Design and modelling of operational amplifier for application in energy systems

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Problem statement

It is known that the operational amplifiers are important building blocks of modern electronics and they are used extensively in many industrial applications such as power engineering,, energy systems, electrical engineering, machinery control systems etc. [1]. For instance, the use of operational amplifiers in electrical device of electronics of agricultural machinery gives possibility increase the efficiency of agro-industrial complex production and significantly increased the productivity [2].

It is important to note that modern microelectronics produces electronic components in small metal-polymeric packages such as a SOT, QFN and others [1, 3]. In this aspect, in Russia, one of the main tasks in electronics industry is the development of integrated circuits for analog signal converters in metal-polymer small-sized packages, as well as the development and development of technology and the replacement of imported analogues.

Therefore, within the framework of the import substitution program, russian electronic company the JSC «GRUPPA KREMNY EL» (Bryansk, Russia) launched the production of new power electronics components (silicon carbide Schottky power diodes, transistors, etc.) in small-sized metal-polymer packages [4]. For instance, in our previous studies it is established that characteristics of the high-voltage silicon carbide Schottky diodes and power silicon bipolar junction transistor made in small type of metalpolymeric packages [4-6] are comparable with the similar leading components types.

Further, to take full advantage of the benefits of amplifiers and ensure the process of introducing new electronic systems, a detailed analysis and evaluation of their characteristics is necessary [1, 3]. It is important to perform a preliminary assessment of various modes of operation of electronic circuits, taking into account the static and dynamic modes of operation of operational amplifiers, their operating frequency range, power gain, and circuit stability conditions [1, 3].

In presented study the main goal is the design and macromodel development of single channel operational amplifier, carrying out of simulation and macromodel verification of a main amplifier's characteristics with aim of following serial industry production by «GRUPPA KREMNY EL» in modern small-sized type of metal-polymeric package (SOT-23-5).

Materials and methods

The method design macromodel for single channel operational amplifier IS-OU1 with following main characteristics: ± 15 V supply voltage, offset voltage ±7 mV, low supply current ~1.3 mA, slew rate ~0.4 V/μs, open loop gain ~100-110 dB, gain-bandwidth product ~0.7-1 MHz, output voltage swing ± 14 V. For modelling the operational amplifier with SPICE was chosen nonlinear operation amplifier model is based on n-p-n type bipolar transistors [3, 5]. The equivalent circuit of the operational amplifier is shown in Figure 1. of measuring of dV/dt value is implemented by the experimental tester which scheme is presented below in Fig. 1 [M.H. Rashid, SPICE for Power Electronics and Electric Power (CRC Press/Taylor & Francis Group, Boca Raton, 2001)].

