Floating Admittance Matrix Modelling Approach to BJT

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Abstract: **The floating admittance matrix (FAM) approach is an elegant method that provides unified approach to analysis of different terminal functions such as impedances, and gains or ratios of voltages, currents and powers of both active and passive network with ease. The zero sum property of the floating admittance matrix provides a check to the researchers to proceed further or re observe the first equation itself. All transfer functions are represented as cofactors of the floating admittance matrix of the circuit.**

Key words: **Amplifier, Common emitter, Floating Admittance Matrix, Zero Sum property, Cofactors.**

I. INTRODUCTION

The well-known conventional and convenient low frequency model of the BJT is h-parameter and hybrid-πmodel. For the purpose of deriving the floating admittance model (FAM) of the BJT, the h-parameters model is considered [1-18]. The same floating admittance matrix is used for the derivation of its voltage gain, current gain, and power gain, input impedance and output impedance of BJT amplifier in any of its three configurations to demonstrate the beauty and superiority this approach[22-24].

If any one of the three terminals of a BJT is taken common to both of its input and output sides, then it can be assumed as four terminal of two port network as indicated in Fig. 1. Here, the emitter terminal is common to both input and output sides. The base, collector and emitter terminals have been assigned digital numbers 1, 2, and 3 respectively to be used in the derivation of the floating admittance matrix of the BJT.

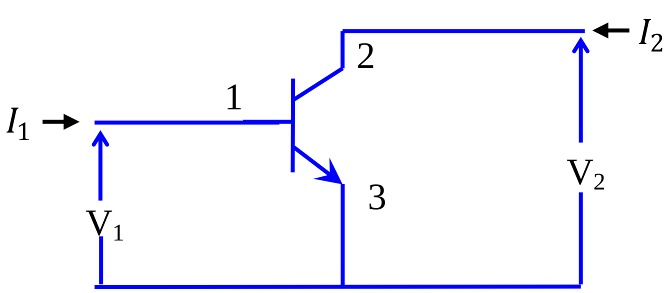

Fig. 1 BIT as Two Port Network

The four variables in Fig. 1 are defined as the base voltage ($V_B = V_1$), the collector voltage ($V_C = V_2$), the input (base) current ($I_B = I_1$, and the output current ($I_C = I_2$). Out of these four variables any two variables can be assumed to be independent variables, then the other two variable become dependent of these independent variables. The selection of independent and dependent variables leads to the various types of parameter representation of the BJT. A few among these representations are;

- Impedance parameters

$$(V_1 = f_1(I_1,\ I_2) \& V_2 = f_2(I_1,\ I_2) \tag{1}$$

- Admittance parameters,

$$(I_1 = f_1(V_1,\ V_2) \& I_2 = f_2(V_1,\ V_2) \tag{2}$$

- Hybrid parameters etc.

$$(V_1 = f_1(I_1,\ V_2) \& I_2 = f_2(I_1,\ V_2) \tag{3}$$

Since the hybrid parameter model of the BJT is the normally used at low frequency to analyze its characteristics, we have to select the independent variable in the mixed mode of voltages and currents. For the purpose, let the input current$I_B = I_1$ and the output voltage $V_2 = V_C = V_{23}$ of the two port network shown in Fig.1 are selected as the independent variables; then the input voltage $V_1 = V_B = V_{13}$and the output current $I_C = I_2$ become the dependent variables and they can be represented mathematically as;

$$V_{13} = f_1(I_1,\ V_{23}) \tag{4}$$

$$I_2 = f_2(I_1,\ V_{23}) \tag{5}$$

The input voltage (V_{13}) from Eq. (4) partially dependence on the input currentI_1 and partially on the output voltage V_{23}.Similarly, the output current I_2 partially depends on the input current I_1 and partially on the output voltage V_{23}.The effect of partial variations in the independent variables I_1 and V_{23} would result into the total variations in the dependent variables V_{13} and I_2 in Eqs. (4) and (5). Hence, these equations can be represented by partial differential equations as;

$$\delta V_{13} = \frac{\partial V_{13}}{\partial I_1}\Delta I_1\bigg|_{V_{23}=k} + \frac{\partial V_{13}}{\partial V_{23}}\Delta V_{23}\bigg|_{I_1=k} = \left(\frac{v_{13}}{i_1}\right) i_1 + \left(\frac{v_{13}}{v_{23}}\right) v_{23} \tag{6}$$

$$\delta I_2 = \frac{\partial I_2}{\partial I_1}\Delta I_1\bigg|_{V_{23}=k} + \frac{\partial I_2}{\partial V_{23}}\Delta V_{23}\bigg|_{I_1=k} = \left(\frac{i_2}{i_1}\right) i_1 + \left(\frac{i_2}{v_{23}}\right) v_{23} \tag{7}$$

