NORMALIZED PARAMETERS OF A MAGNETORESISTIVE SENSOR IN BRIDGE CIRCUITS

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Abstract

Magnetoresistive sensors are considered as part of bridge circuits for measuring magnetic field strength and electric current value. Normalized or relative expressions are introduced to change the resistance of the sensor and the measured bridge voltage to increase the information content of the regime to provide the possibility of comparing the regimes of different sensors. To justify these expressions, a geometric interpretation of the bridge regimes, which leads to hyperbolic straight line geometry and a cross ratio of four points, is given. Upon a change in the sensor resistance, the bridge regime is quantified by the value of the cross ratio of four samples (three characteristic values and the current or real value) of voltage and resistance. The cross ratio, as a dimensionless value, is taken as a normalized expression for the bridge voltage and sensor resistance. Moreover, the cross ratio value is an invariant for voltage and resistance. The proposed approach considers linear and nonlinear dependences of measured voltage on sensor resistance from general positions.

Keywords: magnetoresistive sensors, bridge circuit, projective transformation, cross ratio.

Rezumat

Se analizează utilizarea senzorilor magnetorezistivi ca parte componentă a circuitelor în punte pentru măsurarea intensității câmpului magnetic și a curentului electric. Pentru a spori capacitatea informativă a regimului de lucru, a oferi posibilitatea de a compara regimurile diferitor senzori, sunt introduse expresii normalizate sau relative pentru schimbarea rezistenței senzorului și a tensiunii măsurate a punții. Pentru a fundamenta aceste expresii, se utilizează interpretarea geometrică a regimurilor de punte, ceea ce duce la geometria hiperbolică a liniei drepte și la raportul complex a patru puncte. Atunci când rezistența senzorului se schimbă, regimul de punte este determinat cantitativ de valoarea raportului complex a patru eșantioane (trei valori caracteristice și valoarea actuală) a tensiunii și rezistenței. Raportul complex, ca mărime adimensională, este luat ca expresie normalizată pentru tensiunea punții și rezistența

senzorului. În plus, valoarea raportului complex este un invariant pentru tensiune și rezistență. Abordarea propusă ia în considerare, din punct de vedere general, dependențele liniare și neliniare ale tensiunii măsurate de rezistența senzorului.

Cuvinte cheie: senzori magnetorezistivi, circuit de punte, transformare proiectivă, raport complex.

1. Introduction

Currently, magnetoresistive or spin valve sensors are commonly used to measure magnetic field strength and electric current value [1–4].

Magnetoresistive sensors are based on a number of quantum mechanical effects. Thus, the anisotropic magnetoresistive (AMR) effect is to change the electrical resistance of the ferromagnetic strips of films depending on their orientation relative to an external magnetic field. The magnetoresistive ratio is 2–3%.

Giant magnetoresistance (GMR) is observed in thin metal films consisting of alternating ferromagnetic and conducting non-magnetic layers. The effect is a significant change in the electrical resistance of this structure upon a change in the mutual direction of magnetization of neighboring magnetic layers and, accordingly, electron spins. Magnetization direction can be controlled by an external magnetic field. The device whose resistance is different for electrons with different spin directions is commonly referred to as a spin valve or a valve. It is considered to be open if magnetizations in its layers are oriented in parallel and closed in the opposite case. In most applications, the magnetoresistive ratio is 4–25%.

Tunnel magnetoresistance (TMR) is manifested by the flow of current between two layers of ferromagnets separated by a thin dielectric layer (about 1 nm). At the same time, the total resistance of the device, in which the current flows due to the tunnel effect, depends on the mutual orientation of the magnetization fields of the two magnetic layers and, accordingly, electron spins. The resistance is higher in the case of an antiparallel magnetization of layers. The magnetoresistive ratio is more than 200%.

Manufacturers offer a wide range of sensors of different types [5, 6]. A commonly used full sensor bridge circuit (four identical sensors) ensures the maximum sensitivity and linearity of the transient characteristic.

All magnetoresistive sensors listed are characterized by a typical dependence of the resistance value on the external magnetic field strength. The zero strength value corresponds to the initial resistance. Increasing the intensity in one or another direction of the magnetic field leads to an approximately linear change in the resistance. At fairly high strength values, saturation of the characteristic is manifested and the resistance of the sensor takes the minimum and, accordingly, maximum value.

If the sensor operates as part of the bridge, then the dependence of the measuring diagonal voltage on the resistance of this sensor is used [7]. In the case of a full bridge circuit (four sensors), it is necessary to ensure the opposite direction of the magnetic field for the upper and lower sensors in each branch. After that, the linear dependence of the change in the measuring diagonal voltage on the change in the resistance of the same sensors is obtained [8]. Similarly, it is obtained for a half bridge circuit, when two sensors are located in the same branch.