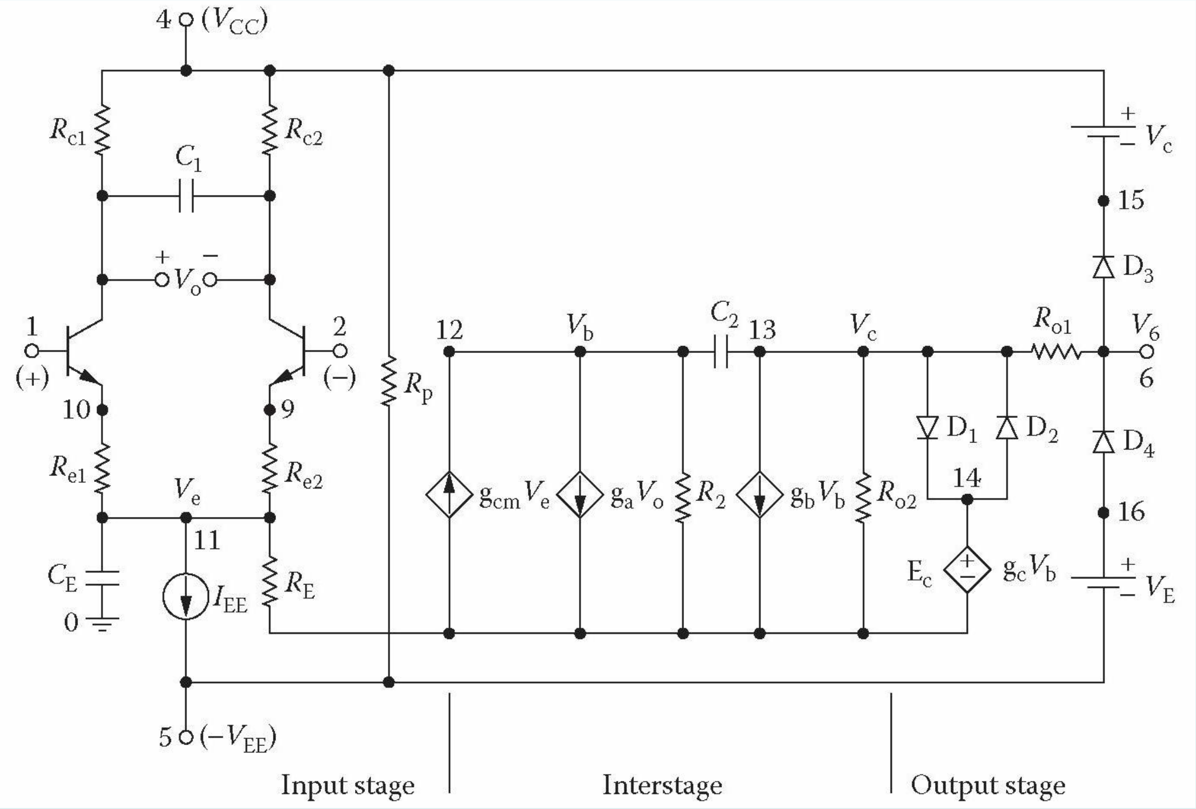


Figure 1. The principal electric circuit diagram of the IS-OU1 operation amplifier of the proposed macromodel [M.H. Rashid, SPICE for Power Electronics and Electric Power (CRC Press/Taylor & Francis Group, Boca Raton, 2001)].

Materials and methods

The parameters for operational amplifier components in circuit were calculated for appropriation with operational amplifier characteristics and written down as subcircuit that is presented in Fig. 2. The macromodel can be used as a subcircuit with a .SUBCKT command in Micro-Cap 12 model editor as SPICE circuit program that gives us to obtain a SPICE macromodel of the IS-OU1 operational amplifier. Afterwards for testing of the operational amplifier obtained macromodel was added to Micro-Cap 12 program base as a IS-OU1.lib library file.

```
* ---- IS-OU1 operational amplifier model subcircuit ----
.subckt IS-OU1    1 2 3 4 5
*                 | | | | |
*                 | | | | output
*                 | | | negative power supply
*                 | | positive power supply|
*                 | inverting input
*                 non-inverting input
*
  c1    11 12 2.8868E-12
  c2     6  7 10.000E-12
  dc     5 53 dy
  de    54  5 dy
  dlp   90 91 dx
  dln   92 90 dx
  dp     4  3 dx
  egnd  99  0 poly(2) (3,0) (4,0) 0 .5 .5
  fb     7 99 poly(5) vb vc ve vlp vln 0 127.32E6 -1E3 1E3 130E6 -130E6
  ga     6  0 11 12 62.832E-6
  gcm    0  6 10 99 628.32E-12
  iee   10  4 dc 5.0001E-6
  hlim  90  0 vlim 1K
  q1    11  2 13 qx1
  q2    12  1 14 qx2
  r2     6  9 100.00E3
  rc1    3 11 15.915E3
  rc2    3 12 15.915E3
  re1   13 10 5.5698E3
  re2   14 10 5.5698E3
  ree   10 99 40.000E6
  ro1    8  5 50
  ro2    7 99 25
  rp     3  4 36.217E3
  vb     9  0 dc 0
  vc     3 53 dc 1.7979
  ve    54  4 dc 1.7979
  vlim   7  8 dc 0
  vlp   91  0 dc 20
  vln    0 92 dc 20
.model dx D(Is=800.00E-18)
.model dy D(Is=800.00E-18 Rs=1m Cjo=10p)
.model qx1 NPN(Is=800.00E-18 Bf=83.333E3)
.model qx2 NPN(Is=800.0000E-18 Bf=83.333E3)
.ends IS-OU1
```

Figure 2. The text macromodel listing for the IS-OU1 operation amplifier.

