Bartosz DOMINIKOWSKI

Politechnika Łódzka, Instytut Systemów Inżynierii Elektrycznej
ORCID: 0000-0002-4762-2005

doi:10.15199/48.2023.12.52

Error detection of isolation amplifiers in measurement systems

Streszczenie. *Detekcja błędów działania urządzeń elektronicznych jest istotna z punktu widzenia niezawodności przesyłania danych. Często systemy pomiarowe wymagają zastosowania specjalnego wzmacniacza izolacyjnego. Układ ten jest wykorzystywany w pomiarach napięciowych dlatego należy jego parametry monitorować. Do sprawdzenia poprawności działania lub awarii układu wykorzystano połączenie algorytmu grupowania danych c-mean ze sterownikiem rozmytym typu TSK. System rozmyty ocenia na podstawie centrów z danych grup z algorytmu c-mean stan pracy wzmacniacza izolacyjnego. (**Detekcja błędów działania wzmacniaczy izolacyjnych w systemach pomiarowych**).*

Abstract. *Detection of errors in the operation of electronic devices is important from the point of view of the reliability of data transmission. Often the measurement systems require a special isolation amplifier. This system is often used in voltage measurements, so its parameters should be monitored. To check the correct operation or failure of the system, a combination of the c-mean data grouping algorithm with a fuzzy controller of the TSK type was used. The fuzzy system evaluates the operating state of the isolating amplifier based on the centers from the given groups from the c-mean algorithm.*

Słowa kluczowe: detekcja uszkodzeń, wzmacniacz izolacyjny, c-mean.
Keywords: fault detection, isolation amplifier, c-mean.

Introduction

Nowadays, electronic isolation circuits are increasingly used in measurement systems incorporating the coupling of electrical circuits by means of inductive, capacitive and optical barriers. Isolation circuits play a key role in the safe transmission of analog or digital information between the signal source and the measurement data acquisition system (microprocessor). Often high-voltage measurement converters are similar in electronic design to an isolation amplifier. For this reason, circuits with such an electrical circuit are often used in industrial measurement. The main purpose of using these circuits is to isolate electrical circuits due to the exposure of a digital circuit operating at low voltage to a high electrical potential. Isolation circuits consist of many blocks such as an isolation transformer, operational amplifiers, input and output data transmission and power supply circuits based on a special *DC*/*DC* converter with an oscillator. Modern power systems are complex electronic circuits that process electrical energy from various sources. Through the large number of electronic circuits, the power system becomes susceptible to various failures. In the event of a failure of one of the power sources due to power management systems, it is possible to switch the power supply to additional efficient voltage sources. In the situation of the lack of supply of an adequate amount of energy (lack of the primary factor, such as solar energy) to renewable sources, whose electricity storage tanks may be uncharged, the isolation amplifier may operate with a reduced voltage range or incorrectly. A supply voltage that is too low results in the transfer of insufficient electrical energy by means of an inverter operating inside the isolation amplifier. Because of these problems, it is necessary to monitor the voltage value at the terminals of its power supply. Electronic circuits have certain voltage regions of operation depending on their design (types of semiconductor components used). When the supply voltage is too low, there is a problem in determining the appropriate operating points at the various locations of the amplifier components.

The number of additional electronic components used in the power system increases its failure rate. Depending on the type of connection structure, the reliability function is determined. The most common is a mixed structure (serial and parallel). In a serial connection, the correctness of the system depends on the correct operation of all components. In parallel, the failure of the measurement system will occur if all components of the system fail. In a mixed connection to determine reliability, the system must be decomposed by using appropriate connection relationships. Modern amplifier power systems are complex and operate in a mixed structure of multiple components. This is another reason for the need to monitor power supply parameters.

