Discussion and Improvement on the Calculation of the Relationship between the Base Emitter of the Bipolar Junction Transistor and the Temperature by Using MATLAB Software

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Original Research Article

ABSTRACT

The purpose of this article is to explore and improve the effect of Bipolar Junction Transistor amplifier base-emitter on temperature changes. The prelude starts with Shockley's theory and its formula calculation. Research motivation, literature data and book principles cooperate with MATLAB application software skills to develop programs; it is used to calculate the relationship between various component parameters and temperature changes. The artificial calculation steps are too cumbersome and prone to clerical errors. Therefore, the program approach has been developed with report-style calculation results with both text and pictures. The feature of computer program calculation is the ability to compare and analyze the results produced at different temperatures, rapidly and repeatedly. The lack of known Bipolar Junction Transistors is replaced by Field Effect Transistors that are not affected by temperature. If the Bipolar Junction Transistor is used as the basis for the design, temperature changes must be considered to ensure the design quality. The purpose of this article is to introduce that the process of calculation has made the shift from an artificial-based way to a computer-based one.

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1. INTRODUCTION

Bipolar Junction Transistors have a place in the development of electronics. However, with the rapid development of technology and customer's requirements, the equipment has to operate in a high-quality and stable environment. Since, the AC emitter resistance value of the Bipolar Junction Transistor is affected by the surrounding temperature of the equipment, the amplifier related data, and such as voltage gain or low-frequency frequency response also drifts. In order to thoroughly understand the phenomenon, in the research process, if the relevant data is calculated with the way of artificial written, the accuracy of the data will be affected by clerical errors due to tedious steps. Therefore, a program algorithm has been developed to provide rapid and effective analysis of temperature changes and the result data has been presented in a report form. In addition to the introduction, the structure of this article has the following paragraphs, literature review, Bipolar Junction Transistor amplifier circuit, artificial calculation steps, application program calculation verification and analysis, improvement plan Field Effect Transistor amplifier and execution program, and conclusions.

2. LITERATURE REVIEW

There are countless books and journal articles published on the design of bipolar junction transistor amplifiers in the field of electrical and electronic engineering. This article only lists two basic electronics teaching books, some introduction to Shockley's theory on the Internet, and a few representative articles published on the use of MATLAB application software as a reference review.

Reference [1] is the Shockley theory, [2] and [3] are the explanations and application instructions of the basic textbooks of bipolar junction transistors; As for [4] and [5] are related to MATLAB software application reference and the examples in the textbooks [6,7] are based on the theoretical integration and application of actual transistor amplifier circuits are the blueprints for calculation and design. In [8], the author had introduced that the junction temperature estimation is obtained by the negative thermistor under dynamic conditions. As for [9,10], the junction temperature can be estimated by

obtaining the dynamic thermal reactance from the frequency response of the system. In [11] the MATLAB application software is used to estimate the junction temperature of the Bipolar Junction Transistor and the result has high accuracy and small error compared with the actual value. Integrate the essence of the above-mentioned documents and cooperate with the data of each component of the amplifier and the parameter value of the transistor. Design a report-style result that is easy to operate and understand, so start the research and development process steps as follows.

3. DESIGN PROGRAM

Continuing the literature data, and then developing computer programs to perform complex calculations to facilitate data collection; this chapter restates Shockley's theoretical equations to guide the calculation of the amplifier circuit and confirm the influence of temperature on the amplifier results.

3.1 Shockley Theory

The voltage and current of the Bipolar Junction Transistor between the base emitter and the emitter will change due to the temperature, which will affect the related results of the amplifier and then produce stability drift. So, the scholar Shockley proposed an explanatory equation for this phenomenon, such as Formula 1. With it, a curve program related to the temperature change and the AC emitter resistance value is developed, as shown in the Appendix program 1. If the temperature changes from 0°C to 50°C, the corresponding AC emitter resistance value is shown in Fig. 1.

$$I_E = I_R \cdot \left(e^{VQ/KT} - 1\right) \qquad (1)$$

When the temperature is 25°C, T is 298 (273+25), and Q/KT is equal to 38.9 in formula 1.

