A PHASE INVERTER WITH FEEDBACK

by

KALAMBUR GURUMURTHY RAMACHANDRAN

B. Sc., University of Madras, India; Diploma of
The Madras Institute of Technology, India

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

Approved by:

Charles A. Halijak
Major Professor

CONTENTS

INTRODUCTION AND SCOPE

The conventional differential amplifier with unbalanced input fed from a voltage amplifier is one type of 'phase inverter'. This phase inverter will be modified in two ways; feedback will be employed; and a bridge will be employed to lessen noise originating in the power supply.

Because of its symmetry, the conventional differential amplifier is simply analyzed by Bartlett's theorem. However, the modified phase inverter with its null bridge circuit does not yield to an easy analysis by the same procedure. Hence, the new phase inverter is investigated in the conventional way by means of Kirchhoff's Network Laws.

The main goal of this report is to find necessary conditions and requirements for outputs from the modified phase inverter amplifiers to be equal and opposite phase signal voltages and a balanced unwanted noise. In particular, output with zero noise voltage is considered. The noise voltage is in series with power supply.

MODIFIED PHASE INVERTER

Circuit Details

The circuit shown in Figure 1 is a differential amplifier with feedback resistance R_f and input capacitances C_2 and C_3 which form a null bridge. Direct coupling is employed for signal transmission from the output of first tube to the input of the phase inverter.

The equivalent circuit is drawn in Figure 2. A linear independent voltage source and an internal resistance r_p represent the vacuum tube. is amplification factor of the vacuum tube.

The following approximations are made without loss of generality:

(i) Stray capacitance and tube interelectrode capacitance effects are neglected;

(ii) The grid resistance of tube V_2 is assumed to be infinite. $R_{C_1} = \infty$;

(iii) Load resistances for the two outputs are assumed to be infinite; that is $R_{C_2} = R_{C_3} = \infty$;

(iv) The blocking capacitor in the feedback link is assumed to be an infinite capacitor;

(v) The decoupling capacitor C_4 is infinite.

The noise voltage V is in series with the power supply of internal impedance Z_1, and the signal e is applied at the input.

The reactances of C_2 and C_3 are X_2 and X_3 respectively.

Circuit Analysis

Consider the equivalent circuit in Figure 2. Superposition principle is used to find the mesh currents.

With $e = o$ and V given, solving for the mesh currents one

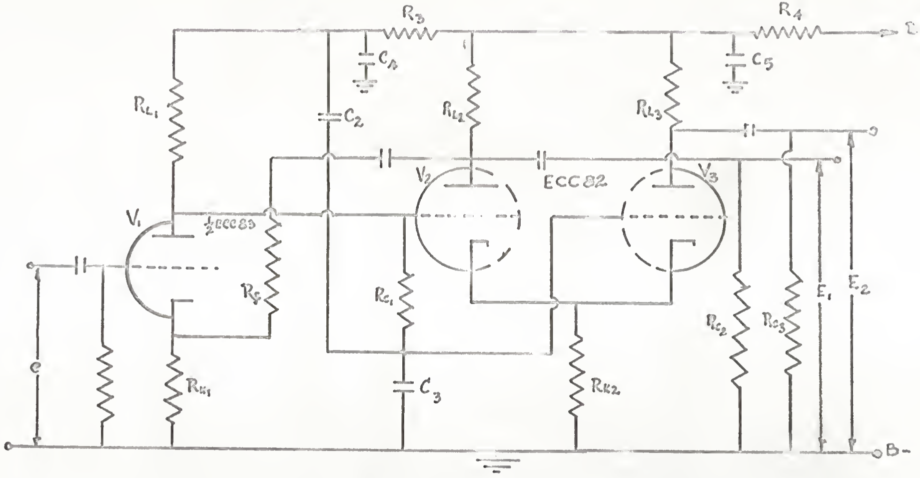

Fig. 1. PUSH-PULL VOLTAGE AMPLIFIER WITH FEEDBACK AND COMPENSATING CAPACITORS.