In measurement systems that use an isolation amplifier, there is often a need to amplify the measured signal. Isolation amplifier systems contain an input signal amplifier. This circuit can be combined in an amplifier configuration with a gain defined by the relation ($1+R_f/R_1$) (where: R_1- external input amplifier resistor of the isolation system, R_f- external feedback resistor of the isolation system amplifier). The danger of loss of measurement data in an isolation circuit can result from: failure in the power supply system of the isolation amplifier, failure of the measurement circuit, temperature effects on the resistance of R_f and R_1, or changes in their values caused by other external factors. In chip resistive circuits, it can open due to: electrolytic corrosion, sulfurization, electrode separation, solder crack, resistive element burnout, or short circuit due to: migration whereas resistive element deterioration cause resistance value reduction. In addition to resistive elements, electrical connections are also susceptible to damage due to high temperature and humidity.

The high frequency of the measurement signal (pulsating signal) is also a big problem. In such a situation, the resistor should be considered with its real parameters. This has a large impact on the value of the resistance, which changes the input processing constant of the amplifier in the isolation circuit. Therefore, the resistance value of the resistive element is also studied.

An important parameter that affects the accuracy and quality of voltage conversion of the isolation system is the operating temperature. At high temperatures from various sources, measurement error occurs.

In electronic circuits, various terminals can be shorted and opened. In such a situation, the value of the current from the amplifier supply may change. Therefore, current measurement from the power supply system is also important in the fault detection system.

The isolation amplifier system uses a *c*-mean data mining-based algorithm for fault diagnosis. The diagnostic system works in a system of two processors. The first is used to collect measurement data, while the second is used to diagnose the operating state of the isolation amplifier.

The algorithm searches for clusters in the measurement data (monitored signals in the isolation amplifier system) and determines the representatives of each group. Then the degree of failure in the isolation amplifier system is determined in a fuzzy manner. Advanced electronic circuit failure diagnostic systems are computationally difficult and complex for a microprocessor. Because of their numerical complexity, they run slowly.

Literature review

Problems of electronic device diagnostics are described in [1-3]. Analog circuit fault detection using soft computing is presented in [4]. The paper deals with multiple soft fault diagnosis of linear analog circuits in [5]. The literature review includes items related to the diagnosis of analog circuits. The problem of diagnostics is well known and well covered in the literature. There is not much information on testing systems during their operation in the literature.

Materials and Methods

Nowadays in electronic circuits, manufacturers are increasingly focusing attention on component protection. Examples include high-voltage and overheating protection systems [6]. Therefore, the measurement system will operate incorrectly in case of certain failures of components working outside the *IC* (integrated circuit). The electrical parameters of components working outside the electronic circuit should be monitored by additional circuits in reliable and accurate measurement systems. The main risks that cause damage to the measurement system include: external environmental factors and incorrect operating parameters. These can cause problems involving incorrect operation of metrology systems in the power supply system, such as a decrease in the value of the supply voltage, shorting or opening a particular branch of the circuit, or an increase in the operating temperature of the electronic system. Temperature affects the value of resistances to a degree that depends on their temperature coefficient. The input conversion constant of the isolation circuit amplifier changes with the temperature-induced change in the value of the resistors. The operating temperature affects the parameters of the amplifier, which amplifies the individual components of the error. This reduces the accuracy of the measurement with the isolation amplifier. The relationship that determines the total output error of input operational amplifier is $A_{CL}{\times}e_1{+}e_o$, where: A_{CL}-voltage gain for the closed-loop feedback of the input amplifier of the isolation system, e_1-input error (determined for the input stage), e_o-output error (determined for the output stage) [7]. In the range of higher amplifier gains, input errors dominate and are amplified. Electronic systems use methods to dissipate heat such as heat sinks or fans. These occupy a large area of the measurement system board or require an auxiliary power supply. Such components cannot always be used due to the limited area of the measurement system board.

Faults in electrical circuits are divide into: permanent, short-lived and those that occur with some recurrence. Some of them can affect on the circuit structure of the measuring system by changing its functionality through which further destructions can occur. In general, the faults of analog circuit can be classified into soft faults and hard faults [8].

Monitoring of the corresponding functionality of the isolation amplifier circuit is performed by means of signals: the value of current and voltage in the supply circuit, the temperature of the elements R_1, R_f operating in the input amplifier branches of the isolation circuit and their resistance values. The resistance is determined by means of an attached voltage source at the time of disconnection of the branch with the tested element.