$\frac{dI_E}{dV} = 38.9 I_R e^{38.9}$ now that $I_R e^{38.9} = I_E + I_R$

$$\frac{dI_E}{dV} = 38.9(I_E + I_R)$$

Assuming $I_R \ll I_E$; $\frac{dI_E}{dV} \cong 38.9(I_E)$

The AC emitter resistance $r^{'}$ can be expressed as $\frac{dV}{dI_E}$, as in formula 2.

$$r^{'} = \frac{dV}{dI_E} = \left(\frac{1}{38.9}\right)/I_E = \frac{0.0257V}{I_E} \qquad (2)$$

3.2 Artificial Calculations Related Results for Bipolar Junction Transistor Amplifiers

Following the above-mentioned knowledge of the AC resistance between the emitters of the Bipolar Junction Transistor, the emitter current value of the transistor must be calculated first. So this article will explain the circuit diagram as shown in Fig. 2 with the actual operation of the transistor amplifier, and the relevant parameters are shown in Table 2. This paragraph will present the results of basic calculations based on artificial calculations at a temperature of 25°C — AC emitter resistance, voltage gain, low-

frequency and high-frequency response, etc. The artificial calculation steps are as follows:

$$V_B = \left(\frac{R_2}{R_1 + R_2}\right) \times V_S = 6.62\ V$$

$$V_E = V_B - 0.7V = 1.92\ V$$

$$I_E = \frac{V_E}{R_E} = \frac{1.92V}{1000\varOmega} = 1.92\ mA$$

$$r^{'} = \frac{0.0257V}{1.92mA} = 13.38\ \varOmega$$

$$R_{l(in)} = \frac{1}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{\beta_{ac} \times r^{'}}\right)} = 1.237\ K\varOmega$$

$$f_{lc(in)} = \frac{1}{2\pi\left(R_S + R_{l(in)}\right)C_1} = 773\ H_Z$$

Table 1. Symbol description of the Shockley equation

Symbol	Explanation
I_E	Current for base-emitter junction forward
$I_R{}'$	Reverse saturation current for base-emitter junction
V	The voltage drop across the depletion of the base-emitter junction
Q	The charge of the electron (ev)=1.602*10.^-19 Coulomb
K	Boltzmann constant =1.380649*10.^-23 Joule / Coulomb
T	Absolute temperature=(273 + T °C)
$r^{'}_e$	Base-emitter junction AC impedance (dV/dI$_E$)
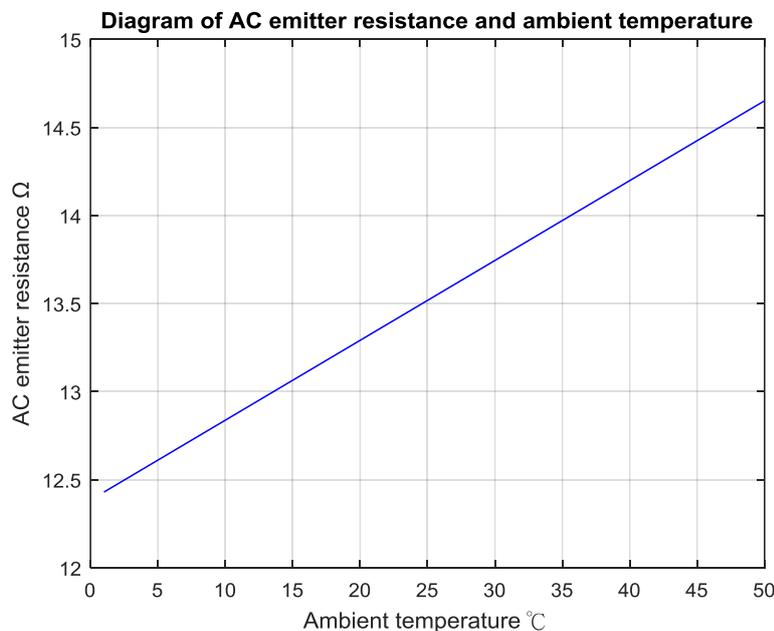
Fig. 1. The relationship between AC emitter resistance and temperature change