In the case of measuring the current value in a conductor, the opposite direction of

magnetic field is provided due to bending of this conductor [9]. This complexity of the construction is excluded in the half bridge circuit [10]. In this circuit, the sensors are located in different branches (one sensor is upper and the other is lower). However, in this case, a nonlinear (fractional linear) dependence of the change in the measuring diagonal voltage on the change in the resistance of the sensors is manifested. The same dependence is shown for a bridge with one sensor.

Thus, it was found in practice that changes in the voltage and resistance value set in kind of increments. With small changes in these values (relative to the initial resistance value) and, accordingly, the linear area of the transition characteristic, the magnetic field strength value or current value is determined. On the other hand, the characteristic values of the sensor resistance (initial, minimum, maximum) also correspond to the characteristic values of the measuring diagonal voltage. Therefore, with large changes in this voltage and resistance, it is necessary to compare the current values of these parameters with characteristic values in order to evaluate the capabilities of the regime, that is, increase its information content. Monitoring tasks now arise, namely, how to determine—in a relative form—the same current changes for different sensors or the same changes at different work points. This is important in practice if one system uses, for example, two sensors to measure the load current and voltage [11].

Generally, normalized or relative values are introduced. There is no problem with one characteristic value. Consider, for example, the simplest circuit with a voltage source, its internal resistance and variable load. In this case, the characteristic value of the load voltage will be its open circuit voltage. For the load current, the characteristic value will be the short circuit current; for the load resistance, the internal resistance of the source. The normalized values are then obtained; they make it possible to evaluate the quality or capabilities of the regime, which is important in practice. However, even in this simple circuit, a problem manifests itself. Different values of these normalized values make analysis difficult.

The considered bridge circuits relate to the electric circuits theory with variable regimes. The developed method of analyzing these circuits, which is based on projective geometry, makes it possible to solve the described problems.

2. Analysis of a Bridge Circuit with a Typical Sensor

A characteristic asymmetrical dependence of the resistance of a spin valve sensor with GMR on magnetic field strength [8] is shown in Fig. 1.

The zero strength value $H = 0$ determines the nominal R_s^0 sensor resistance. As the strength increases, the resistance decreases to saturation. In this case, saturation resistance R_s^p corresponds to the parallel case of magnetizing the sensor layers. At negative strength values, the resistance increases up to saturation. In this case, saturation resistance R_s^{AP} corresponds to the antiparallel case of magnetizing the sensor layers.

Fig. 1. Characteristic R – H curve of a GMR spin valve.

Magnetoresistive ratio is defined by the relative expression

$$M = \frac{R_S^{AP} - R_S^P}{R_S^{AP}}.$$

In the measurement practice, a linear area of characteristic is generally used. The inflection point of the characteristic most often does not correspond to the strength of $H = 0$.

Let us give the known bridge circuits [7] in Fig. 2. Reference resistances R_S^0 and the change in the resistance value ΔR are indicated in these circuits.

Fig. 2. Typical bridge circuits: (a) quarter bridge, (b) half bridge with unidirectional sensors, (c) half bridge with different directional sensors, and (d) full bridge.

The bridges are connected to power supply voltage sources V_0 . Measuring diagonal voltages for circuits (a), (b), (c), and (d) are determined by respective expressions in Table 1.

Table 1. Measuring diagonal voltages for typical bridge circuits

Circuit (a)	Circuit (b)	Circuit (c)	Circuit (d)
$V = \frac{V_0}{4} \frac{\Delta R}{R_s^0 + \Delta R/2}$	$V = \frac{V_0}{2} \frac{\Delta R}{R_s^0 + \Delta R/2}$	$V = \frac{V_0}{2} \frac{\Delta R}{R_s^0}$	$V = V_0 \frac{\Delta R}{R_s^0}$

It is evident that there is a linear and fractional linear dependence of the measuring diagonal voltage on the change in the sensor resistance. In practice, linear bridges are usually used. In the case of nonlinear bridges, various schematic techniques are used to linearize the dependence.

Let us now consider the specific problems.

Case of the linear dependence of bridge voltage

We use the following measuring diagonal voltage:

$$V = \frac{V_0}{2} \frac{\Delta R}{R_s^0}. \quad (1)$$

The normalized expression is obtained at once to change the resistance ΔR relative to the reference or nominal value R_s^0 . This expression provides additional or qualitative information about the current or real regime. If the change in resistance is not large and a linear area of the characteristic is used, then this is quite satisfactory in practice. However, formula (1) does not contain saturation resistances R_s^P and R_s^{AP} . Therefore, if we work in a wide area of the characteristic, this expression does not give direct information about the capabilities of the current or real measurement. Moreover, formally, we can go beyond the area of change in the sensor resistance, as shown for clarity in Fig. 3.