A measuring amplifier with high input impedance is used to measure the supply voltage, while a circuit with a low-ohm resistance shunt is used for current. The temperature of the components is monitored using a thermocouple. The error measurement diagram of the isolation amplifier is shown in Figure 1.

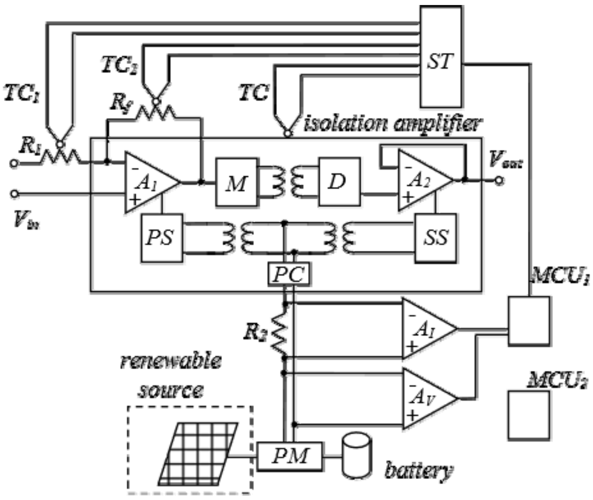

Fig. 1 Induction-coupled isolation amplifier with systems for detecting emergency operating conditions (where: V_{in} – input signal, *M*-modulator, *D*-demodulator, A_1, A_2 – input and output amplifier, *PC*- power *DC*/*DC* converter, *PS*, *SS* – primary and secondary power, *TC*- thermocouple, *PM* - power management, A_I, A_V- current and voltage measurement, *ST*- thermocouple transducer, MCU_1- microprocessor for data acquisition, MCU_2-microprocessor for diagnostic).

The amplifier shown in Figure 1 contains an input operational amplifier (A_1-Figure 1) operating in a non-inverting amplifier configuration. Circuits TC_1 and TC_2 are thermocouples mounted on the bottom of resistor R_1 and R_f. Block *PM* of Figure 1 is the system that manages the electrical energy from the sources supplying the isolation amplifier (renewable source and battery). Measuring amplifiers are connected on its power wires to monitor voltage (A_V) and current (A_I) from shunt R_2. The *TC* thermocouple monitors the operating temperature (*T*) of the isolation amplifier circuit. Detection of emergency operation status and errors of the isolation amplifier is determined according to the algorithm:

Algorithm: *Detection of error operation*

Input: Measurement of supply current and voltage value;
Input: Measurement of temperature;
Input: Determination of resistance value;
    Data input into vectors of n=250 elements:
    $V_s[]$; $I_s[]$; $T_1[]$;$T_2[]$; $T[]$; $R_1[]$; $R_f[]$;
    If ($V_s<V_{min}$) or ($T>T_{max}$) or (R_1==0) or (R_2==0))
        output: Switching to the auxiliary circuit;
    else
        output: Execution of the *c*-mean and *TSK* algorithm;
    end
end.

The algorithm collects temperature measurement data from R_1, R_f elements, supply voltage and current values and enters them into individual vectors. Then the measurement data is checked with a conditional instruction *if* it has not reached values indicating a significant failure. In situation of event significant failure, the algorithm sets the value of the control variable to switch the measurement to additional circuit. If the data are far from the points of significant failure, the algorithm begins to analyze them using the *c*-mean method. The combination of the *k*-means algorithm and fuzzy logic is the *c*-means algorithm. Classification is undertaken based on the evaluation of the fuzzy membership function. The algorithm evaluates to what extent a given element of the consideration set fits into the considered clusters. The membership function takes values from zero to one and all intermediate values. The essence of this algorithm is to determine the data clusters announcing the failure of the measurement system and to determine their centers $c=\{c_1, c_2, ..., c_i\}$, where: c_i- the individual data centers of the measurement point from clusters, *i* - the number of measurement data clusters. The failure detection algorithm uses i=2 data clusters. The data is entered into an expert system that determines the type of failure that occurred. The *c*-mean algorithm is described in [9-11]. The failure is described in linguistic terms. The diagnostic system algorithm searches the data in the consideration space, which has been divided by an orthogonally intersecting grid. This grid forms corresponding sectors in the consideration space. The fault diagnosis algorithm uses two vectors for analysis: the operating temperature of the amplifier (*TC*-Figure 1) and the supply voltage of the isolation system. Sample temperature and voltage measurement data were obtained from the system in Figure 1, which are located on the area under consideration in the form of points $P_n(V_s(n),T(n))$ - Figure 2, where n-number of positions in the vector. These data then form a cluster (Figure 2). The error detection algorithm determines the two clusters and their centers and passes them to the expert's knowledge. The failure information is determined linguistically for example: a high temperature below the value corresponding to the fault means a large measurement error, while a voltage below the nominal value means no signal processing, which means a failure of the isolation amplifier power system. The example data shown in Figure 2 was divided into two clusters using Matlab software.

