*VON)/(PI*(1. + S**2))*S1
C   IONDC2 IS THE BOUNDARY INDUCTOR CURRENT BETWEEN CCM AND DCM-2 MODES
      IF(ION.LE.IONDC2)THEN
C
C   CONVERTER IS IN DCM-2 MODE
C
      KLOSS = 2
      OMEGAN = ION*PI*(1. + S**2)/(2.*(1.-VON + 2.*S + S**2 + S**2*VON))
      ILAVN = ION
      R1PR = 2.*S*(1. + S*VON)/(1. + S**2)
      VCPN = 1.-VON + P1PR
      GOTO 24
      ENDIF
      ILNMAX = 2.*(1.-VON)*(1. + S)/(PI*(1.-S))*S1
      IF(ION.EQ.ILNMAX)THEN
      OMEGAN = 1.
      ALPHA = 0.
      BETA = PI
      R1PRO = 2.*(1.-VON)/(1.-S)
      RPR = R1PRO*S
      VCPN = (1.-VON)*(1. + S)/(1.-S)
      ILAVN = ILNMAX
      IQAVN = VCPN/PI*S1
      IDAVN = 0.
      VCON = VCPN
      ILON = 0.
      GOTO 24
      ENDIF
      CALL RANGE(ZETA,VON,RPRMIN,RPRMAX)
      RPR = RPRMIN
      STEP3 = (RPRMAX-RPRMIN)/2.
      DO 20 K = 1,100
      CALL SER2(RPR,VON,ZETA,OMEGAN,VCPN,ILAVN,IQAVN,IDAVN,R1PRO,
     #  VCON,ILON,ALPHA,BETA,KTOL)
      ERROR = ION-ILAVN
```

```
      IF(ABS(ERROR).LT.1.E-04) GOTO 24
C      CALL AGAIN2(RPRMIN,RPRMAX,R1,R2,RPR,W1,ILAVN,ION,K)
       CALL AGAIN1(ERROR,RPRMIN,RPRMAX,RPR,STEP3)
   20 CONTINUE
   24 RETURN
      END
```

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