Special circuits of operational amplifiers for measurement purposes

Jaroslav Lokvenc, Rene Drtina and Josef Sedivy

***Abstract*—**Capture and processing of analog signals whose level is a function of frequency, usually requires the use of frequency-dependent circuits. They often use active 4-poles that implement the integration or derivation of the processed signal. Steady and largely standardized operational amplifiers involved in the function of integration and derivation amplifiers are described in numerous publication. This paper presents new possibilities for the involvement of bipolar circuits with operational amplifiers. The proposed connections are primarily intended for applications in the field of measurement technology for laboratory and process measurement. They can be used for measuring and other devices for processing low frequency and DC signals. The diagrams are applicable to hybrid and monolithic operational amplifiers, and for special purposes can be realized on discrete based components. The article presents the basic starting points, principles, and equations for these circuits. Application possibilities of these connections are everywhere where it is needed to process and edit analog electrical signal

***Keywords*—**analog signal, measuring equipment, operational amplifier, special districts.

I. Introduction

ALSO developed at a time and dynamically expanding digital technologies remains relatively large area of analog signals that must be processed with the least distortion and transform to the required voltage, current or power level. In the field of measurement technology, power electronics and electrical engineering and the low frequency (audio equipment) are in most cases the primary analog signals.

Department of Electrical Workers laboratory technical subjects Faculty of Education, University of Hradec Králové for many years engaged in the development of innovative circuit with operational amplifiers and their applications in sensing amplifiers for high-voltage measurements in the low-frequency technology, management and control circuits.

Digital data transmission and processing is now obvious trend. Most signal sources especially from the physical or chemical measurement, however, provides only an analog signal. For this reason it is not possible even in times of general digitalization go without sensing techniques and analog signal processing in particular the very low level. Steady and largely standardized operational amplifiers involved are described in numerous publications [1], [3], [6], [7].

This does not mean that the development of analog circuits can be considered closed [1]. Research work in the field of measurement technology, new materials and power electronics also require new approaches in the design of analog of sensors and processing of DC or AC analog signals. Despite the continuing digitization of analog circuits are irreplaceable.

Development of operational amplifiers (monolithic and hybrid) brought over many decades of design solutions. In many cases it is preferable to use today in circuit measurement techniques and low frequency signals bipolar operational amplifiers. Unlike operational amplifiers with FET input circuitry (J-FET, MOS-FET, and others) have a bipolar operational amplifiers usually own less noise and are more resistant to voltage inputs. Especially in the case of hybrid precision bipolar operational amplifiers is achieved peak parameters, and these circuits are often designed for specific use as the customer. On the other hand, involvement in current below the bipolar operational amplifiers (compared with an operational amplifier with FET input circuits) and high input resistance. Bipolar operational amplifiers typically have higher input current, which can, depending on the internal resistance of the signal source and the involvement of the amplifier, causing the DC level shift the output voltage. The aim of those involved is to minimize the negative effect of the input current manifestations of bipolar operational amplifiers and where low-level processing and audio gain control signals to move away from the main signal path and thus reduce the transition noise contact regulatory elements.

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II. Amplifier with Input Impedance and Small Output DC Offset

Features of non-inverting amplifier on a classic amplifier.-.connection are described in numerous publications (e.g. [1], [9]). One of the key issues in the design of the first amplifier input of the measuring instrument or device has its own input current bipolar operational amplifier (Fig. 1).

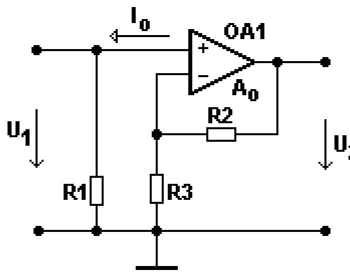

Fig. 1 non-inverting operational amplifier

To transfer A non-inverting operational amplifier is in [9] derived equations

$$A = \left(1 + \frac{R_2}{R_3}\right) \cdot \frac{1}{1 + \frac{1}{A_0} \cdot \left(1 + \frac{R_2}{R_3}\right)} \quad (1)$$

A_0 is the gain of operational amplifier without feedback. Input current I_0 of operational amplifier creates a voltage drop (across resistor R_1) $\Delta U = I_0 \cdot R_1$, which corresponds to the input with no load on the input voltage U_1. This voltage is then transformed to the transmission and the amplifier output to the level of U_2

$$U_2 = I_0 \cdot R_1 \cdot \left(1 + \frac{R_2}{R_3}\right) \cdot \frac{1}{1 + \frac{1}{A_0} \cdot \left(1 + \frac{R_2}{R_3}\right)} \quad (2)$$