In Eq. (6), the ratio $\frac{v_{13}}{i_1}$ is the small change in input port voltage to the small change in input port current which is defined as the self-port (input) resistance or input impedance. Hence, it is replaced by r_{11} or r_i having dimension of resistance (Ω). The ratio $\frac{v_{13}}{v_{23}}$ is the small change in the input-port voltage to the small change in the output-port voltage. Hence, it is called the reverse voltage ratio of input voltage to the output voltage and written as a_{12} (dimensionless quantity). Similarly, the ratio $\frac{i_2}{i_1}$ from Eq. (7) is the of small change in the output-port current to the small change in input-port current and hence called forward current ratio or gain and is represented as a_{21}(dimensionless quantity). The ratio $\frac{i_2}{v_{23}}$ is the small change in the output-port current to the small change in the output-port voltage and hence called self-port output conductance or resistance and represented as $g_{22} = g_o$(Siemen=S).

Assuming Δ = ∂ and also that the small changes in static voltages (V_{13}, V_{23}) and currents (J_1, I_2) result in small signals voltages (v_{13}, v_{23}) and currents (i_1, i_2). Eqs. (6) and (7) reduce to

$$v_{13} = (r_{11})i_1 + (a_{12})v_{23} = (r_i)i_1 + (a_{12})v_{23} \qquad (8)$$

$$i_2 = (a_{21})i_1 + (g_{22})v_{23} = (a_{21})i_1 + (g_o)v_{23} \qquad (9)$$

It is evident from Eqs. (8) and (9) that the dimensions of the 4-parameters $r_{11} = r_i$, a_{12}, a_{21}, and $g_{22} = g_o$ are different. Here, $r_{11} = r_i$ has the dimension of resistance (Ω), the parameters a_{12} and a_{21} are dimensionless, and $g_{22} = g_O$ has the dimension of conductance (Siemen =S). Since all 4-parameters are of different dimensions, it is called hybrid parameter. All the hybrid parameters are represented by letter h and Eqns. (8) and (9) are now expressed as;

$$v_{13} = (h_{11})i_1 + (h_{12})v_{23} = (h_i)i_1 + (h_r)v_{23} = (\frac{1}{g_i})i_1 + (h_r)v_{23} \qquad (10)$$

$$i_2 = (h_{21})i_1 + (h_{22})v_{23} = (h_f)i_1 + (h_O)v_{23} \qquad (11)$$

Equation (10) suggests that the input voltage v_{13} across input port of Fig. 1 is equated as the sum of a voltage drop across the resistance/ impedance (r_{11} or h_i) produced by the flow of the input current (i_1) through and the output voltage (v_{23}) controlled voltage source equal to $(h_r)v_{23}$ as in Fig. 1. This is the internal feedback part of voltage from output side to the input side of the BJT. Similarly, Eq.(11) suggests that the output current i_2 is sum of two current sources $(h_f)i_1$ and $(h_O)v_{23}$. The 1st current source $(h_f)i_1$ is the input current (i_1) controlled current source and the 2nd current source $(h_O)v_{23}$ is the output voltage (v_{23}) controlled current source. With the help of these statements, Eqns. (10) and (11) can be arranged in the form of a circuit as shown in Fig.2.

