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Galvanic separation of analogue signals

The article deals with the issues of galvanic separation of analogue circuits and methods to perform it. The authors described capacitive, inductive and optical couplings, separation with the use of processing as well as non-linearity correction of optoelectronic materials characteristics. The available solutions were presented and their characteristics.

key words: *galvanic separation, analogue systems, Pulse-Width Modulation (PWM), non-linearity correction*

1. INTRODUCTION

The analysis of solutions applied for the last few decades in devices equipped with analogue interfaces allows to observe a marked tendency to reduce the analogue part of these devices to an indispensable minimum. Thanks to the development and availability of AC and CA transducers, signal processors and programmable logic systems, it is possible to perform processing and transmission in a digital form in more and more applications. The same tendency is true about signal separation circuits. However, in particular cases it is still necessary to perform separation of analogue signals. Systemic separation of analogue circuits is usually more difficult that in the case of bi-stable signals, mostly due to the required linearity. The applied solutions depend on the parameters of separated signals (e.g. required accuracy, linearity, frequency band, amplitude), the requirements of separation as such (e.g. required isolation gaps, withstand voltage) and the function the separation performs.

2. INDUCTIVE AND CAPACITIVE COUPLINGS

The most frequently used types of couplings – capacitive and inductive – are linear and have certain amplitude and phase transfer characteristics in the function of frequency. Coupling characteristics result from the elements that are used to construct them and from spurious reactance. What is more, the couplings do not transfer the direct component.

Thus if the separated analogue signal includes the direct component and slow-changing components, and/or the transfer characteristics of the coupling do not allow to send the signal directly due to its too irregular waveform, it is necessary to apply input signal modulation of the carrier wave on the primary side of the separation and its de-modulation on the secondary side. This way it is possible to move the spectrum of the separated signal to such a position that the ratio of the signal width to its carrier frequency is adequately small and refers to the frequency range at which the wave of the coupling transfer characteristics is acceptably regular. The type of modulation and demodulation, along with a proper systemic solution differ depending on a concrete case. However, they are always related to higher systemic complication and higher energy demand.

In practical solutions, the carrier frequency is usually higher than 100 kHz, while the frequencies of transferred signals achieve the values of several dozen kHz. Due to physical characteristics, such as the decreasing capacity of the coupling (due to the increasing distance between the capacitor covers) and the decreasing mutual inductance (due to the increasing distance between the coils of the primary and secondary side of separation), the possibilities to achieve the required isolation gaps and breakdown resistance may be limited. The technological development allowed for inductive and capacitive separation in analogue integrated circuits. In the case of integrated isolated instrumental amplifiers, the use of internal transformers to perform couplings allows to maintain resolution from 12 to 16 bits and a carrier band up to several hundred kHz, however, their maximal voltage hardly ever reaches 10 kV and is often lower. Integrated amplifiers which make use of internal capacitive coupling have lower accuracy, not more than 12 bits, lower carrier band and lower maximum voltage, yet their production costs are lower too. Optical separators are fast, have low production costs and high voltage (typically from 4 to 7 kV) but, due to relatively high non-linearity, they are not used for direct analogue separation that requires high accuracy [1]. Inductive and capacitive couplings are used for galvanic separation of analogue signals, for example those in intrinsically safe separation circuits. In telephone and warning systems there are barrier systems which ensure galvanic separation at two-way transmission of analogue signals. Inductive coupling is used in AUI barriers by the TELOS company. These barriers not only perform galvanic separation for two-way separation of analogue signals, but also transmit other signals, e.g. signals about loop closing or changing the power supply polarity [9].

3. OPTICAL COUPLINGS

There are many different types of optocoupling elements on the market. The most commonly used is the element containing a LED diode and phototransistor. As photodetectors it is possible to use optothyristors, optotriacs and FET transistors as well. Their major task is to ensure separation of bi-stable signals, and for this purpose their parameters are usually optimized, i.e. small delay times or the possibility to cooperate with logic systems. As far as the key aspects of analogue separation are concerned, optoelectronic separating elements can transfer the direct component. However, their DC transfer characteristics are usually non-linear. There are two alternative methods of using non-linear optoelectronic elements to separate analogue signals: separation with the use of processing and separation with the use of non-linearity correction of elements characteristics.