For common practice usually think that $1/A_0 \rightarrow 0$ and then use the simplified equation

$$A = \left(1 + \frac{R_2}{R_3}\right) \quad (3)$$

$$U_2 = U_1 \cdot \left(1 + \frac{R_2}{R_3}\right) \quad (4)$$

From (2) and (4) (after the introduction of $U_1 = I_0 \cdot R_1$) shows that the DC offset at the output of operational amplifier is linearly dependent on the size of the leakage resistance R_1. After connecting the signal source with internal resistance R_i, the resulting leakage resistance parallel combination of $R_1 \| R_\mathrm{i}$ (Fig. 2) and DC offset at the output of op amp will

$$U_{2\,\mathrm{DC}} = I_0 \cdot \left(R_1 \| R_\mathrm{i}\right) \cdot \left(1 + \frac{R_2}{R_3}\right) \quad (5)$$

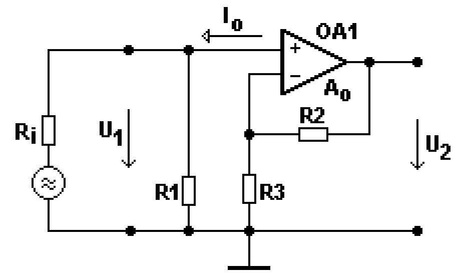

Fig. 2 non-inverting operational amplifier connected to the signal source

DC stability of the input amplifiers with high-end professional equipment deals (among others) by applying more sophisticated (and in some cases, frequency-compensated) chain suppressor cells with constant input and output impedance (Fig. 3). The voltage drop caused by the input current DC.

Stability of the input amplifiers with high-end professional equipment deals (among others) by applying more sophisticated (and in some cases, frequency-compensated) chain depressants segments. These segments have a constant input and output impedance (Fig. 3). The voltage drop caused by the op-amp input current I_0 is then compensated by setting the internal symmetry of the operational amplifier inputs and DC. Offset when switching ranges is not change.

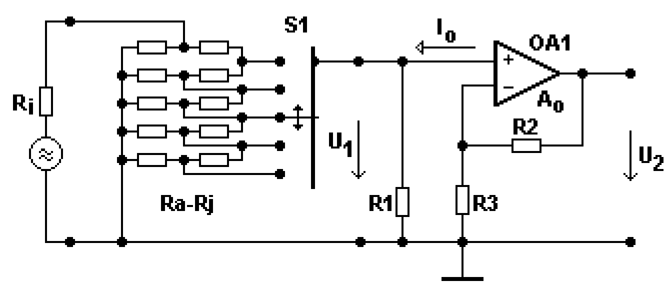

Fig. 3 the input amplifier chain with shock damping element

For laboratory and operational measurements we often need no load sensing output voltage (simple resistive divider Rogowski coils, piezoelectric and capacitive accelerometers, etc.) For this purpose we have developed involving the input amplifier according to Fig. 4, which reaches values of the input resistance of 10^9 ohms and order while retains all the advantages of using a bipolar operational amplifiers.

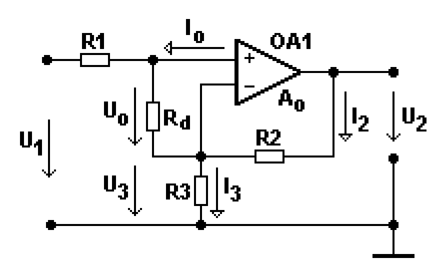

Fig. 4 principle diagram of an amplifier with high input resistance

Input impedance of amplifier R_amp without a connected external differential resistor R_d and $R_1 \rightarrow 0$ is determined by the equation

$$R_{\text{amp}} = \frac{U_1}{I_0} \tag{6}$$

When internal differential operational amplifier input resistance R_0 is also valid

$$I_0 = \frac{U_0}{R_0} = \frac{U_1 - U_3}{R_0} \tag{7}$$

When is connecting an external resistor R_{d} and differential, provided that $R_{\text{d}} \vee R_{0.}$ Substituting (7) to (6) we get

$$R_{\text{amp}} = \frac{U_1}{U_1 - U_3} \cdot R_{\text{d}} = \frac{1}{\frac{1}{R_{\text{d}}} \cdot \left(1 - \frac{U_3}{U_1}\right)} \tag{8}$$

Assuming that $I_2 = I_3$, a I_3 ™ I_0, , and then

$$U_2 = A_0 U_0 \tag{9}$$

$$U_1 = U_3 + U_0 \tag{10}$$

$$\frac{U_3}{U_1} = 1 - \frac{U_0}{U_1} \tag{11}$$

After substitution of (9) into (11)

$$\frac{U_3}{U_1} = 1 - \frac{U_2}{U_1} \cdot \frac{1}{A_0} \tag{12}$$

Where $U_2/U_1 = A$, which is the transfer of the amplifier stage. After substituting (12) into (8) and counting the input resistor R_1 will get the final equation for the op-amp input resistance in non-inverting involvement.

$$R_{\text{amp}} = R_1 + R_{\text{d}} \cdot \frac{A_0}{A} \tag{13}$$

In practice, the resistor R_1 primarily a protective function, which reduces random spikes. Typically is valid $R_1 \vee R_{\text{amp}}$ Then the value R_1 can be neglected and R_{amp} written in the form

$$R_{\text{amp}} = R_{\text{d}} \cdot \frac{A_0}{A} \tag{14}$$

III. Practical Example of Application

The amplifier concept that we used as an input unit displays an XY slow processes. The input was used precision resistor divider (R_{a} to R_{e}) on the ceramic substrate with a total resistance of 1 MΩ, with attenuation -60, -40, -20, -10 and 0 dB attenuator accuracy 0.1% (Fig. 5).