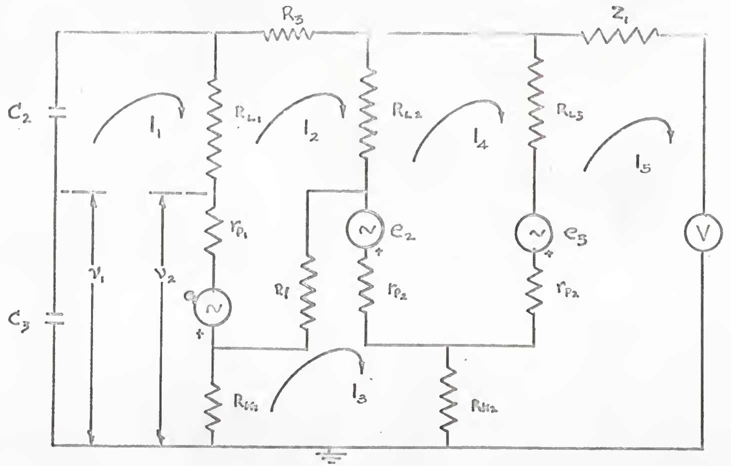

Fig. 2. EQUIVALENT CIRCUIT of PUSH PULL AMPLIFIER.

$$e_1 = \mu_1 [e - (i_1 - i_3) R_{K1}]; \; e_2 = \mu_2 [v_2 - (i_3 - i_5) R_{K2}]; \; e_3 = \mu_2 [v_4 - (i_3 - i_5) R_{K2}].$$

obtains a set of five linear equations which must be solved for i_2, i_4 and i_5, in terms of R_f, X_2 and X_3. Similarly with $v = o$ and e given solving for mesh currents one obtains another set of linear equations which must be solved for i'_2, i'_4 and i'_5 in terms of R_f, X_2 and X_3. These equations, in matrix form, are:

$$\begin{bmatrix} [X_2+X_3+r_{p1}+R_{L1}+R_{k1}(\mu_1+1)] & -(r_{p1}+R_{L1}) & -R_{k1}(\mu_1+1) & 0 & 0 \\ -[R_{L1}+r_{p1}+\mu_1 R_{k1}] & (R_{L1}+r_{p1}+R_3+R_{L2}+R_f) & (\mu_1 R_{k1}-R_f) & -R_{L2} & 0 \\ -[R_{k1}+\mu_2 r_{p1}+R_{k1}(\mu_1+1)] & (r_{p1}\mu_2-R_f) & [R_{k1}+R_f+r_{p2}+R_{k2}+\mu_2 R_{k1}(\mu_1+1)+R_{k2}\mu_2] & -r_{p2} & -R_{k2}(\mu_2+1) \\ \mu_2[X_3+r_{p1}+R_{k1}(\mu_1+1)] & -(r_{p1}\mu_2+R_{L2}) & -[r_{p2}+\mu_2 R_{k1}x(\mu_1+1)] & [2r_{p2}+R_{L2}+R_{L3}] & -(R_{L3}+r_{p2}) \\ -\mu_2 X_3 & 0 & -R_{k2}(\mu_2+1) & -(R_{L3}+r_{p2}) & [r_{p2}+R_{L3}+Z_1+R_{k2}(\mu_2+1)] \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} = \begin{bmatrix} \mu_1 e \\ -\mu e \\ -\mu_1\mu_2 e \\ -\mu_1\mu_2 e \\ 0 \end{bmatrix} \qquad (2)$$

$$
\begin{bmatrix}
\left[X_2 + X_3 + r_{p1} + R_{L1} + R_{k1}(\mu_1+1)\right] & -(r_{p1}+R_{L1}) & -R_{k1}(\mu_1+1) & 0 & 0 \\
-\left[R_{L1}+r_{p1}+\mu_1 R_{k1}\right] & (R_{L1}+r_{p1}+R_3+R_{L2}+R_f) & (\mu_1 R_{k1}-R_f) & -R_{L2} & 0 \\
-\left[R_{k1}+\mu_2 r_{p1}+R_{k1}(\mu_1+1)\right] & (r_{p1}\mu_2-R_f) & \left[R_{k1}+R_f+r_{p2}+R_{k2}+\mu_2 R_{k1}(\mu_1+1)+R_{k2}\mu_2\right] & -r_{p2} & -R_{k2}(\mu_2+1) \\
\mu_2\left[X_3+r_{p1}+R_{k1}(\mu_1+1)\right] & -(r_{p1}\mu_2+R_{L2}) & -\left[r_{p2}+\mu_2 R_{k1} x(\mu_1+1)\right] & \left[2r_{p2}+R_{L2}+R_{L3}\right] & -(R_{L3}+r_{p2}) \\
-\mu_2 X_3 & 0 & -R_{k2}(\mu_2+1) & -(R_{L3}+r_{p2}) & \left[r_{p2}+R_{L3}+Z_1+R_{k2}(\mu_2+1)\right]
\end{bmatrix}
\begin{bmatrix} I'_1 \\ I'_2 \\ I'_3 \\ I'_4 \\ I'_5 \end{bmatrix}
=
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ V \end{bmatrix}
\qquad (2)
$$

In order to have an idea of the part played by R_f, C_2 and C_3 in the circuit, first a conventional circuit with suitable design values is assumed.