3.1. Separation with the use of processing

If optoelectronic non-linear elements are to be used to send an analogue signal, they have to be applied in such a way so that they could work in a bi-stable manner, with the use of analogue signal amplitude to modulate the width of the sent pulses of constant frequency (PWM – Pulse-Width Modulation) or to modulate the frequency of sent pulses of constant width. The drawback of this solution is higher complexity of the circuit on the primary and secondary side. The advantage, in turn, is the possibility to reduce power consumption by working at the minimum sufficient amplitude level. A sample block diagram of an analogue separation circuit with processing can be seen in Fig. 1.

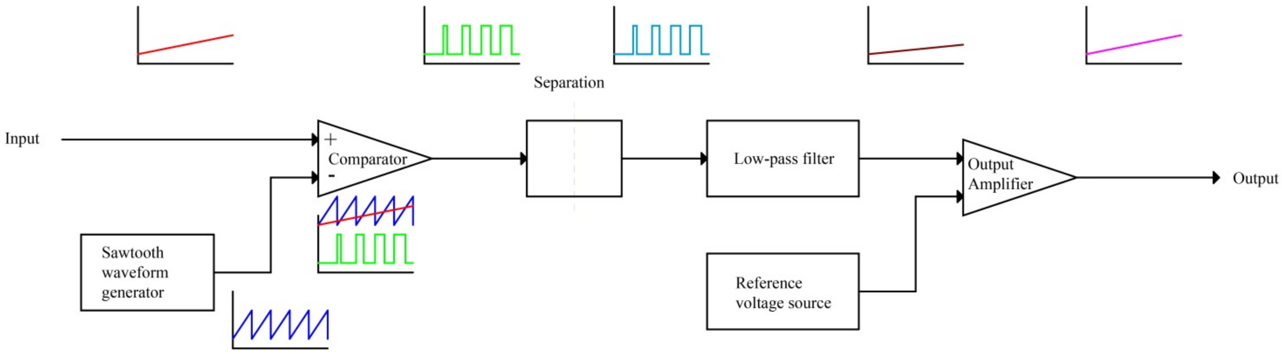

Fig. 1. Block diagram of analogue separation circuit with processing

3.2. Separation with the use of non-linearity correction of elements characteristics

Optoelectronic elements allow to perform separation with or without the use of a carrier waveform, as they transfer the constant component and slow-changing components. In such a situation, however, it is necessary to ensure the linearity of the carrier amplitude characteristics in the required working range. To provide the non-linearity characteristics of optoelectronic elements, feedforward- and feedback-based circuits are used. With such a solution, the accuracy of the non-linearity correction is mainly the result of the similarity of the elements characteristics, not only of the depth of the feedback, which is typical for feedback-based circuits in general.

4. NON-LINEARITY COMPENSATION

One of the most commonly used linear optocouplers is a circuit which includes a LED diode and a feedback PIN photo diode on the primary side, while on the secondary side – an output PIN photo diode. The LED diode is optically coupled with the separated PIN photodiode and the separated feedback photo diode. The feedback photo diode is lit by a small part of the luminous flux of the LED diode. This way it is possible to obtain a feedback signal which is used to regulate the drive current of the diode. This solution allows to compensate the non-linearity of the LED diode characteristics as well as time and thermal variability of the characteristics – this is an important advantage in comparison with compensation systems based solely on the similarity of characteristics of adequately connected, separate elements. On the output PIN photo diode a signal is obtained which is linearly dependant on the controlling luminous flux generated by the LED diode. Time and temperature stability of the input-output coupling coefficient is ensured by the use of adapted PIN photodiodes whose current suits exactly the luminous flux of the LED diode. In this arrangement the photo diode can be used as a photovoltaic or photoconductive element. When the photo diode is used as a photovoltaic element, it operates as a current source, similarly to a semiconductor diode polarized in the direction of conductivity. Then the values of current and output voltage depend on load resistance and the luminous flux. When the photo diode is used as a photoconductive element, the diode is primarily polarized in the reverse direction by an external source. Then the value of output current is proportional to the luminous flux [12]. One of the advantages of using the diode as a photoconductive element is the possibility to achieve a wider transfer band, of about 200 kHz, in comparison with the band of 40 kHz that can be achieved with the diode as a photovoltaic element [7]. Examples of such circuits are IL300 manufactured by VISHAY as well as HCNR200 and HCNR201 by AVAGO. Figure 2 features a basic operating system of an amplifier which separates a unipolar signal with input and output for positive voltages.