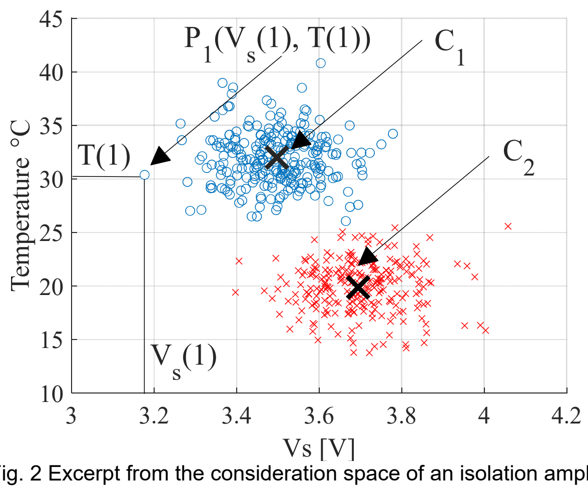

Fig. 2 Excerpt from the consideration space of an isolation amplifier

Based on the data shown in Figure 2, the centers of the clusters entered in Table 1 were determined using an algorithm.

Table 1. Coordinates of cluster data centers

Center	V_s [V]	*T* [°C]
c_1	3,4933	31,9806
c_2	3,6898	19,6405

If the measurement data is found in the sector specified from V_s=0V to 3V, the algorithm stops its operation and switches the measurement to the auxiliary circuit. The nominal voltage for the isolation amplifier under analysis is given in the range from 3V to 5V. The value of the voltage of the power source V_s in the case of the occurrence of an essential fault (short-circuit of terminals) changes rapidly, while in the case of a discharging source it gradually decreases. The operating temperature depends on many factors, among them the environment. In the *c*-mean method in the fault detection algorithm, data is collected for a period of 5 minutes. The number of acquisition data for analysis is 250 for each vector.

In addition to data informing about the operating status of the power source, temperature data of individual external resistors of the input isolation amplifier are provided to the diagnostic system. The effect of temperature on the processing accuracy of the amplifier depends on the temperature coefficient of resistances used (*TCR*). Another factor affecting the measurement accuracy, which is dependent on the operating temperature of the amplifier, is the offset voltage determined by the relations [12]:

$$V_{os(\max)} = V_{os} + \left[\left(\frac{\Delta V_{os}}{\Delta T} \right) \times \left(T_{\max} - T_A \right) \right] \quad (1)$$

where: V_{os}- maximum offset voltage at the input, $\Delta V_{os}/\Delta T$- offset drift at 25°C, T_{max}-system operating temperature, T_A - ambient temperature (25°C).

These parameters are temperature-dependent, and as the temperature increases, the measurement error increases. The higher the gain of the isolation system, the higher the measurement error. A high value of the error can cause loss of measured data when the measured value is small. For this reason, the algorithm analyzes the temperature of not only the resistors but also of the amplifier. A large error value causes loss of measured value. The total error is calculated as the root of the sum of the squares of the individual all component errors. The number of error components is large so it is necessary to monitor the parameters affecting the accuracy.