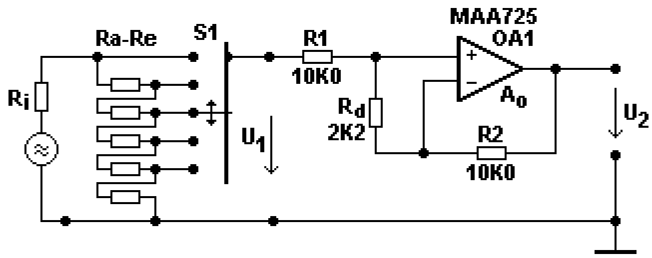

Fig. 5 scheme of the input unit

Without the resistor R_3 is connected (see Fig. 4) the involvement of working as a high-impedance repeater, which are involved in more amplifier stages. Instrument used was proven operational amplifier MAA725 ($A_0 > 10^6$). The basic parameters are listed in Table 1, basic parameters of the input units indicates Table 2.

The advantage of the connection lies in the fact that the necessary input currents (about 60 nA) of operational amplifiers are fed from the output of the amplifier over a relatively low resistance of the resistor R_2. External differential resistor Rd is virtually a short circuit across the internal resistance R_0 differential operational amplifier, thus greatly improving noise ratios of the input units.

Table 1 main parameters of the operational amplifier MAA725

parameter	symbol	typical value
supply voltage	U_{B}	max ± 22 V
input voltage	U_{I}	max ± 20 V
operating temperature	θ_{a}	-55 to 125 °C
input voltage unbalance	U_{I0}	0.5 mV
input current unbalance	I_{I0}	2 nA
input current	I_{IB}	53 nA
input resistance	R_{I}	1.5 MΩ
input noise voltage	U_{INef}	1 μV
common mode rejection	CMR	120 dB
gain	A_0	129 dB
output resistance	R_{O}	150 Ω
output voltage amplitude	U_{Omax}	± 13.5 V
voltage temperature drift	α_{UIO}	0.6 μV/K
current temperature drift	α_{IIO}	42 pA/K
frequency response	BW	max 100 kHz

Table 2 basic parameters of the input units

parameter	symbol	value
input impedance	R_{amp}	> 1 GΩ
gain	A	0.9999945
output noise voltage	U_{N}	100 μV

sensitivity of DC offset	ΔU_2	100 µV/1 MΩ
frequency response at R_i = 1 MΩ	BW	35 kHz

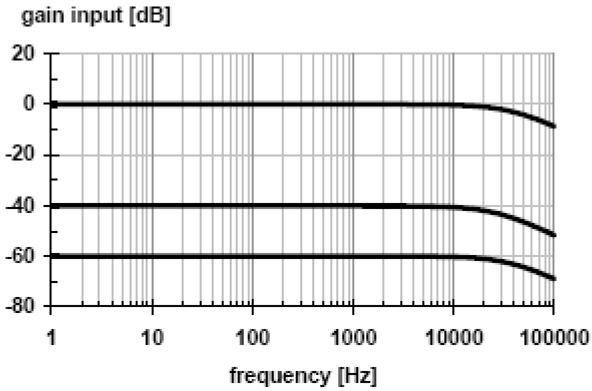

Fig. 6 frequency response the input units with operation amplifier MAA725

The resulting parameters of the amplifier stage can be used in wide limits affect the choice of resistors R_1, R_2, R_3, has a significant influence of the choice of the operating amplifier. In the digital storage oscilloscope images (Fig. 8, Fig. 9) is a input units response on the input signal square. Response on the input signal square (U_{1peak} = 100 mV), operation amplifier MAA725, f = 1 kHz (Fig. 8) and f = 10 kHz (Fig. 9).