Tubes V_1 and V_2, V_3 are chosen to be double triodes, ECC83 and ECC82, respectively. Other circuit element values are:

i) $R_{L1} = 100\text{k}\Omega$

ii) $R_{K1} = 2.7\text{k}\Omega$

iii) $R_{L2} = 30\text{k}\Omega$

iv) $R_{L3} = 30\text{k}\Omega$

The variables are X_2, X_3 and R_f, where X_2 and X_3 are the reactances of the bridge capacitors C_2 and C_3, respectively.

Substituting the assumed circuit values in the equations above, one obtains, for $e = 0$, and V given,

$$\begin{bmatrix} (X_2+X_3+430) & -160 & -430 & 0 & 0 \\ -430 & (200+R_f) & 470 & -30 & 0 \\ -6030 & 1220 & 6307 & -38 & -216 \\ (5610-17X_3) & -1050 & -5122 & 0 & 490 \\ -17X_3 & 0 & -216 & -38 & 264 \end{bmatrix} \begin{bmatrix} I_1' \\ I_2' \\ I_3' \\ I_4' \\ I_5' \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ V \end{bmatrix} \qquad (3)$$

and for $v = o$, and e given,

$$
\begin{bmatrix}
(X_2+X_3+430) & -160 & -430 & 0 & 0 \\
-430 & (200+R_f) & 470 & -30 & 0 \\
-6030 & 1220 & 6307 & -38 & -216 \\
5610-17X_3 & -1050 & -5122 & 0 & 490 \\
-17X_3 & 0 & -216 & -38 & 264
\end{bmatrix}
\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix}
=
\begin{bmatrix} 100e \\ -100e \\ -1700e \\ -1700e \\ 0 \end{bmatrix}
\tag{4}
$$

Mesh currents which are of interest are I_2, I_4, I_5, I'_2, I'_4 and I'_5. These currents as functions of the chosen variables X_2, X_3 and R_f are:

$$
I_2 = -v \frac{3.79\cdot 10^4+3.40X_3+50.8}{-5.28\cdot 10^6+5.57\cdot 10^3R_f - X_2(1.38\cdot 10^4+23.3R_f)+X_3(5.40\cdot 10^3-20.6R_f)} \tag{5}
$$

$$
I_4 = v \frac{3.30\cdot 10^4-1.04\cdot 10^2R_f-X_2(1.25\cdot 10^2+1.98R_f)-X_3(85.3+.405R_f)}{-5.28\cdot 10^6+5.57\cdot 10^3R_f - X_2(1.38\cdot 10^4+23.3R_f)+X_3(5.40\cdot 10^3-20.6R_f)} \tag{6}
$$

$$
I_5 = v \frac{7.96\cdot 10^5+7.97R_f+X_2(1.80\cdot 10^3-0.195R_f)+X_3(1.54\cdot 10^3-0.472R_f)}{-5.28\cdot 10^6+5.57\cdot 10^3R_f - X_2(1.38\cdot 10^4+23.3R_f)+X_3(5.40\cdot 10^3-20.6R_f)} \tag{7}
$$

$$
I'_2 = e \frac{(9.97\cdot 10^5-X_2 1.19\cdot 10^6-X_3 1.05\cdot 10^6)}{-5.28\cdot 10^6+5.57\cdot 10^3R_f - X_2(1.38\cdot 10^4+23.3R_f)+X_3(5.40\cdot 10^3-20.6R_f)} \tag{8}
$$

$$i'_4 = e\,\frac{-5.18\cdot10^6+1.74\cdot10^2R_f-X_2(5.68\cdot10^5+2.83\cdot10^3R_f)-X_3(4.53\cdot10^5-1.99\cdot10^3R_f)}{-5.28\cdot10^6+5.57\cdot10^3R_f-X_2(1.38\cdot10^4+23.3R_f)+X_3(5.40\cdot10^3-20.6R_f)} \tag{9}$$

$$i'_5 = e\,\frac{2.57\cdot10^7-2.18\cdot10^4R_f+X_2(5.88\cdot10^4-7.52\cdot10^2R_f)-X_3(9.83\cdot10^5+1.61\cdot10^3R_f)}{-5.28\cdot10^6+5.57\cdot10^3R_f-X_2(1.38\cdot10^4+23.3R_f)+X_3(5.40\cdot10^3-20.6R_f)} \tag{10}$$

Mesh currents due to e and v are obtained by superposing currents due to e and v alone.