Fig. 3. Correspondence the values of the sensor resistance and voltage.

On the other hand, for these three characteristic values R_s^0 , R_s^P , and R_s^{AP} of the sensor resistance, the question of a reasonable normalized expression for changing the resistance arises.

Case of the fractional linear dependence of bridge voltage

Let us present the expression of the measuring diagonal voltage for the circuit shown in Fig. 2a in the normalized form:

$$V = \frac{V_0}{2} \frac{\Delta R}{2R_s^0 + \Delta R} = \frac{V_0}{2} \frac{\Delta R / R_s^0}{2 + \Delta R / R_s^0}. \quad (2)$$

However, this formula does not contain saturation resistances R_s^P and R_s^{AP} either. Therefore, the same questions as for expression (1) and Fig. 3 arise.

3. Geometry of a Straight Line

Further, we consider some provisions about different geometries of a straight line or determining the segment length [12] according to Fig. 4.

Fig. 4. Three different geometries on a straight line: (a) parabolic Euclidean (ordinary), (b) elliptical Riemann, and (c) hyperbolic Lobachevsky geometry.

For parabolic geometry, the unit of length or scale $0E$ is fixed on a straight line, and the distance d_{AB}^E between points A and B is determined by the formula

$$d_{AB}^P = \frac{AB}{0E}. \quad (3)$$

In the case of elliptical geometry, some point Q is fixed outside the straight line, and the distance is just the "normal" angle $\angle AQB$; that is,

$$d_{AB}^E = \angle AQB.$$

Hyperbolic geometry is defined in a more complex way. In addition to points A and B , two points I and J are fixed. These extreme or base points define an infinitely remote boundary or absolute as points A and B move. Next, the cross ratio (double proportion) of four points is composed:

$$m = (I A B J) = \frac{AI}{AJ} \div \frac{BI}{BJ}. \quad (4)$$

In this case, the distance is as follows:

$$d_{AB}^H = \log \left(\frac{AI}{AJ} \div \frac{BI}{BJ} \right). \quad (5)$$

If one of points A and B tends to the base point, then the cross ratio is 0 or ∞ . In this case, the respective distance is $d_{AB}^H \rightarrow \mu\infty$.

4. Geometric Interpretation of Bridge Regimes

The contributed short information about straight line geometry makes it possible to reasonably enter the necessary expressions.

Case of a linear dependence

According to (1), the measuring diagonal voltage corresponds to the distance of parabolic geometry (3). On the other hand, saturation resistances R_s^P and R_s^{AP} correspond to base points of hyperbolic geometry. Therefore, cross ratio (4) for the three characteristic values R_s^0 , R_s^P , and R_s^{AP} of the sensor resistance and the current value R_s^1 leads to a normalized expression for changing the resistance and, accordingly, for the voltage. The cross ratio values for characteristic points are shown in Fig. 5.

Fig. 5. Correspondence the voltage, resistance, and cross ratio values.

Cross ratio for the resistance and voltage values or samples

$$\begin{aligned} m^1 &= (R_s^P \ R_s^1 \ R_s^0 \ R_s^{AP}) = \frac{R_s^1 - R_s^P}{R_s^1 - R_s^{AP}} \div \frac{R_s^0 - R_s^P}{R_s^0 - R_s^{AP}} = \\ &= (V^P \ V^1 \ V^0 \ V^{AP}) = \frac{V^1 - V^P}{V^1 - V^{AP}} \div \frac{V^0 - V^P}{V^0 - V^{AP}}. \end{aligned} \quad (6)$$

Thus, when a sensor resistance varies from a minimum to maximum value (base values), a bridge regime is quantified by cross ratio value m . Thus, we get additional information about the capabilities of the regime and its qualitative characteristics. A cross ratio is a dimensionless value; therefore, it can be assumed that the m value is the normalized expression for the bridge voltage and sensor resistance, where all characteristic values are used. In other words, the dimensionless coordinate of a resistance value R_s^1 on a straight line relative to an initial value R_s^0 is determined by cross ratio (6) or respective distance (5).

Case of a fractional linear dependence

Let a current or initial value of the sensor resistance correspond to $R_s^1 = R_s^0 + \Delta R$. In this case, expression (2) takes the form

$$V^1(R_s^1) = \frac{V_0}{2} \frac{\Delta R}{2R_s^0 + \Delta R} = \frac{V_0}{2} \frac{R_s^1 - R_s^0}{R_s^1 + R_s^0}. \quad (7)$$

This fractional linear expression represents a projective transformation $R_s^1 \rightarrow V^1$ in the sense of projective geometry in Fig. 6. Let us apply the projective geometry method [13] to analyze a bridge with a fractional linear dependence.