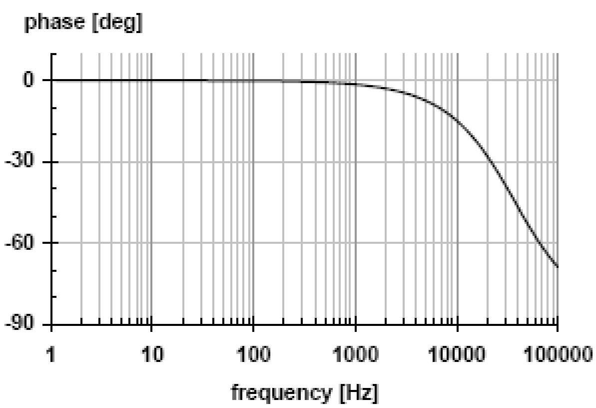

Fig. 7 phase response the input units with operation amplifier MAA725

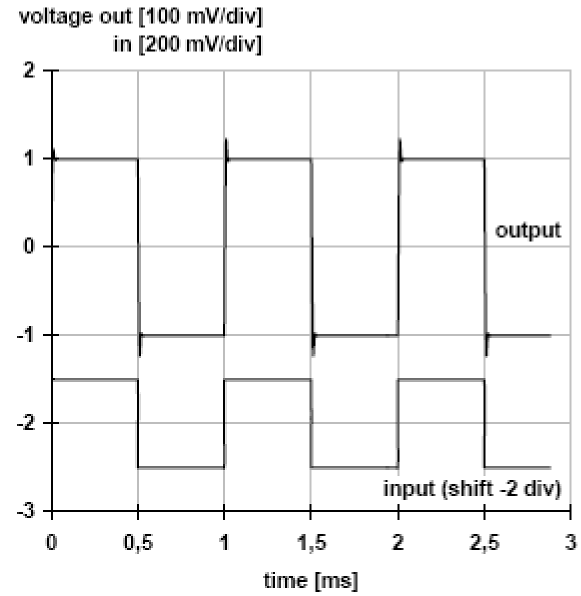

Fig. 8 response of input units on the input signal square 1 kHz

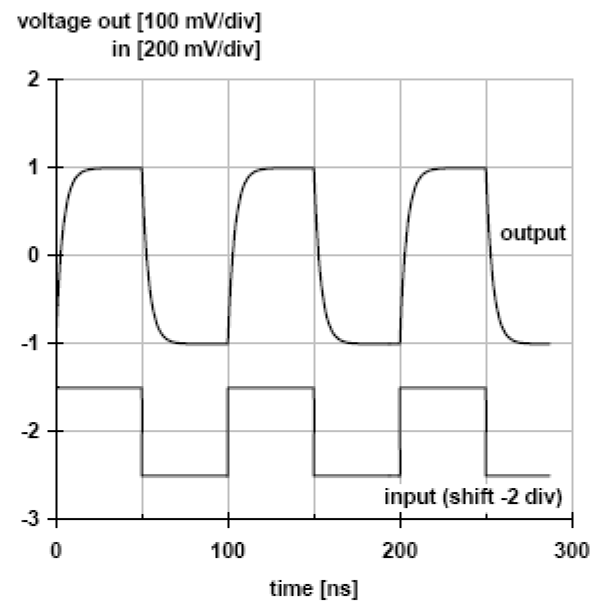

Fig. 9 response of input units on the input signal square 10 kHz

IV. Inverting Operational Amplifier with a Resistor in a Virtual zero

Known from the literature and in practice the normal circuit with operational amplifiers can be designed to expand on our involvement, which provides a general basis for other application options. A frequent requirement in the design of analog circuits is to achieve the desired transmission in the simplest schematic solutions with a minimal number of components or easy way to control any of the parameters, or improve any parameter in comparison with classic involvement. A significant portion of these properties meets the version presented by the amplifier in Fig. 10.

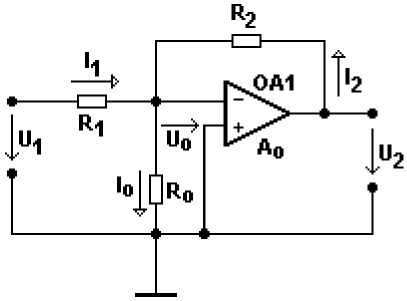

Fig. 10 scheme the amplifier with a resistor in a virtual zero

In the literature [2] is for connection without resistor R_0 derived from (15) transfer (gain) A_{in} involvement in operational amplifier inverting four-pole transfer the load with A_0

$$A_{in} = -\frac{1}{\frac{1}{A_0} + \frac{1}{A_0}\cdot\frac{R_1}{R_2} + \frac{R_1}{R_2}} \tag{15}$$

In practice, the first and second member denominator sum of neglect. If at least two orders of magnitude is smaller than the R_1/R_2-rates and the reciprocal of this ratio is then referred to as ordinary gain A_{in}.

For the connection shown in Fig. 10 are:

$$I_1 + I_2 + I_0 = 0 \tag{16}$$

$$U_2 = -A_0 U_0 \tag{17}$$

After substituting into (16)

$$\frac{U_1 - U_0}{R_1} + \frac{U_2 - U_0}{R_2} - \frac{U_0}{R_0} = 0 \tag{18}$$

After substitute (17) into (18)

$$\frac{U_1 + \frac{U_2}{A_0}}{R_1} + \frac{U_2 + \frac{U_2}{A_0}}{R_2} - \frac{U_2}{R_0 A_0} = 0 \tag{18}$$