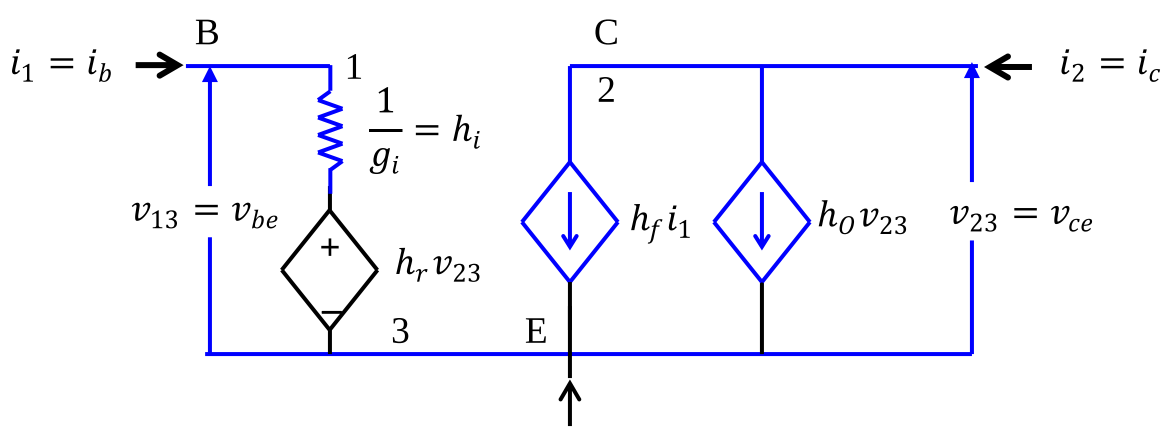

Fig. 2 Two Port mathematical model of BJT

II. FLOATING ADMITTANCE MATRIX OF THE BJT [19-23]

In order to dwell upon the floating admittance model of the BJT, we would like to convert the h-parameter model into the conductance parameters model of the BJT. Since, the current source $(h_{22})v_{23}$ in Fig. 2 appears across the self-output port voltage v_{23}, it can be replaced by an admittance of $h_{22}\left(= h_{22}\frac{v_{23}}{v_{23}}\right) = h_O = g_O$. Fig. 2 simplifies to Fig. 3 using these statements.

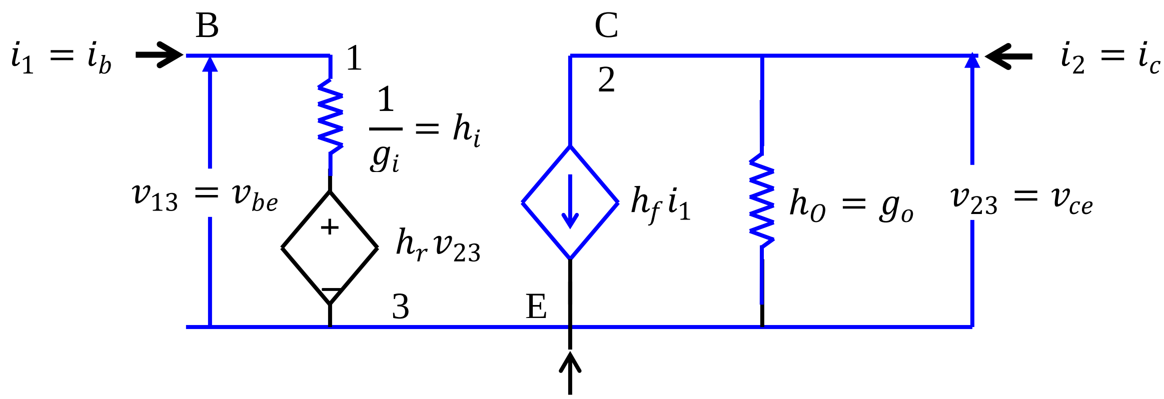

Fig. 3 h-parameter model of BJT

In Fig. 3, the output voltage v_{13} is the potential difference between terminals 1 and 3 and voltage v_{23} is the potential difference between terminal voltage 2 and 3. Hence, it is written as;

$v_{13} = v_1 - v_3 = v_{be} = v_b - v_e$ and $v_{23} = v_2 - v_3 = v_{ce} = v_c - v_e$; (12)

Substituting these values of v_{13} and v_{23} from Eq. (12) in Eqs.(10) and (11) yield

$$v_{13} = v_1 - v_3 = h_{ie} i_1 + h_{re}(v_2 - v_3)$$

$$h_{ie} i_1 = v_1 - v_3 - h_{re}(v_2 - v_3) = v_1 - h_{re} v_2 - (1 - h_{re}) v_3$$

$$i_1 = \frac{1}{h_{ie}} v_1 - \frac{h_{re}}{h_{ie}} v_2 - \left(\frac{1}{h_{ie}} - \frac{h_{re}}{h_{ie}}\right) v_3 \quad (13)$$

$$i_2 = (h_{fe}) i_1 + (h_{Oe})(v_2 - v_3) = (h_{fe}) i_1 + (h_{Oe}) v_2 - (h_{Oe}) v_3 \quad (14)$$