Results and discussions

The testing results of macromodel in buffer (voltage follower) mode which is used to buffer signals by presenting a high input impedance and a low output impedance. In this case the output voltage equals to the input voltag.
In Figure 3 is shown testing circuit for testing of SPICE macromodel of operational amplifier in this mode. The operational amplifier was connected to ± 15 V supply voltage and then to non-inverting node was applied signal with amplitude voltage of 14 V (1 MHz the signal frequency, 1 kHz the carrier frequency, 1mΩ the serial resistance).
Circuit and testing results of input voltage dependence on output voltage for operational amplifier of IS-OU1 in voltage follower mode are presented below in Figure 3.

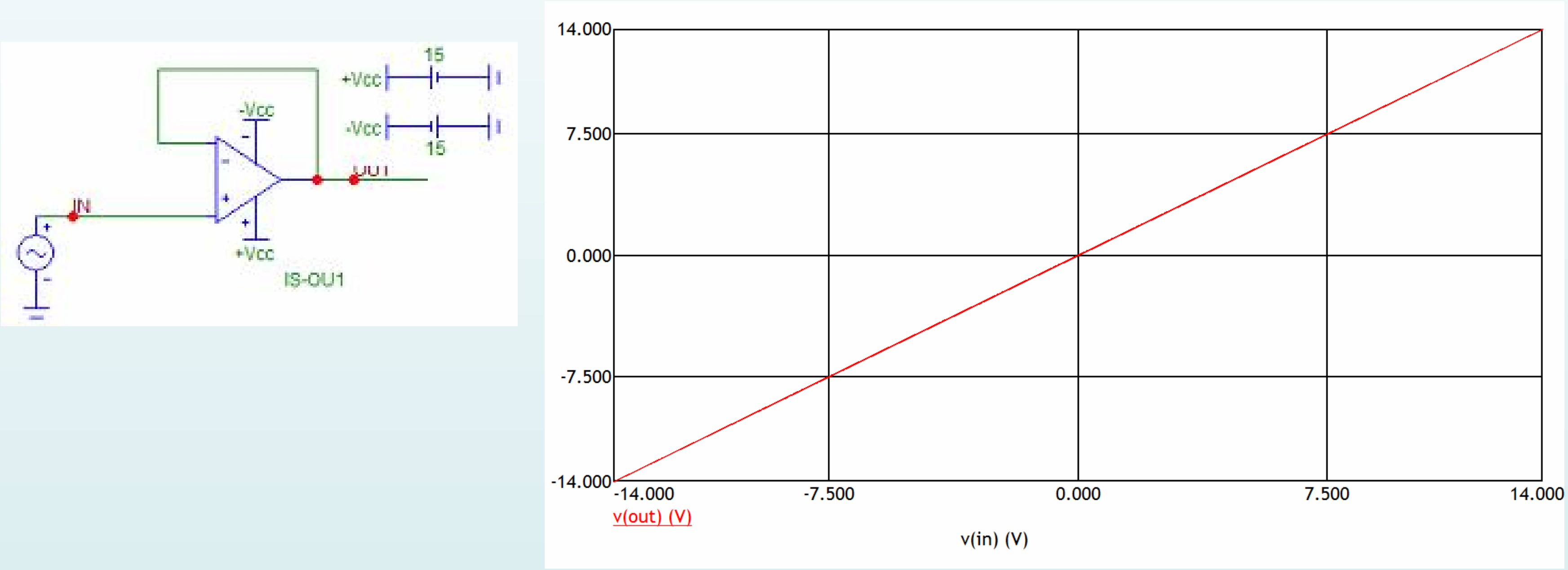


Figure 3. Circuit for testing of IS-OU1 operational amplifier macromodel in voltage follower mode (left); The input voltage dependence on output voltage for operational amplifier of IS-OU1 in voltage follower mode (right).

