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ŠOTNER, R.; DOMANSKÝ, O.; LANGHAMMER, L.; PETRŽELA, J.

Proceedings of 30th International Conference Radioelektronika (RADIOELEKTRONIKA 2020),
pp. 1-6

eISBN: 978-1-7281-6469-4

DOI: <https://doi.org/10.1109/RADIOELEKTRONIKA49387.2020.9092366>

Accepted manuscript

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Comparison of Simple Design Methods for Voltage Controllable Resistance

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Abstract—This paper compares several ways of electronic resistance control for tunable applications (filters, oscillators, amplifiers, etc.). Simulation (PSpice) and experimental tests of basic J-FET transistor-based adjustable resistor, optocoupler as well as more advanced active solutions using active devices (variable gain amplifiers, voltage-mode multiplier) are performed in order to see available linear range, readjustability range and expected frequency features.

Keywords— Electronic control, J-FET, resistor, variable gain amplifier, voltage driving

I. INTRODUCTION

Integrated circuit design [1] offers very easy way of adjustability in applications depending on resistor value(s). Especially very simple construction of operational transconductance amplifier (OTA) [2]-[4] and its simple application for resistor emulation [2] represents the main benefit of this way. However, standard constructors and designers have quite limited possibilities. There are several ways including also discontinuously settable digital potentiometers [5], [6] or digital to audio converters [7]. Unfortunately, many analog and mixed applications and systems require continuous adjustability of resistance value where these solutions are not suitable. The continuous control of resistance value, solved by analog way, has certain limitations. The highest issues are linearity of voltage dependence across the element on current and frequency bandwidth limitation. Standard component base, available for designers, offers several types of J-FET and MOSFET transistors [8], that can be used for resistor replacement (operating in linear/triode regime [1], [8]) but also some special types of electronically adjustable active elements can be selected as better option for indicated features (resistivity control in circuit application with operational amplifiers for example).

The following text compares several typical and also unusual ways of electronic control of resistance and compares their linearity, range of applied current and voltage across the element, frequency bandwidth and range of available resistance value.

II. EASILY AVAILABLE METHODS OF RESISTANCE CONTROL

A. Single J-FET transistor

The simplest method of replacement of resistor by electronically adjustable equivalent supposes usability of MOSFET transistor [1], [8] in triode/linear (ohmic regime). The method is very simple and straightforward but result has several important drawbacks and limitations discussed in experimental part. The basic circuits using depletion Junction

FET (J-FET) [8] of N channel polarity are shown in Fig. 1. The driving voltage V_{set} has negative polarity for this type of transistor. Large signal analysis of circuit in Fig. 1(a) determines equivalent resistance of JFET in form ($V_{GS(off)}$ is threshold voltage and I_{DSS} is maximal drain short channel current for zero bias):

$$R_{eq_large} = \frac{V_{GS(off)}}{I_{DSS} \left[(V_{GS} - V_{GS(off)}) - \frac{V_{DS}}{2} \right]} \quad (1)$$

Small-signal resistance (for $V_{DS} < V_{GS} - V_{TH}$) is defined as:

$$R_{eq_small} = \frac{V_{GS(off)}}{I_{DSS} (V_{GS} - V_{GS(off)})} \quad (2)$$

unfortunately, nonlinearity of this solution for larger V_{DS} voltages is high (usability up to tens of mV and low tens-hundreds of μA), therefore Senani et al. [9], [10] presented improved version using resistor divider in Fig. 1(b) (having equal resistances) in order to reduce influence of V_{DS} in (1). This modification has form:

$$R_{eq} \cong \frac{V_{GS(off)}^2}{I_{DSS} (V_{set} - 2V_{GS(off)})} \Big|_{R_a=R_b=R} \quad (3)$$

The values of $R_{a,b}$ should be several times (100 k Ω) larger than expected channel resistance R_{eq} . However, the range of resistance adjustability is very narrow.

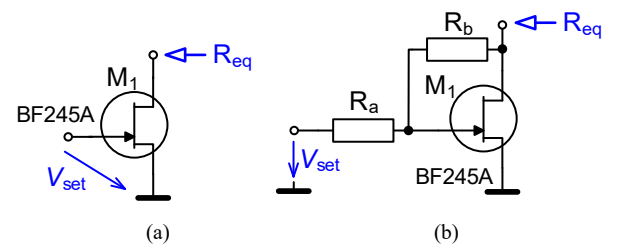


Fig. 1. J-FET(N) grounded resistors: a) basic concept, b) modified concept.