The output from the *c*-mean algorithm is passed to a fuzzy controller with *TSK* (Takagi Sugeno Kang) inference. This system works based on the rules $R^{(i)}$ defined by the relations [13]:

$$IF\ (V_s\ is\ A_n)\ and\ (T\ is\ A_n),\ THEN\ (y = a_k) \quad (2)$$

where: V_s-source voltage, *T*-temperature of system operation (measurement with *TC* - see Fig. 1), *y*-output, *a*-constant, *k*-number of variables, *i*- number of rules, A_n-linguistic value of fuzzy set.

Since the system is a two-input with one output operating in a *MISO* (multiple input single output) structure so there is no need for an *ANFIS* network. The input of the fuzzy controller is centers c_1 substituted to input *of the* TSK_1 *(Figure 3)*, c_2 substituted to input of the TSK_2 (TSK_2 - identical to TSK_1 – *Figure* 3), which are obtained from the *c*-mean algorithm. The fuzzy controller at the output according to relation (2) generates three values of the constant a_k with values: 0, 1, 2 depending on the type of failure. Each value of a_k corresponds to a given state of the tested system: 0 - means the system does not work properly (notification of the algorithm before the execution of *c*-mean), 1 - means optimal operation of the system 2 - the system works with a measurement error. Two a_k values will be generated for two centers c_1 and c_2. The output from diagnostic system is worst case of a_k value (for example a_1=1 (optimal operation) and a_2=0.25 (system does not work properly) the output is 0.25).

The *TSK* inference model in applied fuzzy systems has the greatest popularity due to its simple fuzzy inference steps [13]. In this fuzzy controller, the antecedent function is defined not fuzzy, but crisp. As a result, no defuzzifier is needed in the system [13]. The knowledge base of the fuzzy system is defined by relation (2). Knowledge presented in this way makes it possible to refer expertly to the diagnosis of electronic systems. A detailed description of a fuzzy controller with *TSK* inference is presented in [13]. For the construction of the fuzzy controller, 7 triangular membership functions were used for each input and 48 control rules, which are defined by relation (2). Figure 3 shows the signal processing scheme of the fault diagnosis system in an electronic isolation system.

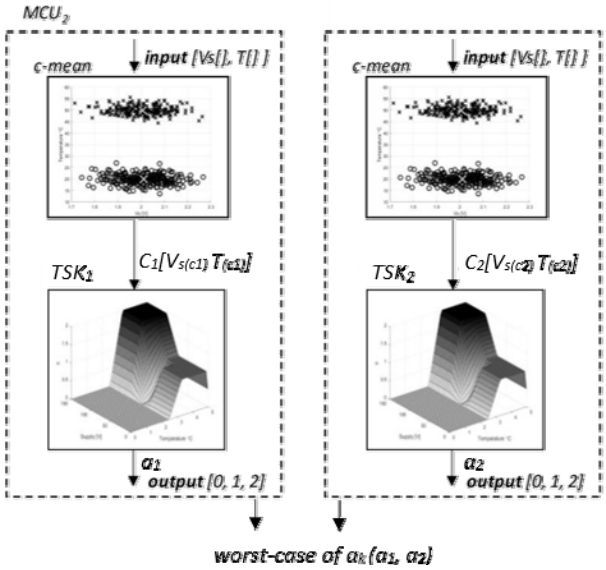

Fig. 3 Signal processing scheme of the isolation amplifier fault diagnosis system

In the MCU_2 processor, two identical *TSK* controller work (TSK_1 and TSK_2). The input signal for TSK_1 is center c_1 and for TSK_2 it is c_2. Each of these controller generates an output value. The worst-case failure is taken into account.