Table 2. Related parameters of Bipolar Junction Transistor amplifier circuit

Symbol	T	Vs	R₁	R₂	RE	Rc	RL	Rs	C₁	C₂	C₃	Cbe	Cbc	βac
Data	25°C	10V	62K	22K	1K	2.2K	10K	600Ω	0.1uf	10uf	0.1uf	20pf	2.4pf	100
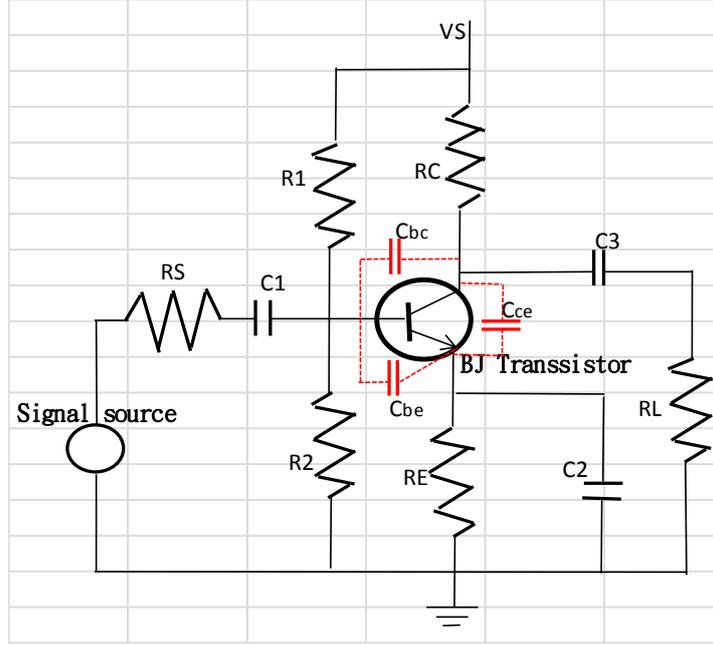
Fig. 2. Bipolar Junction transistor amplifier circuit

$$R_{l(th)} = \frac{1}{\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_S}\right)} = 579\ \Omega$$

$$R_{l(emitter)} = \frac{R_{l(th)}}{\beta_{ac}} + r' = 19.17\ \Omega$$

$$f_{lc(pass)} = \frac{1}{2\pi\left(\frac{1}{\left(R_{l(emitter)}\right)}+\frac{1}{R_E}\right)C_2} = 747\ H_Z$$

$$f_{lc(out)} = \frac{1}{2\pi(R_L+R_C)C_3} = 130\ H_Z$$

$$Av_{(mid)} = \frac{\frac{1}{\left(\frac{1}{R_C}+\frac{1}{R_L}\right)}}{r'} = 134$$

$$\text{Attenuation rate} = \frac{\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{\beta_{ac}\times r'}\right)}{R_S+\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{\beta_{ac}\times r'}\right)}$$
$$= 0.67$$

$$Av_{(tot)} = Av_{(mid)} \times 0.67 = 91.12$$

$$C_{hin(Miller)} = C_{be}\left(Av_{(tot)}+1\right) = 1842\ pf$$

$$C_{hin(tot)} = C_{hin(Miller)} + C_{bc} = 1844.4\ \text{pf}$$

$$R_{h(in)} = \frac{1}{\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{\beta_{ac}\times r'}+\frac{1}{R_S}\right)} = 404\ \Omega$$

$$f_{hc(in)} = \frac{1}{2\pi R_{h(in)}C_{hin(tot)}} = 21.36\ MH_Z$$

$$C_{hout(Miller)} = C_{bc}\left(\frac{Av_{(tot)}+1}{Av_{(tot)}}\right) = 2.43\ \text{pf}$$