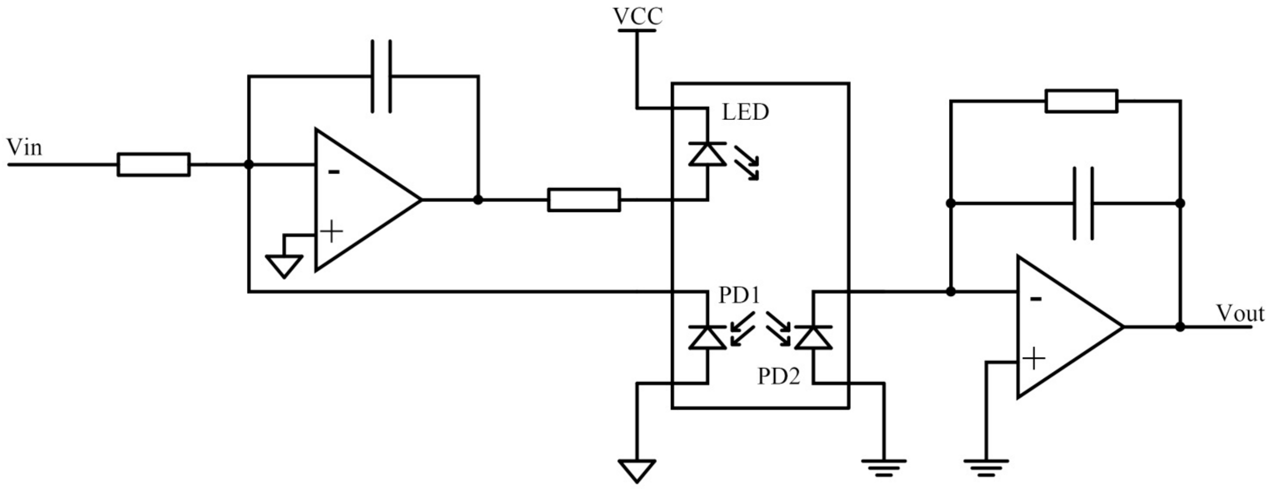

Fig. 2. Basic operating circuit of an amplifier which separates a unipolar signal with input and output for positive voltages (based on [3])

Thanks to its simple internal structure, the circuit is very universal in terms of its functionality and can be used in numerous configurations presented in [3].

In analogue optocouplers, for example in H11FxM optocouplers, IRED diodes are used as well as symmetrical, two-sided FET phototransistors. This element can be used as a resistor with separated control or as an analogue switch [6]. In order to avoid signal distortion caused by non-linear characteristics of output resistance in the IRED diode current function, the elements can be used with adequately small changes of the current amplitude. It is also possible to use them to separate signals with bigger amplitude ranges, thanks to the use of a feedback circuit, in which two optocouplers are used, in order to compensate non-linearity. Then the same current flows through series-connected LED diodes of two optocouplers. One optocoupler is used for separation, while the output of the other works in the feedback circuit of the diode regulation system [5]. An example of the above application is presented in Fig. 3.