B. Optocoupler

Optocouplers, having resistive output port, were very popular in recent works as parts for adjustability and tunability of oscillation frequency and oscillation condition in several types of modern oscillators [11]-[14]. However, types (3WK16341) used in [11]-[14] are quite obsolete and unavailable. The modern type of the optocoupler NSL-32SR3 [15] in Fig. 2 represents quite new device very useful for many applications [16]. These resistive equivalents have quite slow reaction on driving voltage (units of ms) but it is not important issue in adjustable applications (condition for oscillation control [11]-[14]). The resulting form for equivalent resistance is:

Research described in the paper was supported by Czech Science Foundation project under No. 19-22248S. For the research, infrastructure of the SIX Center was used.

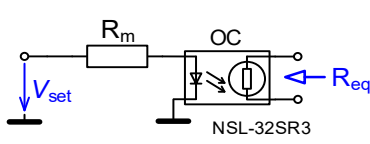
$$R_{OC} \cong 0.2 \cdot \left(\frac{R_m}{V_{OC} - V_{th}} \right) \cong 0.2 \cdot \left(\frac{R_m}{V_{OC} - 1.6} \right). \quad (4)$$


Fig. 2. Optocoupler with resistive output used as floating resistance equivalent.

C. Variable Gain Amplifier

The variable gain amplifier (VGA) [3] in the function of equivalent adjustable resistance offers very useful way and also good linearity. The basic operation supposes resistor connected in the feedback and the variable gain serves for control of overall resistance in the input node (Fig. 3). The resulting equation for overall resistance has form:

$$R_{eq} \cong \frac{R_{ext}}{(1+A)}, \quad (5)$$

for solution in Fig. 3(a) and

$$R_{eq} = R_{ext} (1+A), \quad (6)$$

for solution in Fig. 3(b). The application of VGA in the resistance equivalent offers simple possibility for negative resistance emulation ($\mp \leftrightarrow \pm$). Unfortunately, instability issues must be solved in the case of negative resistance quite frequently. This solution was used in recent works very effectively [17]-[19]. There are devices that allow linear driving of gain A (VCA822 [20], VCA824 [21]). Exponential driving of voltage gain A ($A = 10^{2(V_{set} - 1)}$) offers very large range of resistance control in some types of VGA (VCA810 [22] for example).

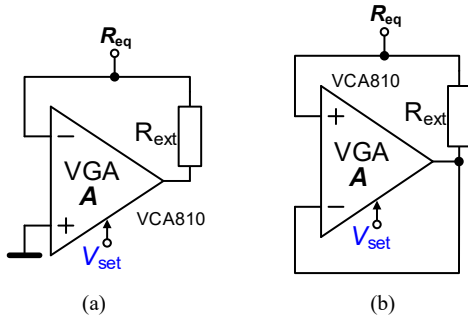


Fig. 3. Grounded equivalent resistance based on variable gain amplifier: a) single feedback, b) two feedbacks.

The voltage-mode multipliers (AD835 [23] for example) also offer very interesting feature for linearly tunable resistance. Typical concept of the controllable resistance is shown in Fig. 4 and has practically identical topology as previous solution using VCA. Therefore, also definition and equation for equivalent resistance has identical form as (5). Again, polarity of R_{ext} connection is not important because of simple change by driving voltage $\pm V_{set}$.

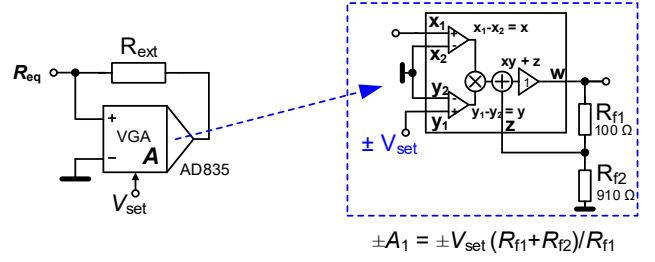


Fig. 4. Grounded equivalent resistance based on variable gain amplifier using voltage-mode multiplier.