$$R_{hc} = \frac{1}{\left(\frac{1}{R_C}+\frac{1}{R_L}\right)} = 1805\ \Omega$$

$$f_{hc(out)} = \frac{1}{2\pi R_{hc}C_{hout(Miller)}} = 36.80\ MH_Z$$

The complicated calculation steps − AC emitter resistance, amplifier gain, low-frequency and high-frequency input and output frequency response and other related data been completed finally. During the calculation process, clerical errors will affect the accuracy of the relevant data.

```
*****************************************************************
         Related data in the Bipolar Junction Transistor amplifier circuit
              X=[T|Vₛ|R₁|R₂|Rₑ|R꜀|Rₗ|Rₛ|C₁|C₂|C₃|Cbe|Cbc|βac];
   X= [25 10 62*10.^3 22*10.^3 1*10.^3 2.2*10.^3 10*10.^3 600 0.1*10.^-6 10*10.^-6 0.1*10.^-6
                    20*10.^-12 2.4*10.^-12 100]
              AC emitter resistance Ω: X3 =   13.3897
              Low frequency input frequency Hz: ans =   866
           Low frequency input bypass frequency Hz: ans =   846
              Low frequency output frequency Hz: ans =   130
                    Av total gain: ans =   90
              High frequency input frequency Hz:ans =   214645
           High frequency output frequency Hz: ans =   36391804
*****************************************************************
```

Fig. 3. Bipolar Junction Transistor execution results at low frequency and high frequency at 25°C

3.3 Program Design Bipolar Junction Transistor

After the above-mentioned artificial calculation steps, the process is very cumbersome and easy to cause clerical errors and affect accuracy, leading to data distortion.

In order to prevent the defects of artificial calculation, a computer program algorithm was developed to replace artificial work, thereby shortening calculation time and improving efficiency and accuracy. This program will integrate Shockley's equations and artificial algorithm programs into MATLAB application software. It only needs to establish parameter input methods and calculation skills and cooperate with grammar to integrate into a simple, accurate and time-saving calculation tool.

The computer programs only perform in the MATLAB application software operating environment of the personal computer, after those parameters are keyed in (such as the attached program 2). This alone can accurately calculate the AC emitter resistance, voltage gain,

low and high-frequency response results, as shown in Fig. 3.

4. VERIFICATION AND ANALYSIS

From the parameter values of the relevant components in the Bipolar Junction Transistor amplifier circuit in Fig. 2, key in the development program to accurately calculate the relevant results. In order to verify the example, the result data obtained at a temperature of 25°C is shown in Fig. 3; In addition, the data obtained from three different temperatures of 0°C, 25°C, and 50°C are cited, and taking few key items are selected for comparative analysis, as shown in Table 3. The comparison percentage is the ratio of 0°C to 50°C.

From the MATLAB program and the artificial calculation results, the relevant data are roughly consistent, and then the feasibility of the program is proved. However, its characteristic is that the "Shockley theory" is executed by a program to analyze the relationship between its base emitter voltage, emitter current and temperature, and it is found that the temperature rise is proportional to the AC emitter resistance, as shown in Fig. 1.

Table 3. Comparison of results of transistor amplifier circuit at different temperatures

Name \ Temperature	0°C	25°C	50°C	Comparison%
Base-emitter voltage value	0.023	0.025	0.027	18
AC emitter resistance Ω	12.26	13.38	14.51	18
Low frequency input frequency Hz	914	866	824	-9.8
Low frequency output frequency Hz	130	130	130	0
Total gain	96	90	85	-11
High frequency input frequency MHz	0.21	0.21	0.21	0
High frequency output frequency MHz	36.4	36.39	36.36	-0.13

Table 4. Comparison and analysis of important items and temperature

Name	Explanation
Base-emitter voltage value	The temperature rises proportionally
AC emitter resistance	The temperature rises proportionally
Low frequency input frequency	Temperature rises in inverse proportion
Low frequency output frequency	Temperature rise data unchanged
Total gain	Temperature rises in inverse proportion
High frequency input frequency	Temperature rise data unchanged
High frequency output frequency	Temperature rise data unchanged

In addition, take the results of three different temperature data, as shown in Table 3, select important items and temperature changes for comparative analysis, as shown in Table 4. The overall program calculation can be executed repeatedly, not afraid of clerical errors in complicated calculations, and can graphically show the impact of temperature changes on the Bipolar Junction Transistor amplifier.