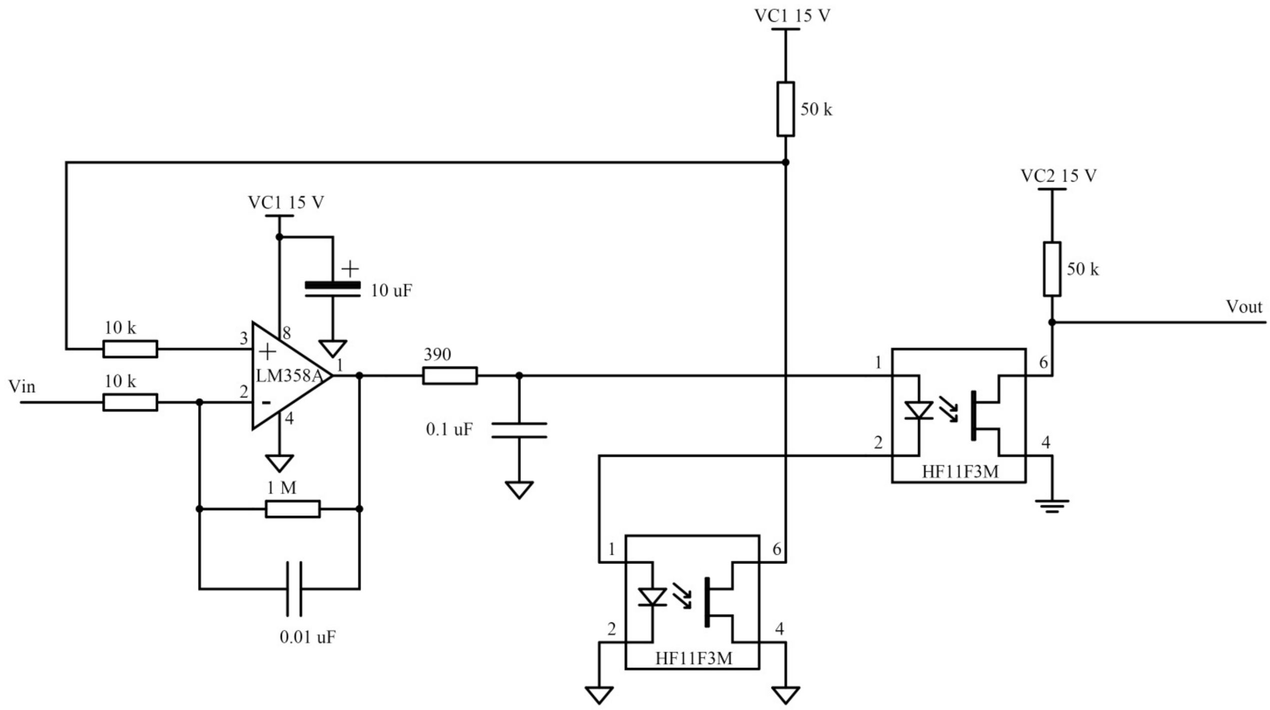

Fig. 3. Non-linearity compensation circuit of optocoupler characteristics which makes use of the characteristics similarity (based on [5])

However, it is important to note that such a compensation method is based only on the characteristics similarity. Therefore, due to minimal differences between the characteristics of applied elements, even those coming from the same production lot, the non-linearity correction accuracy is limited. A more advantageous compensation method is the above described, dedicated solution with two photodetectors integrated in one element: one for separation and the other for feedback. In this case the coupling is performed through the real luminous flux which falls on the output photodetector and the feedback photodetector simultaneously.

In the case of optical analogue coupling a solution is also an optocoupler, i.e. one with the input in the form of a LED diode and an output in the form of a photo-conductive cell. These elements operate like an electronically controlled potentiometer which has a resistor as an output element. The voltage in this resistor can be DC and/or AC, while the amplitude can vary between 0 and the maximal value determined by admissible parameters. Since the input proportionally affects the amplitude of the complex waveform at the output, the element can act as an analogue control element with optical separation. The conductivity characteristics of such an optocoupler (output resistance depending on input current) has a wide dynamical range and, additionally, the output resistance changes in a manner which is close to the linear one in the range of two or more decades. Still, such elements have a disadvantage, i.e. the hysteresis phenomenon or memory effect whose idea is that the input resistance depends not only on the temporary value of input current but also on the value that this current had adopted for a longer period of time. The material used in the output photoresistor is the factor which determines the hysteresis characteristics, characteristics of the resistance dependency on temperature, conductivity characteristics incline, and response time. When using optocouplers of this type it is necessary to take into account the above dependencies [10].