III. ANALYSIS OF PRESENTED SOLUTIONS

Solutions of discussed adjustable resistance circuits are analyzed by computer simulations (Pspice) and experimentally (optocoupler NSL-32SR3 has no model).

A. Simulation of J-FET in linear regime

The simplest method of electronic resistance adjustability, shown in Fig. 1(b), was simulated for BF245A J-FET element [24] using both identical resistors $R_a = R_b = R = 100 \text{ k}\Omega$. and parameters $V_{GS(off)} = -1.8 \text{ V}$, $I_{DSS} = 4 \text{ mA}$. The DC driving voltage V_{set} was changed between -1.79 and -0.1 V while resistance varied from 560 up to 211Ω (theory $450 \rightarrow 231 \Omega$). The analysis in Fig. 5 indicates DC behavior and limits of linearity (up to $\pm 1.8 \text{ mA}$ for maximum 560Ω). Frequency features of the impedance are analyzed in Fig. 6 (good performance up to 10 MHz approximately – flat response). The dependence of resistance on driving parameter (R_{eq} vs V_{set}) is indicated in Fig. 7.

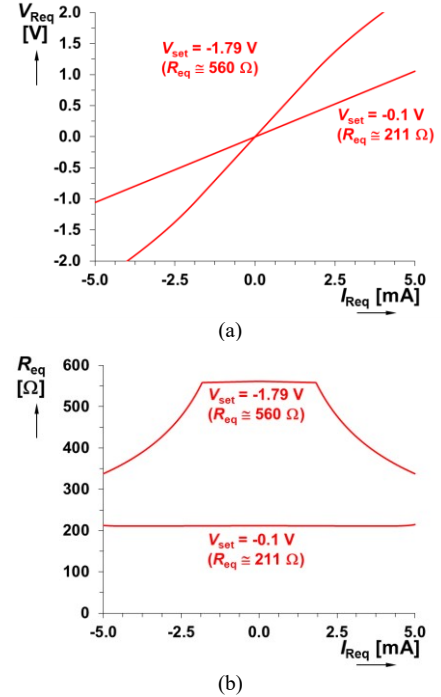


Fig. 5. J-FET-based resistor analysis: a) voltage across element vs current trough element, b) resistance in dependence on current trough element.

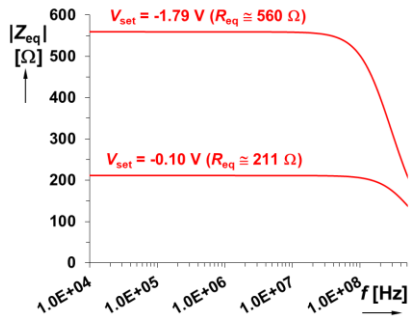


Fig. 6. Frequency responses of impedance magnitude (J-FET).

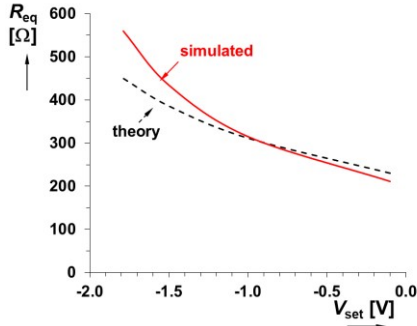


Fig. 7. J-FET Dependence of resistance on driving voltage (J-FET).

B. Measurement of optocoupler

The device NSL-32SR3 [15] in Fig. 2 was experimentally tested for parameters: $R_m = 2.2 \text{ k}\Omega$, $V_{\text{set}} = 1.62 \rightarrow 5 \text{ V}$. The R_{eq} varied between $15 \text{ k}\Omega$ and 160Ω ($22 \text{ k}\Omega \rightarrow 127 \Omega$ theoretically). Resulting behavior in DC domain indicates excellent performance in dynamics and linearity (Fig. 8) in wide range (more than $\pm 30 \text{ mA}$) for $R_{\text{eq}} = 160 \Omega$. Flatness of impedance magnitude frequency responses (Fig. 9) is observable up to 500 kHz ($R_{\text{eq}} = 15 \text{ k}\Omega$). Figure 10 shows the dependence of R_{eq} on V_{set} .