After adjustments

$$\frac{U_1 + \frac{U_2}{A_0}}{R_1} + \frac{U_2 + \frac{U_2}{A_0}}{R_2} - \frac{U_2}{R_0 A_0} = 0 \tag{18}$$

$$U_1 \cdot \left(\frac{1}{R_1}\right) + U_2 \cdot \left(\frac{1}{A_0 R_1} + \frac{1}{R_2} + \frac{1}{A_0 R_2} - \frac{1}{R_0 A_0}\right) = 0 \tag{19}$$

The resulting transfer of inverting amplifiers $A_{in} = U_2/U_1$

$$A_{in} = -\frac{1}{\frac{1}{A_0} + \frac{1}{A_0}\cdot\frac{R_1}{R_2} + \frac{R_1}{R_2} + \frac{1}{A_0}\cdot\frac{R_1}{R_0}} \tag{20}$$

Comparing (15) and (20) it can be concluded that the fourth member of the denominator, which is now in total, in addition, can also be neglected. For example, to further gain an additional error in the size of -1 %, then

$$\frac{1}{A_0}\cdot\frac{R_1}{R_0} \le \frac{R_1}{R_2}\cdot 10^{-2} \tag{21}$$

By adjusting the inequalities (17) we obtain the condition

$$R_0 \ge R_1 \cdot \frac{A_{in}}{A_0}\cdot 10^2 \tag{22}$$

From inequality (18) implies that if we use in connection with the augmentation of operational amplifier load order $A_0 = 10^6$ and more, as the R_0 can choose a relatively small resistor tens to hundreds of ohms.

The seemingly unusual connection of virtual zero operational amplifier inverting input to ground through resistor R_0 is essentially a variant of the census two-input amplifiers, where one of the inputs is grounded both census and resistors have different values of the order [3]. The inclusion of this resistor therefore does not gain a significant decline in the value of A_{in}. If the exact value depends on the transmission, it can be corrected by increasing the appropriate resistor R_2. Table 2 presents examples that show the difference between the amplification according to equations (15) and (20) subject to conditions (22) for the lowest possible value of the resistor R_0 when error amplification ΔA_0 = -1 % load and the amplifier gain 10^6th order.

Table 3 comparative table gain amplifiers

equation	**values of resistors (kΩ)**			**transmission**
	$\mathbf{R_1}$	$\mathbf{R_2}$	$\mathbf{R_0}$	$\mathbf{A_{in}}$
(15) (20)	10 10	1 000 1 000	-- 0,1	-99,989 -99,000
(15) (20)	1 000 1 000	1 000 1 000	-- 0,1	-0,999 -0,990

The table shows that adding a resistor to transfer virtually unchanged, resistor, however, significantly improves the amplifier noise ratios.

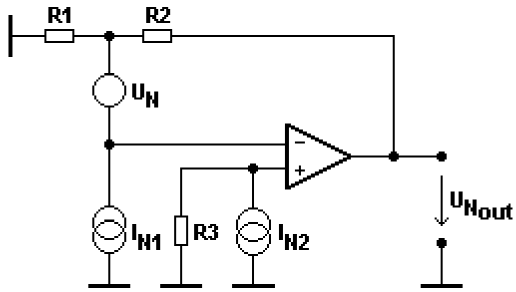

Fig. 11 operational amplifier noise model [9]

Size noise voltage at the output of operational amplifier in the classic inverting circuit (Fig. 11) is according to [9] given by the equation

$$U_{\mathrm{Nout}} = \left(1+\frac{R_2}{R_1}\right)\cdot\sqrt{U_{\mathrm{N}}^2 + I_{\mathrm{N1}}^2\cdot\left(R_1\|R_2\right)^2 + I_{\mathrm{N2}}^2 R_3^2} \qquad (23)$$

where $I_{\mathrm{N1}}\cdot(R_1\|R_2)$ is the noise voltage operational amplifier inverting input. In our engagement, implemented according to Fig. 10 are inverting input of operational amplifier connected in parallel resistors R_1, R_2 and R_3. Inverting input voltage noise operational amplifier with a resistor R_3 is a virtual zero $I_{\mathrm{N1}}\cdot(R_1\|R_2\|R_3)$. For example, the noise voltage inverting input of operational amplifier μA725 for I_{N1} = 120 pA and $R_1 = R_2 = 1$ MΩ is 60 μV.

For values of I_{N1} = 120 pA, $R_1 = R_2 = 1$ MΩ, $R_0 = 10$ kΩ, is the noise voltage of 1,18 μV.

Even at his own noise voltage $U_N = 100$ μV represents connection leakage resistor R_0 (Fig. 10) the resulting reduction in noise level at the output of operational amplifier 4 dB. Transmission characteristics of a comprehensive engagement depends on the relative values of resistors R_1, R_2, R_0, and the operating amplifier (Fig. 12, Fig 14). For example, were used resistors $R_1 = R_2 = 1$ MΩ, R_0 resistor had a value of 1 kΩ and 10 kΩ (Fig.10).