5. IMPROVEMENT

According to the above description, it is known that the operation of the Bipolar Junction Transistor will affect its stability and frequency response with temperature changes. In order to overcome this deficiency, a Field Effect Transistor will be used to replace it. This paragraph will use Shockley's theoretical formula, such as formula 3, to find the I_D from the known parameter I_{DSS} and V_P values, then formula 4 and formula 5 are used to compile the program in sequence. Taking a Field Effect Transistor (FET) amplifier circuit diagram and related, parameters execute the program and display the calculation results in graphs.

5.1 Artificial Calculations Related Results for Field Effect Transistor Amplifier

In order to demonstrate and narrate, a Field Effect Transistor amplifier circuit is specially used, as shown in Fig. 4 and related component parameter values, as shown in Table 5. Following the artificial calculation procedure in [7], the steps are as follows: There are three important formulas, such as formulas 3, 4, and 5. then follow the above method to calculate the steps and input the parameters of the Field Effect Transistor amplifier circuit components, and complete the computer programming with MATLAB software technology.

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2 \tag{3}$$

$$g_{mo} = \frac{2I_{DSS}}{|V_P|} \tag{4}$$

$$g_m = g_{mo}\left(1 - \frac{V_{GSQ}}{V_P}\right) \tag{5}$$

$$R_i = R_G = 1\,M\Omega$$

$$f_{LG} = \frac{1}{2\pi(R_{sig} + R_i)C_G} = 15\,H_Z$$

$$R_O \cong R_D = 4.7\,K\Omega$$

$$f_{LC} = \frac{1}{2\pi(R_O + R_L)C_C} = 46\,H_Z$$

$$R_{eq} = \frac{1}{\left(\frac{1}{R_S} + \frac{1}{1/g_m}\right)} = 333\,\Omega$$