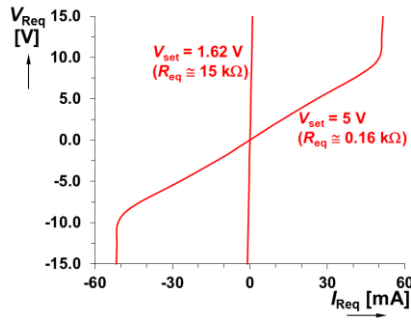


Fig. 8. Voltage across the optocoupler element vs current through element.

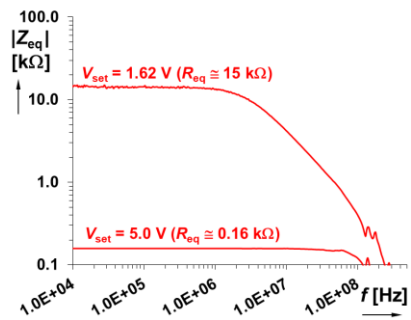


Fig. 9. Frequency responses of impedance magnitude (optocoupler).

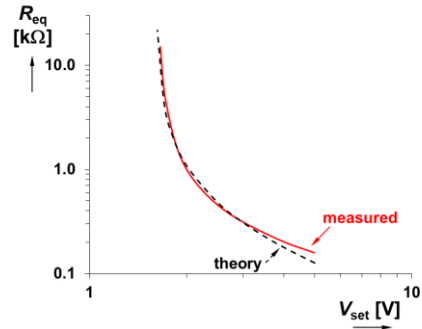


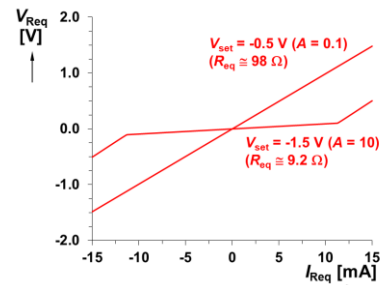
Fig. 10. Dependence of resistance on driving voltage (optocoupler).

C. Simulation of Variable Gain Amplifier Based Resistance

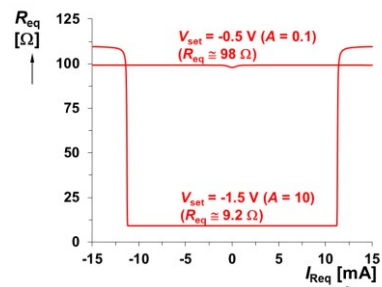
Tests of VGA using VCA810 [22] in adjustable resistor (Fig. 3(a)) bring results valid for $R_{\text{ext}} = 100 \Omega$ and variation of $V_{\text{set}} = -0.5 \rightarrow -1.5 \text{ V}$. Dynamics with good linearity restricts into the range $\pm 10 \text{ mA}$ (Fig. 11) with flat magnitude up to 10 MHz (Fig. 12) and adjustability of resistance R_{eq} in Fig. 13 between 98 and 9.2Ω ($91 \rightarrow 9.1 \Omega$ theoretically).

The second version of the circuit in Fig. 3(b) allows narrower range of good linearity (Fig. 14) than solution in Fig. 3(a), approximately only $\pm 1 \text{ mA}$ for $R_{\text{eq}} = 1.2 \text{ k}\Omega$ ($V_{\text{set}} = -1.5 \text{ V}$). Frequency features show flat magnitude up to 3 MHz (Fig. 15). Adjustability of R_{eq} was tested between 0.12 and $1.2 \text{ k}\Omega$ ($0.11 \rightarrow 1.1 \text{ k}\Omega$ theoretically), see Fig. 16.

Two previous solutions used exponentially adjustable gain. However, the linear driving of gain can be also interesting. The typical modern device known as voltage-gain multiplier AD835 [23] was selected for these purposes (Fig. 4). The value of $R_{\text{ext}} = 100 \Omega$ was applied also in this case but driving voltage V_{set} was adjusted from 0.1 up to 1 V . Figure 17 illustrates better width of linearity than previous case ($\pm 5 \text{ mA}$) for very similar range of R_{eq} between 0.19 and $0.9 \text{ k}\Omega$ ($0.2 \rightarrow 1.1 \text{ k}\Omega$ in theory). Frequency features in Fig. 18 show constant R_{eq} value up to 200 kHz . Dependence of R_{eq} on V_{set} is given in Fig. 19.