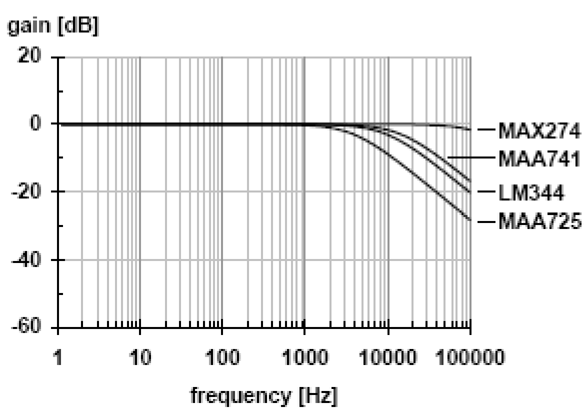

Fig. 12 frequency response at R_0 = 10 kΩ

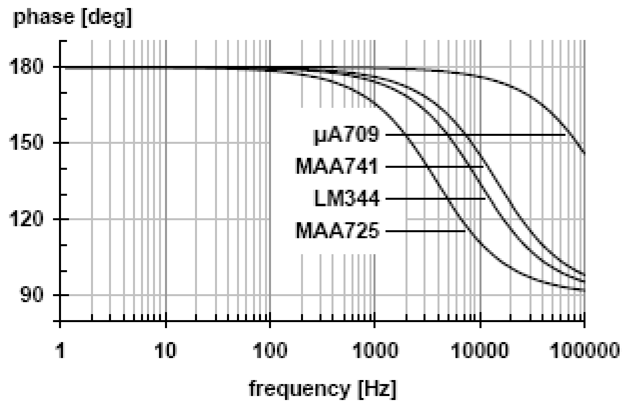

Fig. 13 phase response at R_0 = 10 kΩ

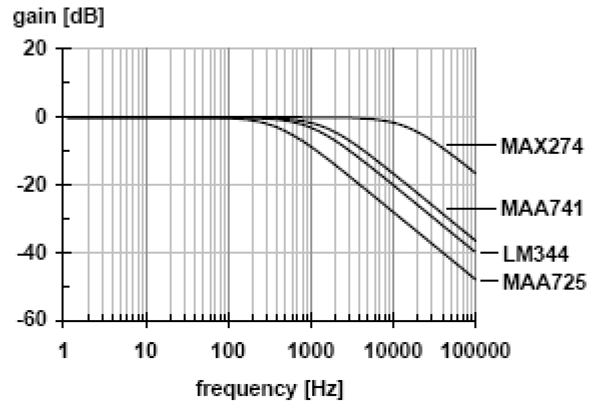

Fig. 14 frequency response at R_0 = 1 kΩ

In addition to reducing the impact of temperature dependence of the asymmetry in the input current level shift the output DC voltage operational amplifier at zero input voltage. It can be justified, remaining static unbalance of the input currents to balance the inclusion of the resistor R_0 between the ground and the non-inverting amplifier input, as is usual in such cases the classic connections [5]. The advantage of those adaptations is the fact that the amplifier inputs are connected to a small value resistor, resulting in increased resistance to interference voltage capacitive coupling in strong alternating fields. Temperature dependence of offset voltage at connection is slightly worse than classical.

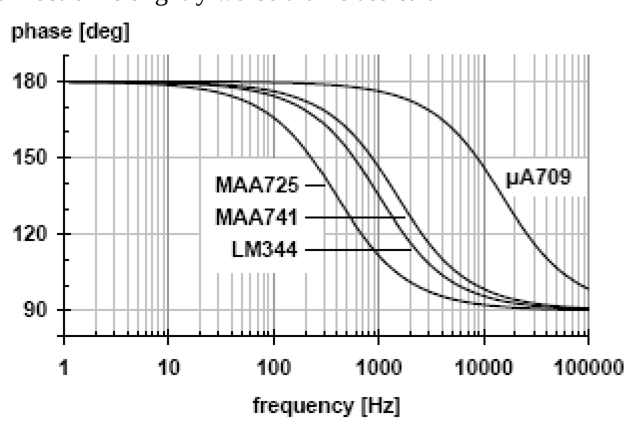

Fig. 15 phase response at R_0 = 1 kΩ

Because transmission voltage temperature drift amplifier has gain approximately $R_2/(R_1 \| R_0)$. The basic connection of operational amplifier is therefore especially suitable for amplifying the AC voltage, the fluctuations in the output DC voltage level of the operational amplifier by about 50-100 mV due to temperature changes in the area is not a problem, but better noise characteristics prevail. In particular, the advantages of this treatment reflected the differential involvement with one or two resistors R_0, possibly using other passive elements [5].

V. Non-inverting Operational Amplifier with Differential Input Unbalanced

Involvement of the operational amplifier with a resistor in a virtual zero, according to Fig. 10, can be modified into the next version, which allows a simple application for voltage amplification in a large range of values selectable transmission (amplification) using a single variable passive element. The usefulness of such variants is a simple universal circuit arrangement of other elements of the amplifier. Other circuit parameters remain involved in normal and acceptable values for this application.