5. READY-TO-USE SOLUTIONS AVAILABLE ON THE MARKET

Separation of analogue circuits is performed inside integrated systems as well. The Analog Devices company uses the iCoupler technology to make the ADuM4190 isolated error amplifier, which is dedicated chiefly to linear feedback power supplies. The iCoupler technology is also applied in many digital photo camera [2, 4]. In order to perform feedback in convertors, one can use optocouplers whose conductivity coefficient changes with time and temperature. The application of an amplifier with separation, whose characteristics do not change with time and temperature, enables to achieve better pulse response, higher power density and better stability of the power supply system controlled by the amplifier. The circuit has a wide range of supply voltages of the primary and secondary side, from 3 to 22 V, band width of 400 kHz, temperature range from 40 to 125°C, and isolation strength of 5000 V rms. The reference voltage for the error amplifier with the accuracy of 1% is provided by an internal, precise 1.225 V source. The inverting and non-inverting inputs of the amplifier on the primary side are accessible from the outside when feedback voltage is to be connected from the output of the isolated convertor controlled by the circuit, through a suitable voltage divider. The output of this amplifier is also accessible from the outside, enabling to connect RC compensation elements. In the circuit structure the output voltage of the amplifier on the primary side is used to modulate the width of pulses sent with the use of a separation transformer, similarly as in digital iCoupler separators. On the secondary side the PWM signal is processed into voltage which controls the output error amplifier. The output signal of this amplifier is accessible on the secondary side directly or through an extra transistor output stage [2]. The application and functional block diagram of the ADuM4190 amplifier can be seen in Fig. 4.