$$f_{LS} = \frac{1}{2\pi R_{eq}C_C} = 238\,H_Z$$

$$Av_{(mid)} = -g_m\frac{R_D * R_L}{R_D + R_L} = -2.99$$

$$R_{THi} = \frac{R_{sig} * R_G}{R_{sig} + R_G} = 9.9\,K\,\Omega$$

$$C_{Mi} = \left(1 - Av_{(mid)}\right) * C_{gd}$$

$$C_i = C_{Wi} + C_{gs} + C_{Mi}$$

$$f_{Hi} = \frac{1}{2\pi R_{THi}C_i} = 893\,KH_Z$$

$$R_{THo} \cong \frac{R_D * R_L}{R_D + R_L} = 1.5\,K\,\Omega$$

$$C_{Mo} = \left(1 - \frac{1}{Av_{(mid)}}\right) * C_{gd}$$

$$C_o = C_{Wo} + C_{ds} + C_{Mo}$$

$$f_{Ho} = \frac{1}{2\pi R_{THo}C_o} = 13010\,KH_Z$$

Table 5. Field effect transistor amplifier circuit related parameters

Symbol	V_{DD}	R_{SIG}	R_G	R_D	R_S	R_L	C_G	C_C	C_S	C_{gd}	C_{gs}	C_{ds}	C_{wo}	C_{wi}	I_{DSS}	V_P	V_{GSQ}
Data	20	10K	1M	4.7K	1K	2.2K	0.01uf	0.5uf	2uf	2pf	4pf	0.5pf	5pf	6pf	8mA	- 4	- 2
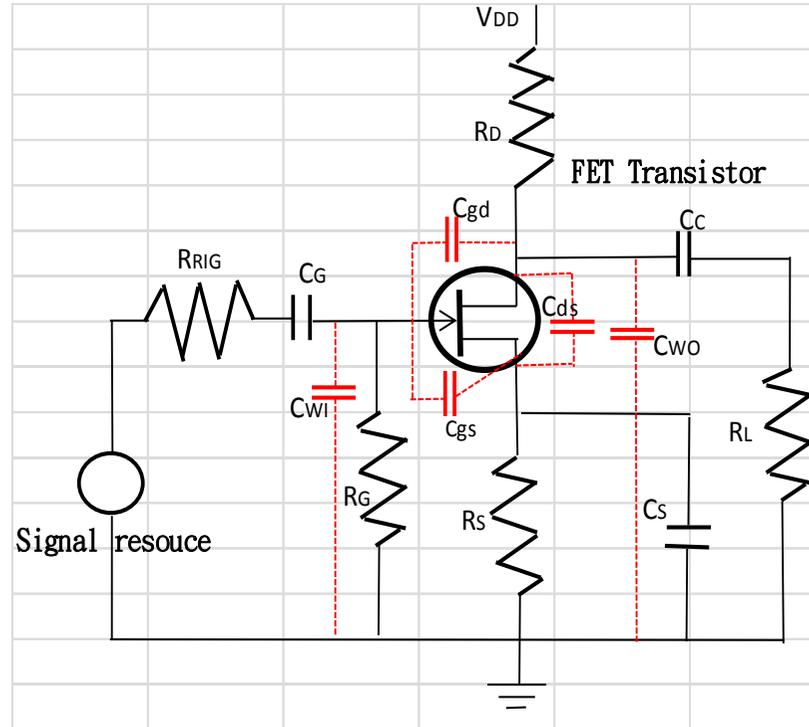
Fig. 4. Field effect transistor amplifier circuit

```
****************************************************************
Related data in the Field Effect Transistor amplifier circuit
X=[V_DD|R_S|G|R_G|R_D|R_S|R_L|C_G|C_C|C_S|Cgd|Cgs|Cds|Cwo|Cwi|ID_SS|V_P|Vgsq];
X=[20 10*10.^3 1*10.^6 4.7*10.^3 1*10.^3 2.2*10.^3 0.01*10.^-6 0.5*10.^-6 2*10.^-6 2*10.^-12 4*10.^-
12 0.5*10.^-12 5*10.^-12 6*10.^-12 0.008 -4 -2]
Low frequency input frequency Hz: ans =    15
Low frequency output frequency Hz: ans =    46
Low frequency input bypass frequency Hz: ans = 238
Av gain: X8 =  -2.9971
High frequency input frequency KHz: ans =    893
High frequency output frequency KHz: ans =  13010
****************************************************************
```

Fig. 5. Field effect transistor gain and low-frequency and high-frequency execution results

5.2 Program Design for Field Effect Transistor

The execution program will be compiled, as shown in Appendix program 3, in the MATLAB software operating environment of the personal computer, key in the corresponding parameters in sequence. The result is shown in Fig. 5.

6. CONCLUSION

This article uses "Shockley's theory" to explore the stability of amplifier operation based on the relationship between the voltage and temperature of the Bipolar Junction Transistor between the base and the emitter. The description explains that the advantages of program calculations can avoid the trouble caused by human clerical errors. Its biggest feature is that it can repeatedly and quickly calculate and display the temperature change result data in the report. The operation is simple and only needs to input the components and related parameters in program. The collector load resistance of the Bipolar Junction Transistor has a great influence on the emitter current and the low and high frequency output frequency. Therefore, the load resistance in the amplifier circuit must be carefully calculated from the two values of R_C and R_L. Following the relationship between the Shockley equations 3 and 5 used in the Field Effect Transistor and the input circuit involved, the low and high frequency output frequency response must be carefully obtained. The most important point is that the temperature-dependent shortcomings of Bipolar Junction Transistor amplifiers can be improved by Field Effect Transistors. These computer programming algorithms are helpful to engineers and students in electrical engineering and electronics and related fields in research and design.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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APPENDIX

Program 1:

```
clear;
x=zeros(1,50);
for i=1:50
x(i)= (1/((1.602*10.^-19)/((273.15+i)* 1.38*10.^-23)))*1000
end
x1=x/1.9;
disp(x1)
plot(x1, 'b')
grid on
title('Diagram of AC emitter resistance and ambient temperature')
xlabel('Ambient temperature °C')
ylabel('AC emitter resistance Ω')
```