Substituting h-parameter in the form of conductance parameters as;

$$g_i = \frac{1}{h_i}, g_r = \frac{h_r}{h_i} = g_i h_r, g_m = \frac{h_f}{h_i} = g_i h_f,\ h_o = g_O \quad (15)$$

Equation (13) and (14) are simplified by substituting Eq. (15) in them as;

$$i_1 = g_i v_1 - g_i h_r v_2 - g_i (1 - h_r) v_3 \quad (16)$$

Substituting the value of i_1 from Eq.(16) in Eq.(14) yields

$$i_2 = h_{fe} g_i v_1 - h_{fe} g_i h_r v_2 - h_{fe} g_i (1 - h_r) v_3 + (h_{Oe})(v_2 - v_3)$$

$$i_2 = g_m v_1 + (g_O - g_m h_r) v_2 - \{g_O + g_m (1 - h_r)\} v_3 \quad (17)$$

From Fig. 3, $i_1 + i_2 + i_3 = 0$ (18)

$$i_3 = -i_1 - i_2$$

$$= -(g_i + g_m) v_1 - \{g_O - (g_m + g_i) h_r\} v_2 - \{g_O + (g_m + gi)(1-hr) v3 \quad (19)$$

Equations (16), (17) and (19) have been derived without considering any reference or ground point.

Now Eqns. (16), (16) and (19) are arranged in the form of matrix as;

$$\begin{bmatrix} i_1 = i_b \\ i_2 = i_c \\ i_3 = i_e \end{bmatrix} = \begin{bmatrix} g_i & -g_i h_r & -g_i (1 - h_r) \\ g_m & g_o - g_m h_r & -g_o - g_m (1 - h_r) \\ -g_i - g_m & -g_o + (g_m + g_i) h_r & g_o + (g_m + g_i)(1 - h_r) \end{bmatrix} \begin{bmatrix} v_1 = v_v \\ v_2 = v_c \\ v_3 = v_e \end{bmatrix} \quad (20)$$

The typical values of these h-parameters of any BJT at low frequencies are assumed to be as;

$$g_{ie} = 1mS, h_{re} = 10^{-4}, h_{fe} = 100, h_{oe} = g_o = 10^{-6}S = 0.001mS, g_m = 100mS,$$

$g_{ie} h_{re} = 0.0001mS, g_m h_r = 100mSx10^{-4} = 10^{-5}S = 0.01mS,$

$g_i (1 - h_r) = 1mS(1 - 0.0001) = 0.9999mS,\ g_o - g_m h_r = 0.001 - 0.01 = 0.009mS$

After substituting these parameter values, Eq. (20) reduces to

$$\begin{bmatrix} i_1 = i_b \\ i_2 = i_c \\ i_3 = i_e \end{bmatrix} = \begin{bmatrix} 1 & -0.0001 & -0.9999 \\ 100 & 0.001 - 0.01 & -0.001 - 100x(0.9999) \\ -101 & -0.001 + (101)0.0001 & 0.001 + (101)(0.9999) \end{bmatrix} \begin{bmatrix} v_1 = v_v \\ v_2 = v_c \\ v_3 = v_e \end{bmatrix}$$

$$\begin{bmatrix} i_1 = i_b \\ i_2 = i_c \\ i_3 = i_e \end{bmatrix} = \begin{bmatrix} 1 & -0.0001 & -0.9999 \\ 100 & -0.0090 & 99.991 \\ -101 & 0.0091 & 100.9909 \end{bmatrix} \begin{bmatrix} v_1 = v_v \\ v_2 = v_c \\ v_3 = v_e \end{bmatrix} \quad (21)$$

We observe from Eq. (21) that the algebraic sum of all elements of any row or any column is zero. This verifies the zero sum property of the floating admittance matrix.

Now we would like to demonstrate the advantages of floating admittance matrix approach to the circuits analysis in different configurations of amplifiers containing BJTs in particular using the floating admittance model of the BJT derived in Eq. (21).