Results and discussions

The testing results of transient simulation for **operational amplifier of IS-OU1 macromodel in buffer (voltage follower) mode are shown in Figure 4. As follows from Figure 4 amplifier demonstrates required mode of operation in buffer mode with voltage amplitude** ± **14 V.**

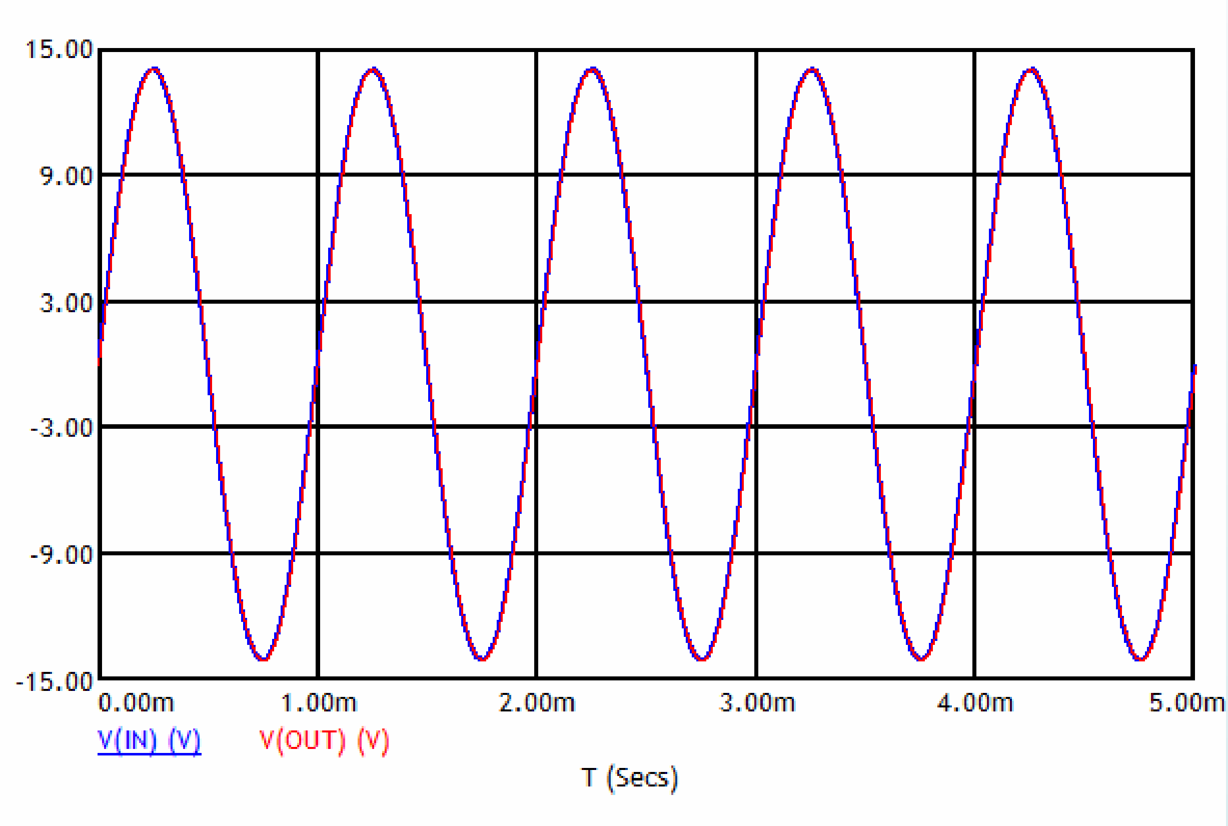
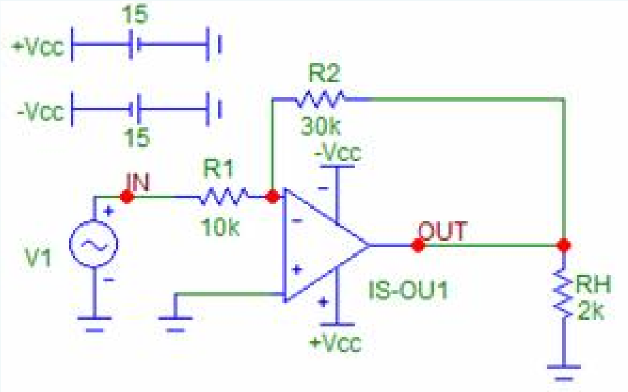