(a)



(b)

Fig. 11. The first VGA-based resistor analysis : a) voltage across element vs current through element, b) resistance in dependence on current through element.

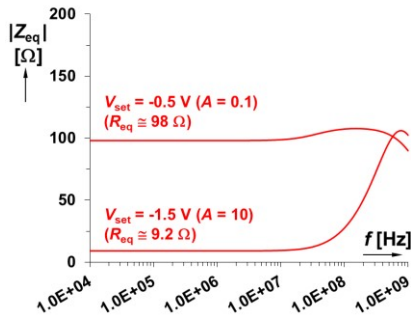


Fig. 12. Frequency responses of impedance magnitude (first VGA-based resistor).

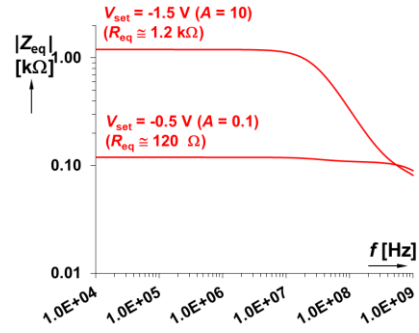


Fig. 15. Frequency responses of impedance magnitude (second VGA-based resistor).

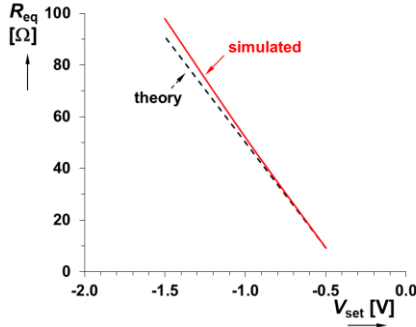


Fig. 13. Dependence of resistance on driving voltage (first VGA-based resistor).

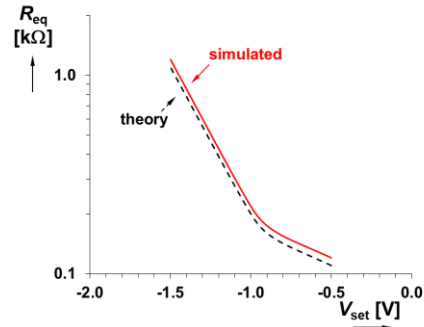
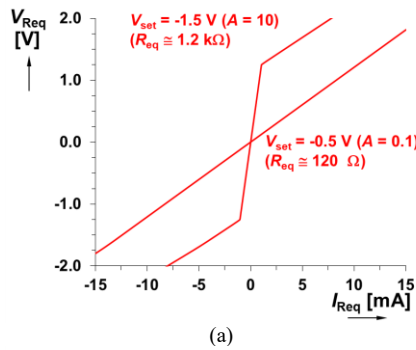
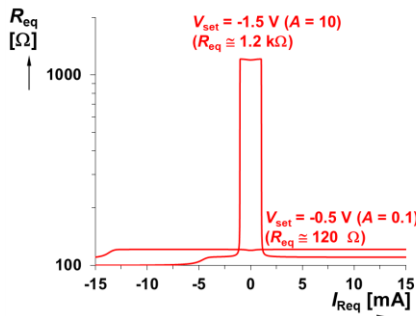


Fig. 16. Dependence of resistance on driving voltage (second VGA-based resistor).

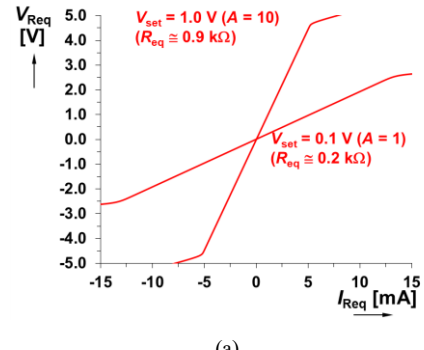


(a)