The points of the resistance axis are projected onto the voltage axis from point P as the projection center. It is evident that the proportions of the segment lengths on these axes are broken. On the other hand, there is a value that is retained for this projection. This value or invariant of the transformation is a cross ratio, similar to (6), of respective four points or samples of the resistance and voltage.

Fig. 6. Projective transformation $R_s^1 \rightarrow V^1$ defines the cross ratio value m .

Thus, this case, which is more general, corresponds to the discussed linear dependence if the projection center $P \rightarrow \infty$. In this case, the projection of points of the resistance axis onto the voltage axis is carried out by parallel lines. Next, we will consider both cases from a common perspective.

Change of the bridge regime

Let the subsequent value of the sensor resistance correspond to R_s^2 and determine the respective voltage value V^2 . In this case, the subsequent cross ratio value is as follows:

$$m^2 = (V^P \ V^2 \ V^0 \ V^{AP}) = \frac{V^2 - V^P}{V^2 - V^{AP}} \div \frac{V^0 - V^P}{V^0 - V^{AP}},$$

$$m^2 = (R_s^P \ R_s^2 \ R_s^0 \ R_s^{AP}) = \frac{R_s^2 - R_s^P}{R_s^2 - R_s^{AP}} \div \frac{R_s^0 - R_s^P}{R_s^0 - R_s^{AP}}.$$

The cross ratio has a group property if a subsequent m^2 value is expressed relative to an initial m^1 value through its change m^{21} by a group operation (addition or multiplication). The expression structure shows the execution of the group multiplication operation:

$$m^2 = m^{21} \cdot m^1.$$

Next, we introduce the regime change m^{21} by the cross ratio

$$m^{21} = m^2 \div m^1 = \left(\frac{R_S^2 - R_S^P}{R_S^2 - R_S^{AP}} \div \frac{R_S^0 - R_S^P}{R_S^0 - R_S^{AP}} \right) \div \left(\frac{R_S^1 - R_S^P}{R_S^1 - R_S^{AP}} \div \frac{R_S^0 - R_S^P}{R_S^0 - R_S^{AP}} \right) =$$

$$\frac{R_S^2 - R_S^P}{R_S^2 - R_S^{AP}} \div \frac{R_S^1 - R_S^P}{R_S^1 - R_S^{AP}} = (R_S^P \ R_S^2 \ R_S^1 \ R_S^{AP}), \quad (8)$$

$$m^{21} = (V^P \ V^2 \ V^1 \ V^{AP}) = \frac{V^2 - V^P}{V^2 - V^{AP}} \div \frac{V^1 - V^P}{V^1 - V^{AP}}. \quad (9)$$

The structure of cross ratio (9) shows the mutual reduction of possible additive and multiplicative errors of measurement of voltage samples.

Next, knowing the V^2, V^1 voltage values, we find the regime change (9) and calculate the subsequent resistance value by (8)

$$R_S^2 = \frac{R_S^1(m^{21}R_S^{AP} - R_S^P) - (m^{21} - 1)R_S^{AP}R_S^P}{R_S^1(m^{21} - 1) - (m^{21}R_S^P - R_S^{AP})}. \quad (10)$$

The obtained transformation translates an initial point R_S^1 to a subsequent point R_S^2 . The transformation parameter m^{21} forms a segment of invariable “length,” and we observe the movement of this segment in Fig. 7.

Fig. 7. Hyperbolic projective transformation determines the moving of a segment of invariable length.

Here, the change in the usual length is visible. For the base fixed points R_S^P, R_S^{AP} , this length is decreasing to zero. Let the initial point $R_S^1 = R_S^P$. In this case, the subsequent point

$$R_S^2 = \frac{R_S^P (m^{21} R_S^{AP} - R_S^P) - (m^{21} - 1) R_S^{AP} R_S^P}{R_S^P (m^{21} - 1) - (m^{21} R_S^P - R_S^{AP})} = \frac{-R_S^P R_S^P + R_S^{AP} R_S^P}{-R_S^P + R_S^{AP}} = R_S^P.$$

Similarly, if $R_S^1 = R_S^{AP}$, then $R_S^2 = R_S^{AP}$. Expression (10) and Fig. 7 show how to set the same changes at different initial or work points, compare regimes of different sensors, etc.

The described approach provides the basis for consideration of symmetric characteristics $R(H)$ [6], in particular, for superconducting spin valves [14].

5. Conclusions

- (i) The geometric method provides a general approach for determining and comparing the regime of different bridge circuits in a normalized or relative form.
- (ii) Normalized mode parameter expressions include all the characteristic regime values.
- (iii) The proposed invariant expressions in the form of a cross ratio represent a qualitative estimate of the real regime and exclude a variety of different values of the regime parameters.
- (iv) Additive and multiplicative errors of measurement of voltage samples are mutually reduced for the cross ratio.

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