Typical differential amplifier according to [1] and [9] (Fig. 16) is designed for processing signals from sources connected symmetrical lines. The advantage of this circuit is theoretically perfect suppression of the summation signal, usually interference induced to the connecting wires.

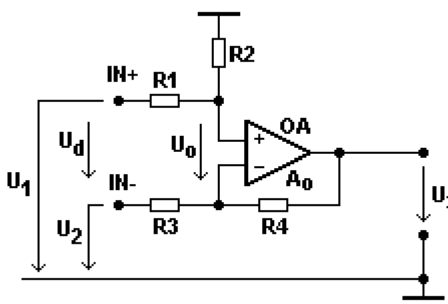

Fig. 16 scheme of the classics defferential amplifier

Assuming that $R_1 = R_3$, $R_2 = R_4$ and R2 = $A_0 \rightarrow \infty$, then according to [1] and the other for the output voltage U_3 are

$$U_3 = (U_1 - U_2) \cdot \frac{R_2}{R_1} = U_d \cdot \frac{R_2}{R_1} \tag{24}$$

Where $U_d = U_1 - U_2$ is the differential (differential) input-voltage operational amplifier. For the real operational amplifier can be according to [1] and others to derive an equation for calculating the output voltage U_3 shaped

$$U_3 = (U_1 - U_2) \cdot \frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{A_0} \cdot \left(1 + \frac{R_2}{R_1}\right)} \tag{25}$$

The new proposal involving amplifier (Fig. 17) combines the advantages of the differential stage (Fig. 14) with the characteristics of an amplifier with a resistor in a virtual zero (Fig. 10).

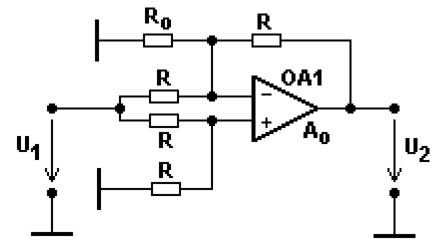

Fig. 17 scheme of the differential amplifier input unbalanced

In the [11] is one-input inverting operational amplifier with a resistor R_0 is derived for inverting transfer, at which $R_1 = R_2 = R_3 = R_4 = R$ leads to a new shape inverting transfer A_{in}.

$$A_{in} = -\frac{1}{\frac{2}{A_0} + 1 + \frac{R_0}{2 \cdot R_0 + R}} \tag{26}$$

The differential operational amplifier can be used for its non-inverting input, which is not included in the resistor R_0, derived in the same condition $R_1 = R_2 = R_3 = R_4 = R$, the transfer A_n non-inverting input of this, the equation of the form

$$A_n = \frac{1}{2} \cdot \frac{1}{\frac{1}{A_0} + \frac{R_0}{2 \cdot R_0 + R}} \tag{27}$$

When connected in parallel both inputs are then the sum of transmission A_n and A_{in}. Assuming that the voltage gain operational amplifier load A_0 is greater than 10^6 and the amplification circuit is chosen in the range of 10^{-3} to 10^3, can be members of the (26) and (27), includes the A_0 put equal to zero and adding the following simplified receive transmissions resulting A_{TOT}-shaped transmission

$$A_{TOT} = \frac{R}{2 \cdot R_0} \tag{28}$$

From (28) shows that a single resistor R_0 is easy to change the overall transmission amplifiers, if we choose appropriately the same size of the other resistors in the circuit.

The advantage of this solution is that the regulatory element of R_0 is not a direct signal path and one outlet is connected to signal ground. This will largely reduce clogging of interference signal in the regulation of income when using normal potentiometer thus reduce noise collector, which is seen in cases where the signal is processed through a potentiometer. Transmission parameters, like the preceding circuit, depend on the values of resistors and operational amplifiers used. When using precision resistors (at least 0.1 % accuracy) and precision instrumentation operational amplifier (Fig. 18, Fig. 19) can be expected when disconnected resistor R_0. A_{TOT} transfer at -100 dB.