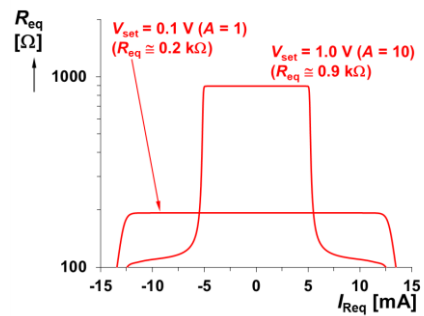


(b)

Fig. 14. The second VGA-based resistor analysis : a) voltage across element vs current through element, b) resistance in dependence on current through element



(a)



(b)

Fig. 17. Voltage-mode multiplier-based resistor analysis : a) voltage across element vs current through element, b) resistance in dependence on current through element

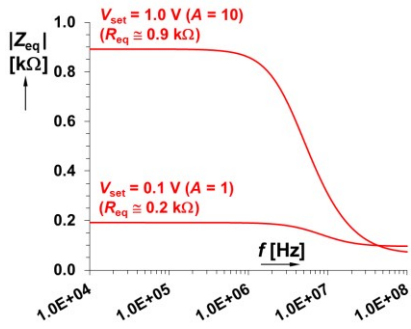


Fig. 18. Frequency responses of impedance magnitude (voltage-mode multiplier-based resistor).

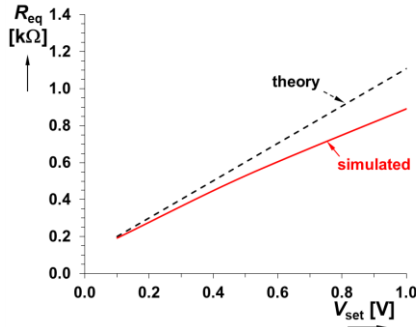


Fig. 19. Dependence of resistance on driving voltage (voltage-mode multiplier-based resistor).

TABLE I. COMPARISON OF STUDIED SOLUTIONS

Type	R_{eq} range [kΩ]	V_{set} range [V] (absolute)	Ratio ($R_{eq,max}/R_{eq,min} ; V_{set,max}/V_{set,min}$)	Frequency limit [MHz]	Linear range [mA]
Fig. 1(b)	0.21→0.56	0.1→1.8	0.15	10	±1.8
Fig. 2	15→0.16	1.62→5	30	0.5	±30
Fig. 3(a)	0.098→0.009	0.5→1.5	3.6	10	±10
Fig. 3(b)	0.12→1.2	0.5→1.5	3.3	3	±1
Fig. 4	0.19→0.9	0.1→1	0.5	0.2	±5

IV. COMPARISON OF STUDIED SOLUTIONS

All tested types were designed with very similar or identical values of external R_{ext} component (when applicable) in order to ensure very similar conditions for all tests. Table 1 shows comparison of studied solutions from several points of view (R_{eq} range, ratio of readjustability in dependence on applied driving voltage, frequency limitation, and linearity restriction). The conclusions are following. As expected, the J-FET has the narrowest range of R_{eq} control and linearity. Due to the simplicity, the frequency features should be good (about 10 MHz). Both VGA-based equivalent resistors have quite good ratio of readjustability. However, the linear dynamics of the second type (Fig. 3(b)) is very similar to J-FET (Fig. 1(b)) type (the worst one from the studied cases). The best dynamical performances were obtained for optocoupler in Fig. 2 (wide dynamical range of good linearity and readjustability ratio), however, frequency features are almost the worst from studied cases. The optocoupler represents very useful solution for circuit structures using

many floating passive resistors. Perfect examples of application are frequency filter [25], oscillator [16].

V. CONCLUSION

Presented results show important findings. Standard MOSFET or J-FET transistors are suitable only for very simple applications where quite narrow range of resistance (even for linearized solution) and quite low signal level (< 500 mV) is processed. However, many standard application work with significantly higher levels (typically more than 500 mV). The very simple way of usage of OTA-based adjustable resistance exists as discussed [2]. The IC design offers promising features when appropriate linearization method can be applied. However, the commercial availability of these devices (OTAs using differential pair) is very limited (two or three active products) and they suffer from bandwidth or linearity issues.

We tested five types of easily available electronically (voltage) adjustable equivalent of resistance operating in dynamics of units-tens of mA and frequency bandwidths in hundreds and units of MHz. These circuits can be used in various applications based on operational amplifiers and other active elements effectively.

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