III. COMMON EMITTER AMPLIFIER CONFIGURATION [20-23]

The first assumption in the analysis of common emitter amplifier (CE) configuration is that the BJT is biased in the linear region of operation. The second assumption is that the external resistances used in biasing the BJT in the linear region are much larger than the small signal resistances of the BJT. The third assumption is that all bypass and coupling capacitors and the DC supply voltage (s) behave as short circuits at the signal frequency of operation. Hence, in all three configurations to follow, only source and load resistances would be considered in deriving different equations, for simplicity as in Fig. 4.

The coefficient matrix in Eq. (20) is called the floating admittance matrix for a 3-terminal BJT and is separated from it as;

$$\begin{bmatrix} g_i & -g_i h_r & -g_i(1-h_r) \\ g_m & g_o - g_m h_r & -g_o - g_m(1-h_r) \\ -g_i - g_m & -g_o + (g_m + g_i)h_r & g_o + (g_m + g_i)(1-h_r) \end{bmatrix} \quad (22)$$

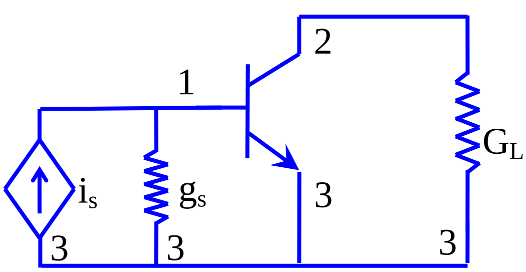

Fig. 4 Common Emitter Amplifier

The floating admittance matrix of external source and load conductance g_s and G_L of Fig. 4 are expressed as;

$$\begin{array}{ccc} 1 & 2 & 3 \\ \end{array} \qquad \begin{array}{ccc} 1 & 2 & 3 \\ \end{array}$$

$$\begin{bmatrix} g_s & 0 & -g_s \\ 0 & 0 & 0 \\ -g_s & 0 & g_s \end{bmatrix}\begin{matrix} 1 \\ 2 \\ 3 \end{matrix} \text{ and } \begin{bmatrix} 0 & 0 & 0 \\ 0 & G_L & -G_L \\ 0 & -G_L & G_L \end{bmatrix}\begin{matrix} 1 \\ 2 \\ 3 \end{matrix} \quad (23)$$

Merging Eqs.(22) and (23) as per its node number yields the floating admittance matrix of Fig. 4 as;

$$\begin{bmatrix} g_i + g_s & -g_i h_r & -g_i(1-h_r) - g_s \\ g_m & g_o - g_m h_r + G_L & -g_o - g_m(1-h_r) - G_L \\ -g_i - g_s - g_m & -g_o + (g_i + g_m)h_r - G_L & g_o + (g_i + g_m)(1-h_r) + g_s + G_L \end{bmatrix} \quad (24)$$

The input impedance or input resistance between terminals 1 and 3 of Fig. 4 is expressed in terms of co-factors of Eq. (24) as;

$$Z_{in} = Z_{13} = \frac{|Y_{13}^{13}|}{|Y_3^3|}\Big|_{g_s=0} \quad (25)$$

Similarly, the output impedance or output resistance between terminals 2 and 3 of Fig. 4 is expressed in terms of co-factors of Eq. (24) as;

$$Z_o = Z_{23} = \frac{|Y_{23}^{23}|}{|Y_3^3|}\Big|_{G_L=0} \quad (26)$$

The voltage gain between terminals 2 & 3 and 1 & 3 of Fig. 4 is expressed in terms of co-factors of Eq. (24) as;

$$A_v|_{13}^{23} = \frac{v_{23}}{v_{13}} = sgn(2-3)sgn(1-3)(-1)^{2+3+1+3}\frac{|Y_{23}^{13}|}{|Y_{13}^{13}|} \quad (27)$$

The current gain of Fig. 4 is expressed in terms of co-factors of Eq. (24) as;

$$A_i|_{13}^{23} = \frac{v_{23}}{v_{13}} = sgn(2-3)sgn(1-3)(-1)^{2+3+1+3}\frac{|Y_{23}^{13}|}{|Y_3^3|}G_L \quad (28)$$