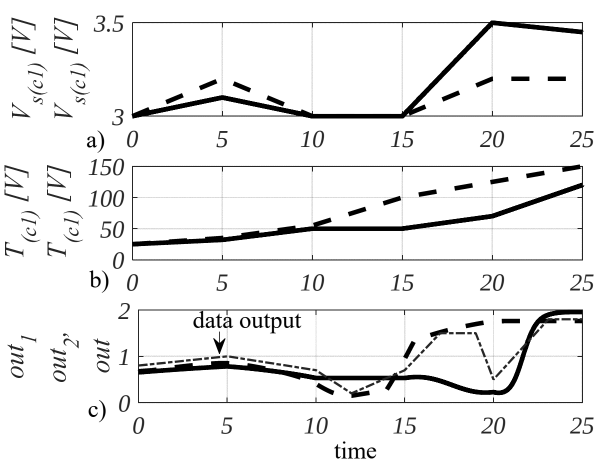

Fig. 4 Signals of isolation amplifier (a) centers of supply voltage, (b) centers of amplifier operating temperature and (c) output value from the diagnostic algorithm for two center

Results

Input data was experimentally generated in the isolation amplifier system. Based on measured data (supply voltage and temperature of isolation amplifier), the algorithm determined the centers (c_{1i}, c_{2i}, *i*-number of measurement series) which are connected by a line in Figure 4a and Figure 4b. The output from the fuzzy system is the worst-case from two output of TSK_1 and TSK_2 controller what shown in the Figure 4c. The results obtained confirm the correct operation of the diagnostic algorithm. The algorithm assigns values continuously and It does not generate exact values but fuzzy ones.

Discussion

Failure detection is important from the point of view of switching the measurement circuit to an additional one.

The proposed isolation amplifier malfunction test system can be applied to various measurement systems. Examples include low-noise *LNA* (Low Noise Amplifiers) amplifiers that match measurement signals to the *ADC* parameters of the measurement data acquisition system.

***Autorzy**: dr inż. Bartosz Dominikowski, Politechnika Łódzka, Instytut Systemów Inżynierii Elektrycznej, ul. Stefanowskiego 18, 90-537 Łódź, E-mail: bartosz.dominikowski@p.lodz.pl*

REFERENCES

[1] Rutkowski J., Słownikowe metody diagnostyczne analogowych układów elektronicznych, *WKŁ*, (2003)

[2] M. Tadeusiewicz, S. Hałgas, An algorithm for multiple fault diagnosis in analog circuits, Int. J. Circ. Theory Appl., vol. 34, pp. 607-615, (2006)

[3] M. Tadeusiewicz, S. Hałgas, M. Korzybski, „An algorithm for soft-fault diagnosis of linear and nonlinear circuits", IEEE Trans. Circ. Syst.-I., vol. 49, pp. 1648-1653, 2002

[4] K. Gunanandhini., P. Jayachandar., S. P. Karthi., Analog Circuit Fault Detection using Soft Computing Techniques, International Journal of Engineering Research & Technology (IJERT), Vol. 5 Issue 05, (2016)

[5] Michał Tadeusiewicz., Marek Ossowski., A Verification Technique for Multiple Soft Fault Diagnosis of Linear Analog Circuits, International Journal of Electronics and Telecommunications, (2018)

[6] Walt Jung., Op Amp Applications Handbook, Analog Devices, (2002)

[7] Lew Counts, Charles Kitchen., A Designer's Guide to Instrumentation Amplifiers, 3RD Edition, Analog Devices, (2006)

[8] Lu, X., Lu, Z., Wu, Q., Wang, J., Yang, C., Sun, S., Shao, D., Liu, K., Soft Fault Diagnosis of Analog Circuit Based on EEMD and Improved MF-DFA. Electronics (2023), 12, 114

[9] Jian Yu, Miin-Shen Yang. A Generalized Fuzzy Clustering Regularization Model with Optimality Tests and Model Complexity Analysis, IEEE Transactions on Fuzzy Systems, (2007) 904-915

[10] Tomasz Ciechulski, Stanisław Osowski., Prognozowanie zapotrzebowania na moc w KSE z zastosowaniem grupowania rozmytego, R. 95 NR 10, Przegląd Elektrotechniczny (2019)

[11] Khang, T.D.; Vuong, N.D.; Tran, M.-K.; Fowler, M. Fuzzy C-Means Clustering Algorithm with Multiple Fuzzification Coefficients. Algorithms (2020)

[12] Frederick F. Driscoll., Robert F. Coughlin., Operational Amplifiers and Linear Integrated Circuits 6th Edition, Prentice Hall, (2001)

[13] Piegat A., Fuzzy Modeling and Control, Springer (2001)