Figure 4. The input and output voltage depending on time for IS-OU1 operational amplifier in voltage follower mode.

Results and discussions

In Figure 5 is shown testing circuit for testing of SPICE macromodel of operational amplifier in inverting amplifier mode with V_1=3 V, R_1=10 kΩ, R_2=30 kΩ, *RH*=2 kΩ (load resistance).
The operational amplifier was connected to ± 15 V supply voltage and then to non-inverting node was applied signal with amplitude voltage of 14 V (1 MHz the signal frequency, 1 kHz the carrier frequency, 1mΩ the serial resistance).
Then the IS-OU1 operational amplifier was connected to ± 15 V supply voltage and then to inverting node was applied signal with amplitude voltage V_1=3 V (1 MHz the signal frequency, 1 kHz the carrier frequency, 1 mΩ the serial resistance).
Figure 5 presents transient simulation results of amplifier macromodel testing in inverting amplifier.



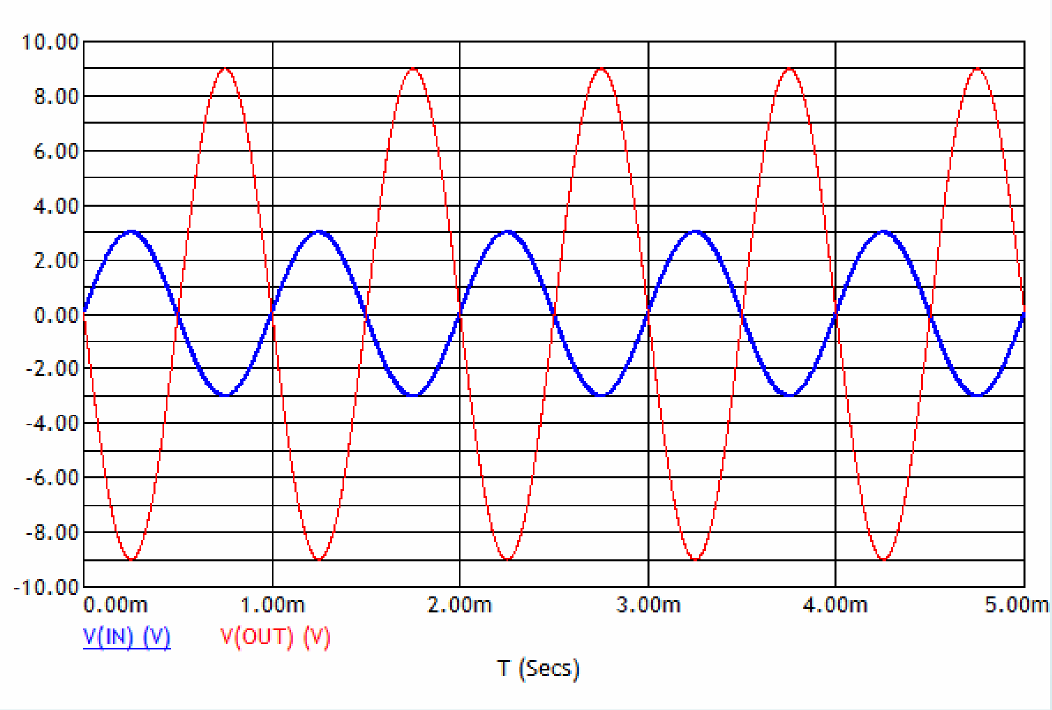


Figure 5. Circuit for testing of IS-OU1 operational amplifier macromodel in inverting amplifier mode (left); The input and output voltage depending on time for IS-OU1 operational amplifier in inverting amplifier mode (right).