The power gain is obtained as the multiplication of the voltage and the current gains as;

$$A_p\Big|_{13}^{23} = (A_v|_{13}^{23})(A_i|_{13}^{23}) \quad (29)$$

The pertinent first order and second order cofactors are evaluated from Eq. (24) for subsequent use in deriving the mathematical equation of voltage gain, current gain, input resistance, output resistance, Power gain etc.are;

$$|Y_3^3|_{g_s=0} = \begin{vmatrix} g_i + \cancel{g_s} & -g_i h_r \\ g_m & g_o - g_m h_r + G_L \end{vmatrix}$$
$$= g_i(g_o - g_m h_r + G_L) + g_m g_i h_r$$
$$= \frac{h_{oe}}{h_{ie}} - \frac{h_{fe}}{h_{ie}} x \frac{h_{re}}{h_{ie}} + \frac{G_L}{h_{ie}} + \frac{h_{fe}}{h_{ie}} x \frac{h_{re}}{h_{ie}} = \frac{h_{oe}}{h_{ie}} + \frac{G_L}{h_{ie}}$$
$$= \frac{h_{oe}}{h_{ie}} + \frac{1}{h_{ie}R_L} = \frac{1 + h_{oe}R_L}{h_{ie}R_L}$$

$$|Y_{13}^{13}| = g_o - g_m h_{re} + G_L = h_{oe} - \frac{h_{fe}}{h_{ie}}h_{re} + \frac{1}{R_L}$$
$$= \frac{h_{ie}h_{oe} - h_{fe}h_{re}}{h_{ie}} + \frac{1}{R_L}$$
$$= \frac{\Delta h_e}{h_{ie}} + \frac{1}{R_L} = \frac{h_{ie} + \Delta h_e R_L}{h_{ie}R_L}$$

Where, Δh_e = determinant of h-parameter matrix $= h_{ie}h_{oe} - h_{fe}h_{re}$

$$|Y_3^3| = \begin{vmatrix} g_i + g_s & -g_i h_r \\ g_m & g_o - g_m h_r + G_L \end{vmatrix}$$
$$= (g_i + g_s)(g_o - g_m h_r + G_L) + g_m g_i h_r$$
$$= (g_i g_o - \cancel{g_i g_m h_r} + g_i G_L) + g_s(g_o - g_m h_r + G_L) + \cancel{g_m g_i h_r}$$

$$= \left(\frac{h_{oe}}{h_{ie}} + \frac{1}{h_{ie} R_L}\right) + \left(\frac{h_{oe}}{r_s} - \frac{h_{fe}}{h_{ie}} x \frac{h_{re}}{r_s} + \frac{1}{r_s R_L}\right)$$
$$= \left(\frac{1 + h_{oe} R_L}{h_{ie} R_L}\right) + g_s\left(\frac{h_{ie} h_{oe} - h_{fe} h_{re}}{h_{ie}} + \frac{1}{R_L}\right)$$
$$= \left(\frac{1+h_{oe} R_L}{h_{ie} R_L}\right) + g_s\left(\frac{\Delta h_e}{h_{ie}} + \frac{1}{R_L}\right) = \left(\frac{1+h_{oe} R_L}{h_{ie} R_L}\right) + g_s\left(\frac{h_{ie} + \Delta h_e R_L}{h_{ie} R_L}\right) \quad = \left(\frac{1+h_{oe} R_L + g_s(h_{ie} + \Delta h_e R_L)}{h_{ie} R_L}\right)$$

$$|Y_3^3|_{G_L=0} = \begin{vmatrix} g_i + g_s & -g_i h_r \\ g_m & g_o - g_m h_r + \cancel{G_L} \end{vmatrix}$$
$$= (g_i + g_s)(g_o - g_m h_r) + g_m g_i h_r$$
$$= (g_i g_o - \cancel{g_i g_m h_r}) + g_s(g_o - g_m h_r) + \cancel{g_m g_i h_r} = g_i g_o + g_s(g_o - g_m h_r)$$
$$= \frac{h_{oe}}{h_{ie}} + g_s\left(h_{oe} - \frac{h_{fe}}{h_{ie}} h_{re}\right) = \frac{h_{oe}}{h_{ie}} + g_s\left(\frac{\Delta h_e}{h_{ie}}\right)$$
$$= \frac{h_{oe} + g_s \Delta h_e}{h_{ie}}$$
$$|Y_{23}^{23}| = g_i + g_s = \frac{h_{ie} + r_s}{h_{ie} r_s}$$