Output voltages E_1 and E_2 from tubes V_2 and V_3 are

$$E_1 = (i'_4-i'_2)\,R_{L2}+i'_5Z_1 + V-(i_4-i_2)\,R_{L2}+ i_5Z_1 \tag{11}$$

and

$$E_2 = (i'_5-i'_4)\,R_{L3} + i'_5\,Z_1 + V-(i_5-i_4)\,R_{L3}+ i_5Z_1 \tag{12}$$

Substituting for mesh currents in terms of X_2, X_3 and R_f and simplifying, one obtains:

$$E_1 = e\,\frac{-15.28\cdot10^8-2.13\cdot10^4R_f+X_2(1.92\cdot10^6-9.24\cdot10^3R_f)+X_3(1.86\cdot10^6+6.17\cdot10^3R_f)}{-5.28\cdot10^5+5.57\cdot10^2R_f-X_2(1.38\cdot10^3+2.33R_f)+X_3(5.40\cdot10^2-2.06R_f)}$$

$$+v\left[1-\frac{1.10\cdot10^6-3.10^2R_f+X_2(16\cdot10^2-6.2R_f)+X_3(1.2\cdot10^3-1.67R_f)}{-5.28\cdot10^5+5.57\cdot10^2R_f-X_2(1.38\cdot10^3+2.33R_f)+X_3(5.40\cdot10^2-2.06R_f)}\right] \tag{13}$$

and

$$E_2 = e\,\frac{16.58\cdot 10^{6} - 8.78\cdot 10^{4} R_f + X_2(1.94\cdot 10^{6} + 5.49\cdot 10^{3} R_f) - X_3(2.57\cdot 10^{6} + 1.24\cdot 10^{4} R_f)}{-5.28\cdot 10^{5} + 5.57\cdot 10^{2} R_f - X_2(1.38\cdot 10^{3} + 2.33 R_f) + X_3(5.40\cdot 10^{2} - 2.06 R_f)}$$

$$+ v\left[1 - \frac{3\cdot 10^{6} + 3.3\cdot 10^{2} R_f + X_2(7.6\cdot 10^{3} + 5.2 R_f) + X_3(6.25\cdot 10^{3} - 0.8 R_f)}{-5.28\cdot 10^{5} + 5.57\cdot 10^{2} R_f - X_2(1.38\cdot 10^{3} + 2.33 R_f) + X_3(5.40\cdot 10^{2} - 2.06 R_f)}\right] \qquad (14)$$

For brevity call the coefficients of e and v in the above equations a_{11}, a_{12}, a_{21}, and a_{22}; these equations become

$$E_1 = a_{11} e + a_{12} v$$

$$E_2 = a_{21} e + a_{22} v$$

It is required to find the relation between R_f, X_2 and X_3 for various output voltage requirements.

(i) Ideal conditions of zero noise voltage at the output with equal but out-of-phase output signal voltages, require

$$a_{12} = 0 \qquad \text{(a)}$$

$$a_{22} = 0 \qquad \text{(b)}$$

and

$$a_{11} = -a_{21} \quad \text{(c)}$$

These conditions yield

$$X_2(3.10^3-3.9R_f)+X_3(6.6\cdot 10^2+0.33R_f)-8.6\cdot 10^2R_f+1.53\cdot 10^6=0 \tag{15}$$

$$X_2(9.10^4+75.R_f)+X_3(5.7\cdot 10^4+12R_f)-2.3\cdot 10^3R_f+35\cdot 10^6=0 \tag{16}$$

$$X_2(1.1\cdot 10^4-7.5R_f)+X_3(630-16R_f)-2.2\cdot 10^2R_f+2.4\cdot 10^5=0 \tag{17}$$

Solving these bilinear algebraic equations for R_f yields

$$0.47R_f^4-1.55\cdot 10\,R_f^3+1.11\cdot 10^6R_f^2-0.32\cdot 10^9R_f+1.97\cdot 10^{11}=0 \tag{18}$$

This equation has two real roots at $R_{f1}=2.88$ M and $R_{f2}=0.73$ M .