Program 2:

```
clear all  % 28/07 2021
fprintf('****************************************************************\n')
fprintf ('Related data in the Bipolar Junction Transistor amplifier circuit')
X=input ('X=[T|Vs|R₁|R₂|RE|RC|RL|Rs|C₁|C₂|C₃|Cbe|Cbc|βac];\n X= ');
A=1.602*10.^-19;
B= 1.380649*10.^-23;
C= (273.15+ X (1))*B;
D = A/C;
E = (1/D);
X1=(X(4)/(X(3)+X(4)))*X(2);
X2=(X1-0.7)/X(5);
fprintf ('AC emitter resistance Ω')
X3=E/X2
X4=1/(1/X(3)+1/X(4)+1/(X3*X(14)));  %
fprintf ('Low frequency input frequency Hz')
X5=1/(6.28*(X4+X(8))*X(9));
fix(X5)   %
X6=1/(1/X(3)+1/X(4)+1/X(8));
X7=X6/X(14)+X3;
fprintf ('Low frequency input bypass frequency Hz')
X8=1/(6.28*(1/(1/X7+1/X(5)))*X(10));
fix(X8)   %
fprintf ('Low frequency output frequency Hz')
X9=1/(6.28*(X(6)+X(7))*X(11));
fix(X9)   %
X10=(1/(1/X(6)+1/X(7)))/X3;
fix(X10);
X11=1/(1/X(3)+1/X(4)+1/(X(14)*X3))/(X(8)+(1/(1/X(3)+1/X(4)+1/(X(14)*X3))));
fprintf ('Av total gain')
X12=X11*X10;
fix(X12) %
X13=X(12)*(X12+1);
X14=X13+X(13);
X15= 1/(1/X(3)+1/X(4)+1/X(8)+1/(X(14)*X3));
fprintf ('High frequency input frequency Hz')
X16=1/(6.28*X15*X14);
fix(X16)
X17=X(13)*((X12+1)/X12);
```

```
X18=(1/(1/X(6)+1/X(7)));
fprintf ('High frequency output frequency Hz')
X19=1/(6.28*X18*X17);
fix(X19)
fprintf('****************************************************************\n')
```

Program 3:

```
clear all  % 11/08 2021
fprintf('****************************************************************\n')
fprintf ('Related data in the Field Effect Transistor amplifier circuit')
X=input ('X=[V_DD|R_SIG|R_G|R_D|R_S|R_L|C_G|C_C|C_S|C_gd|C_gs|C_ds|C_wo|C_wi|I_DSS|V_P|V_gsq];\n X=');
syms X1
S=solve(X(15)*(1-(X1*X(5)/X(16)).^2-X1),X1);
S1=min(S);
X1=2*X(15)/abs(X(16)); %gmo
X2=X1*(1-(X(17)/X(16))); %gm
fprintf ('Low frequency input frequency Hz')
X3=1/(6.28*(X(2)+X(3))*X(7));
fix(X3)   %
fprintf ('Low frequency output frequency Hz')
X4=1/(6.28*(X(4)+X(6))*X(8));
fix(X4)
X5=(X(5)*(1/X2))/(X(5)+(1/X2));
fprintf ('Low frequency input bypass frequency Hz')
X6=1/(6.28*X5*X(9));
fix(X6)   %
fprintf ('Av gain')
X7=(X(4)*X(6))/(X(4)+X(6));  % Rth
X8=-X2*X7
X9=(X(2)*X(3))/(X(2)+X(3));  % Rth
X10=X(14)+X(11)+(1-(X8))*X(10); % CI
fprintf ('High frequency input frequency KHz')
X11=(1/(6.28*X9*X10));
X12=X11/10.^3;
fix(X12)
X13=X(13)+X(12)+X(10)*(1-1/X8);  % C_O
fprintf ('High frequency output frequency KHz')
X14= (1/(6.28*(X(4)*X(6)/(X(4)+X(6)))*X13))/10.^3;
fix(X14)
fprintf('****************************************************************\n')
```