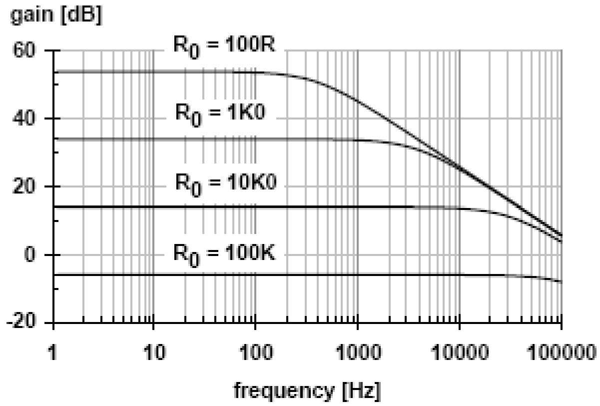

Fig. 18 frequency response at R_0 = 100 Ω to 100 kΩ operational amplifier MAA725

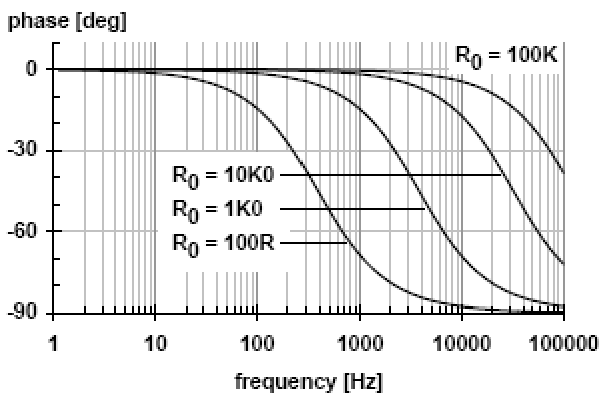

Fig. 19 phase response at R_0 = 100 Ω to 100 kΩ operational amplifier MAA725

Another modification of the wiring may be used for the development of frequency-dependent transmission cells, while preserving all the advantages of using a bipolar op amp circuitry and baseline characteristics (e.g. reducing the output noise voltage due to the reduction of the value of R_0, while increasing gain).

For those involved also have the option to replace the transistor as a resistor R_0 and get involved, which would have been reflected in the regulatory circuits of audio dynamics compressors or automatic circuit balancing technique sensitivity at higher frequencies [8]. Such involvement can also use circuits constructed from discrete components. These circuits are usually designed as a customer for a specific use and usually are made of selected components with minimum tolerances. These circuits can be reasonably expected to significantly lower variance parameters, and thus significantly reduce the negative effects.

For the temperature dependence of offset voltage of the amplifier with true differential input unbalanced conclusions set out in the amplifier with a resistor in a virtual zero.

Change the DC offset is dependent on the choice of resistors R and R_0 and the symmetry and type of operational amplifier. Example for R = 100 kΩ and R_0 in the range of 1 kΩ to 10 MΩ is shown in the chart for operational amplifiers and MAA725 and MAA741 (Fig. 20).

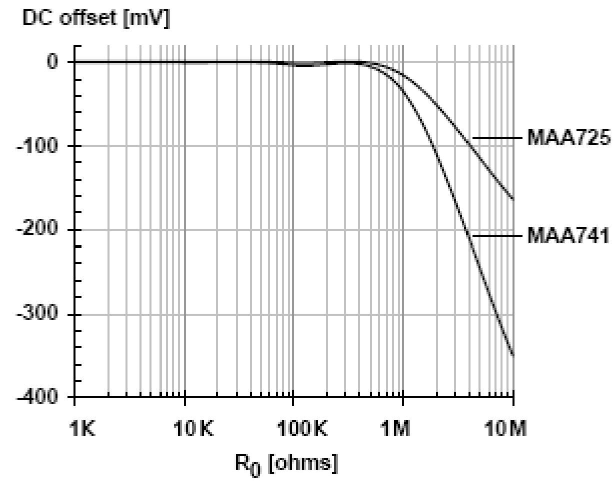

Fig. 20 DC offset dependence on the value of R_0 and the type of operational amplifier (R = 100 kΩ)

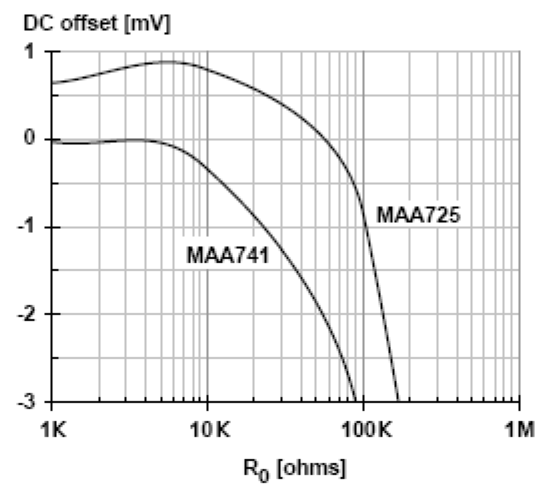

Fig. 21 detail of DC offset dependence on the value of R_0 and the type of operational amplifier (R = 100 kΩ)

VI. Conclusion

Proposed involvement of operational amplifiers has been developed especially for signal processing of current and voltage sensors in the electricity and industrial drives. Primarily, therefore, expected operating frequency of 50/60 Hz with the functionality of up to 5 kHz using a frequency converter. Another possibility is the application of measurement techniques, low frequency signals and DC applications. For low frequency applications it is necessary to use an operational amplifier with a guaranteed minimum bandwidth 20 Hz to 20 kHz in the whole range of anticipated profits or regulation.

All those involved can be used even in circuits constructed from discrete components or a combination of operational amplifiers and discrete components. Such circuits are usually designed as a customer for a specific use and usually are made of selected components with minimum tolerances. These circuits can then be reasonable to assume a significantly lower dispersion parameters, tolerances and guaranteed result in significant reduction of negative effects.

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