Values of X_2 and X_3 at R_{f1} and R_{f2} can be obtained and are

$R_{f1}=2.88\text{M}\Omega$; $X_2=-0.104\text{M}\Omega$, $X_3=+0.0396\text{M}\Omega$

$R_{f2}=0.730\text{M}\Omega$; $X_2=-0.750\text{M}\Omega$, $X_3=-0.897\text{M}\Omega$

These two values give ideal outputs.

It is seen that only for $R_f=0.730\text{M}\Omega$ the circuit chosen yields desired outputs. For $R_f=2.88\text{M}\Omega$, it is required to have an inductor and a capacitor for cancellation of noise and for out-of-phase output signal voltages of equal amplitude; it is preferable to avoid inductance in practical amplifiers.

For this ideal condition, the values of α_{12} and α_{22} are, of course, zero. Values of $\alpha_{11} (= -\alpha_{21})$ are evaluated for ideal outputs and are shown in Table I.

Table I: Values of R_f, X_2, X_3 and $_{11}(= -\alpha_{12})$ for ideal outputs.

R_f in $M\Omega$	X_2 in $M\Omega$	X_3 in $M\Omega$	$\alpha_{11} 10^{-3} (= -\alpha_{21} 10^{-3})$
0.730	-0.750	-0.897	+1.825
2.880	-0.104	+0.039	+1.550

Values of the output voltages are

$$E_1 = 1.825 \times 10^3 \, e$$

$$E_2 = -1.825 \times 10^3 \, e$$

(iii) For a less stringent requirement of zero noise voltage at the outputs only, with unbalanced signal outputs, X_2, X_3 and R_f must satisfy Equations (15) and (16).

Unknowns X_2 and X_3 can be solved for different values of R_f and are shown in Table II.

The unbalanced signal output voltage $\Delta E = (\alpha_{11} - \alpha_{21}) e$ for zero noise output voltage and for different values of feedback resistance, R_f, is calculated and is given in Table II.

Table II: Values of X_2, X_3, a_{11} and $E = (a_{11} - a_{21})e$ for different values of R_f.

R_f in MΩ	X_2 in MΩ	X_3 in MΩ	$a_{11} 10^{-3}$	ΔE volts/m. v. input
3.0	-0.1060	+0.074	+1.645	+1.370
2.8	-0.0450	-0.167	-1.630	+0.305
2.0	-0.0945	-0.200	+1.510	+1.520
1.0	+0.067	-0.623	-9.725	+5.95
0.75	+0.250	-0.995	+0.011	-0.007
0.50	+1.180	-2.760	+9.680	-6.780

It can be noticed that a_{11} and a_{12} are voltage amplification factors of the input signal at respective outputs.

CONCLUSION

A phase inverter voltage amplifier with feedback and compensating reactances for low noise at outputs has been investigated. Analysis show that it is possible to have zero noise and balanced signal outputs for proper choise of feedback resistance and null bridge reactances.

Calculations reveal that for zero noise and balanced signal outputs there are two values for feedback resistance R_f. But, however, only one of the values of R_f requires capacitive bridge reactances for zero noise and balanced signal outputs. The other value of R_f requires the undesirable inductive bridge reactances for the same output conditions. The value and nature of null bridge reactances depend rather critically on the feedback resistance.

ACKNOWLEDGMENT

The author wishes to express his thanks to Dr. Charles A. Halijak, Department of Electrical Engineering, for constant help and encouragement during the preparation of this report.

REFERENCES:

Offner, F.
"Push-pull Resistance Coupled Amplifiers", 'Review of Scientific Instruments', 8 (1937), pp. 20-21.

Seely, Samuel
Electron Tube Circuits, McGraw-Hill Publishing Company, New York, 1961.

A PHASE INVERTER WITH FEEDBACK

by

KALAMBUR GURUMURTHY RAMACHANDRAN

B. Sc., University of Madras, India; Diploma of
The Madras Institute of Technology, India

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

ABSTRACT

A phase inverter voltage amplifier with feedback resistance and with additional components in the conventional circuit which form a bridge at inputs of the phase inverter is investigated. Two capacitors in series are connected between the plate supply voltage of the preamplifier, feeding the phase inverter, and ground. The common point of the capacitors is connected to the grid of the phase inverter tube which is not directly fed by the preamplifier. The capacitors are added for suppression of noise from the power supply.

Calculations reveal that, for zero noise and balanced outputs there are two possible values for reactances in the bridge. One set consists of capacitive reactances and the other uses capacitive and inductive reactances for zero noise and balanced signal outputs.

Calculations for zero noise but unbalanced signal outputs are also made.