Results and discussions

From AC simulation results, presented on Figure 6, the bandwidth is determined by looking at the 6.542 dB point, which is located at 3 dB given a signal gain of 9.542 dB gives us value of 265.449 kHz.
The obtained by calculation the amplifiers bandwidth *BW* equals 275 kHz.

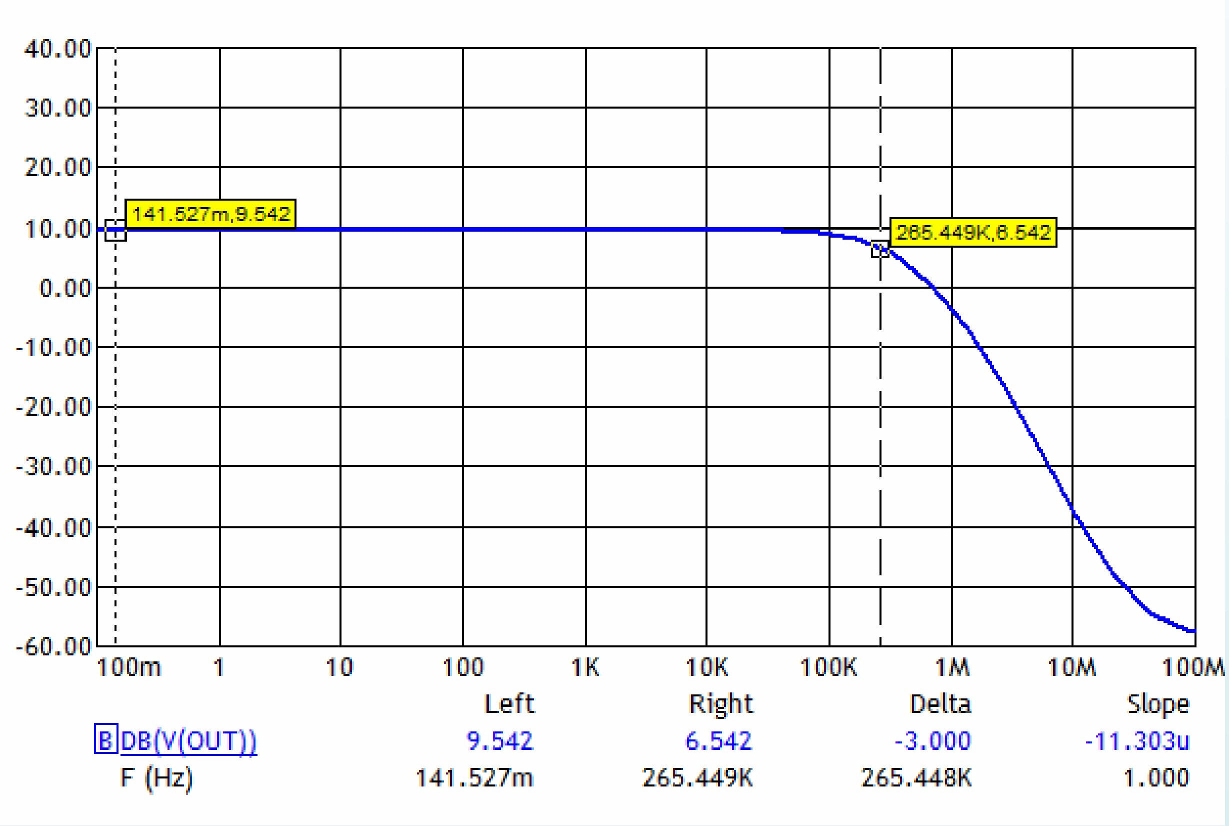
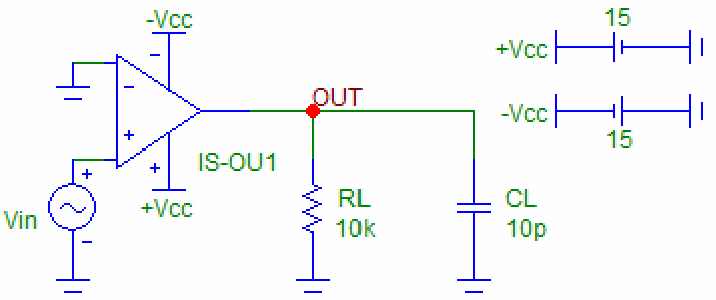