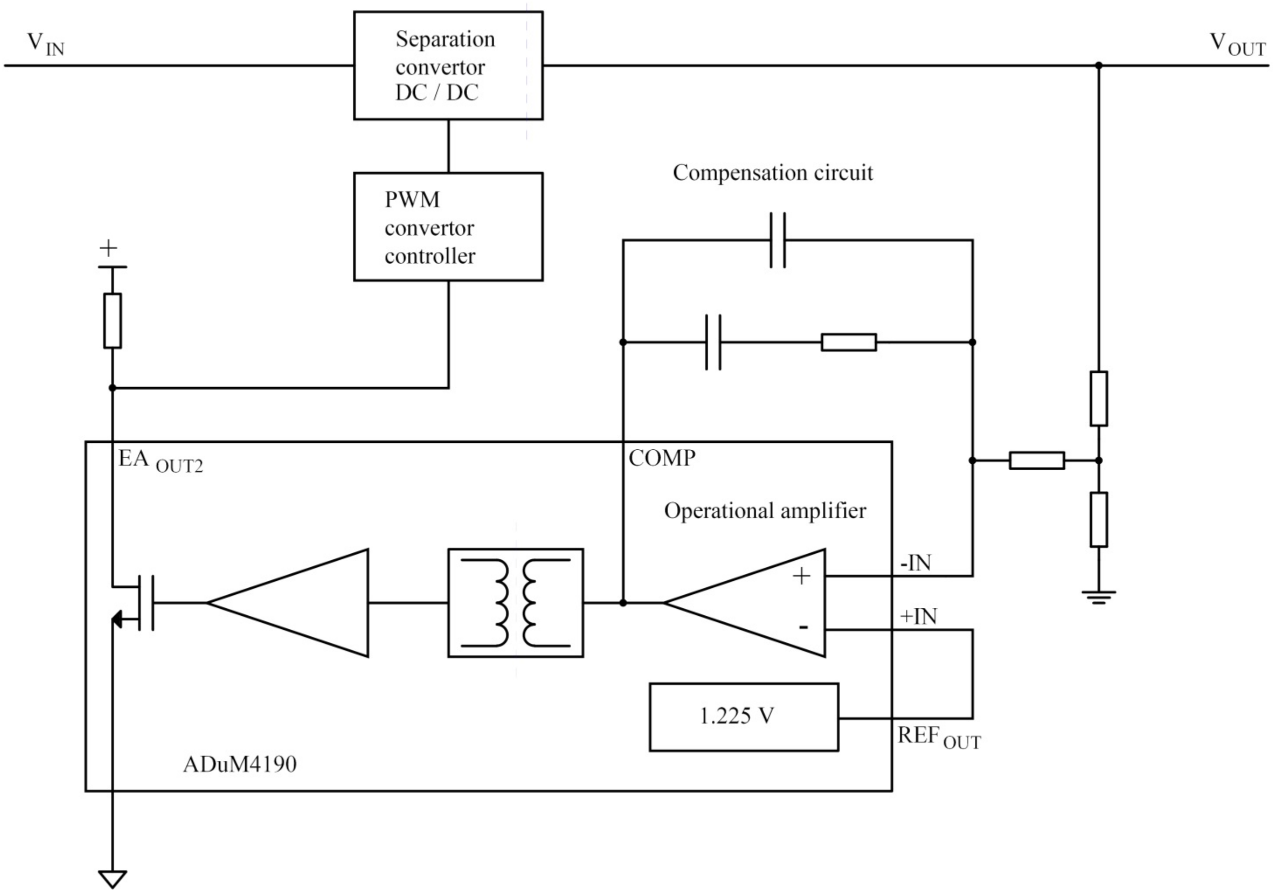

Fig. 4. The application and functional block diagram of the ADuM4190 amp

6. SEPARATION IN TELEPHONE AND WARNING SYSTEMS

In applications such as intrinsically safe devices and systems, which require isolation gaps that are impossible to achieve inside integrated circuits, a practical solution are dedicated interface systems adapted to connect to external, discreet separation elements. An example of such a solution are integrated circuits IA3222 and IA3223 by Silabs [11] which allow to have a separated interface of a telephone line. Figure 5 features a functional block diagram of the interface with the use of the above mentioned circuits.

Capacitive coupling, which is galvanic separation between the IA3223 codec circuit and the IA3222 linear interface circuit, is composed of three condensers with rated capacity of 0.7 pF, placed in adequate lines between the circuits. The fact that the required coupling capacity is very small makes it easier to ensure the required isolation gaps. These circuits are used for galvanic separation of analogue signals with two-way transmission in telephone and warning systems, for example in TBI barriers made by COMONET. Similarly to the barrier described in section 2, this barrier performs not only galvanic separation for two-way separation of analogue signals, but also transmits the signals, e.g. signals about loop closing or changing the power supply polarity [8].

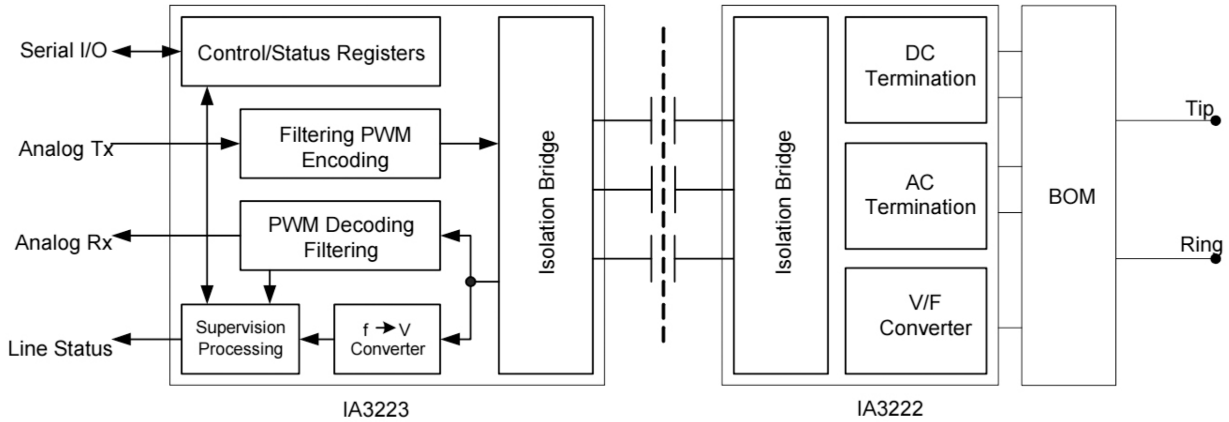

Fig. 5. Functional block diagram of the interface with the use of IA3222 and IA3223 circuits [11]

7. CONCLUSIONS

The separation of analogue signals is more complicated than the separation of digital ones. These days there is a strong tendency to carry out analogue-to-digital conversion of the signal and to perform the separation on the digital side. With the increase in the number of analogue channels which have to be separated, the advantages of digital-side separation are clearly seen, as this kind of separation allows to send data from many analogue channels through one separated digital channel. Otherwise, these data would require a separate separation circuit for each channel or they would need modulation and different carrier frequencies for particular channels within one separation circuit. In spite of rapid development of digital technologies, analogue separation solutions are still used in some applications. For example, in applications which require constant and low energy consumption it is easier to achieve the above assumptions by using a low-power analogue circuit with separation than by using a signal processor of FPGA circuit and performing the signal separation in a digital form. Another area of application are security systems due to the possibility to ensure minimum operating times. Digital separation of these systems, including processing, separation and analysis on the digital side, would result in too big delays. Elements available on the market allow to select the best suitable solution of analogue separation.

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