The voltage gain between terminals 2 & 3 and 1 & 3 of Fig. 4 is expressed in terms of co-factors of Eq. (24) as;

$$A_v\Big|_{13}^{23} = \frac{v_{23}}{v_{13}} = (-1)(-1)(-1)\frac{|Y_{23}^{13}|}{|Y_{13}^{13}|} = -\frac{|Y_{23}^{13}|}{|Y_{13}^{13}|} = -\frac{g_m}{\frac{h_{ie} + \Delta h_e R_L}{h_{ie} R_L}} = -\frac{g_m h_{ie} R_L}{h_{ie} + \Delta h_e R_L}$$
$$= -\frac{h_{fe} R_L}{h_{ie} + \Delta h_e R_L} \cong -\frac{h_{fe} R_L}{h_{ie}} = -g_m R_L \qquad (30)$$

The input impedance or input resistance between terminals 1 and 3 of Fig. 4 is expressed in terms of co-factors of Eq. (24) as;

$$Z_{in} = Z_{13} = \frac{|Y_{13}^{13}|}{|Y_3^3|}\Bigg|_{g_s=0} = \frac{\frac{h_{ie} + \Delta h_e R_L}{h_{ie} R_L}}{\frac{1 + h_{oe} R_L}{h_{ie} R_L}} = \frac{h_{ie} + \Delta h_e R_L}{1 + h_{oe} R_L} \qquad (31)$$

The output impedance or output resistance between terminals 2 and 3 of Fig. 4 is expressedin terms of co-factors of Eq. (24) as;

$$Z_o = Z_{23} = \frac{|Y_{23}^{23}|}{|Y_3^3|}\Bigg|_{G_L=0} = \frac{\frac{h_{ie} + r_s}{h_{ie} r_s}}{\frac{h_{oe} + g_s \Delta h_e}{h_{ie}}} = \frac{h_{ie} + r_s}{r_s(h_{oe} + g_s \Delta h_e)} = \frac{h_{ie} + r_s}{r_s h_{oe} + \Delta h_e} \qquad (32)$$

The current gain of Fig. 4 is expressed in terms of co-factors of Eq. (24) as;

$$A_i\Big|_{13}^{23} = \frac{v_{23}}{v_{13}} = sgn(2-3)sgn(1-3)(-1)^{2+3+1+3}\frac{|Y_{23}^{13}|}{|Y_3^3|} G_L \qquad (33)$$
$$= (-1)(-1)(-1)\frac{|Y_{23}^{13}|}{|Y_3^3|} G_L = -\frac{|Y_{23}^{13}|}{|Y_3^3|} G_L$$
$$= -\frac{g_m G_L}{\frac{1 + h_{oe} R_L + g_s(h_{ie} + \Delta h_e R_L)}{h_{ie} R_L}}$$
$$= -\frac{g_m G_L h_{ie} R_L}{1 + h_{oe} R_L + g_s(h_{ie} + \Delta h_e R_L)}$$
$$= -\frac{h_{fe}}{1 + h_{oe} R_L + g_s(h_{ie} + \Delta h_e R_L)}$$
$$= -\frac{h_{fe}}{1 + h_{oe} R_L} \text{ for } g_s = 0 \ \ (\cong -h_{fe}) \qquad (34)$$

Equation (34) is available in all standard books which is the approximate ones after assuming$g_s = 0$. Our method is simple and yields exact ones.

The power gain is obtained as the multiplication of the voltage and the current gains as;

$$A_p\Big|_{13}^{23} = \left(A_v\big|_{13}^{23}\right)\left(A_i\big|_{13}^{23}\right) = \left(-\frac{g_m h_{ie} R_L}{h_{ie} + \Delta h_e R_L}\right)\left(-\frac{h_{fe}}{1 + h_{oe} R_L}\right) \cong g_m R_L x h_{fe} = h_{fe} g_m R_L \qquad (35)$$

IV. CONCLUSION

The floating admittance matrix approach is very simple, once conceived. The computer can be used to solve all the elements of the FAM and the voltage gain, current gain, power gain, input resistance (impedance), and output resistance (impedance) of any complex floating admittance matrix of any circuit to the fractional part of the values.

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