Figure 6. The voltage gain (dB) depending on frequency (Hz) for IS-OU1 operational amplifier in inverting amplifier mode.

Results and discussions

In Figure 6 is shown testing circuit for determination of the open loop gain for IS-OU1 operational amplifier.
As can be seen from the Figure 6 the obtained open loop gain value equals ~105.9 dB (that is closely acquainted with range (100-110 dB) in proposed macromodel) and unity gain cross frequency value f_T=859.57 kHz.



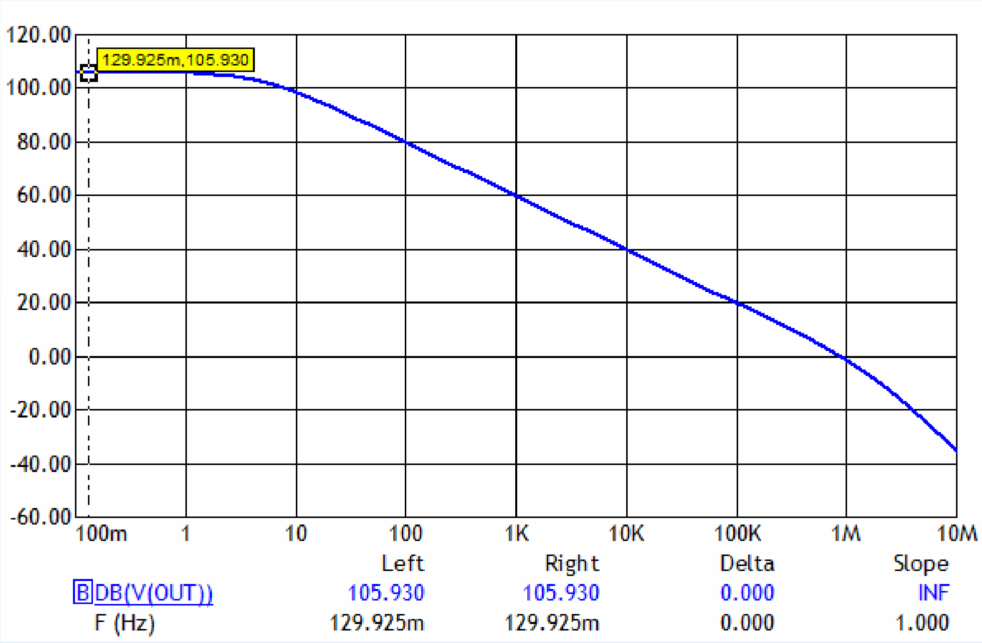


Figure 6. Circuit for determination of the open loop gain for IS-OU1 operational amplifier (left); The open loop gain (dB) depending on frequency (Hz) for IS-OU1 operational amplifier macromodel (right).

Conclusions

In summary, macromodel of an operational amplifier IS-OU1 design is based on n-p-n type bipolar transistors has been developed. The proposed macromodel is developed using standard algorithm and build-up SPICE techniques for macro-modelling of operational amplifiers with $\pm$ 15 V supply voltage and simulates the characteristics, including output voltage swing 14 V, open loop gain ~105.9 dB, adequate operation in voltage follower and inverting amplifier modes.

The proposed design and model can be used for industry production and processing the test signals and to reduce the computational effort needed for fault simulations in large engineering electrical systems.

Acknowledgements

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