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Review of Scanners for DC to 20 kHz electrical metrology applications

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ABSTRACT

Scanners are tools for various measurement systems that eliminate human errors and automate measurement processes. This article reviews the scanners focused on low-frequency metrological measurements. The undesirable effects of the diverse types of scanners are described, and methods to characterize them and reduce their impact on measurement systems are specified. In the scope of the present paper an evaluation of the different types of scanners is carried out, highlighting their main characteristics. Additionally, a list of scanner design considerations for typical low-frequency electrical metrology applications is given.

1. Introduction

In many low-frequency electrical metrology applications scanners are essential elements that allow the interconnection among different measurement systems. The scanner can be designed to be controlled by a software installed on a PC. This instrument enables different standards measurements without the need of performing manual interconnections, eliminating human errors and allowing automatic measurements to be taken at night which is usually when the best conditions are available to perform the measurement.

Until now, different ways of developing scanners have been reported. Some of them work through relays, which make it possible to switch between devices in few milliseconds, are easy to automate, and usually have dimensions of just few centimeters [1–7]. Other scanners work by motors that move rails in 2 or 3 axis to interconnect the output with different inputs, allowing excellent electrical isolation between sets of input and output channels [8,9]. Some others use pneumatic systems to perform the interconnection between the channels [10]; this avoids the presence of electromagnetic noise that can affect the measurement results. Also, some scanners use mechanical rotating switches and electrical motors to automate the process [11].

Different kinds of scanners exist because each application involves additional requirements to avoid errors in measurement results due to the presence of the scanner in the measurement system. Among the most common unwanted effects introduced by the scanners, the following can be listed: thermal Electromotive Force (EMF) present in the interconnections, which induces voltages up to hundreds of nV that affect voltage and DC resistance measurements [11]; the low-isolation resistance between the different channels that mostly alter the results of high-resistance DC measurements [9]; the presence of coupling capacitances between channels that generate currents loops in the measurement circuit [2,10]. These effects can significantly affect the results of the measurement system in which the scanner is integrated. Before using a scanner, it is necessary to characterize all the influencing quantities that may affect the results.

Therefore, which of the different ways of developing a scanner is the best option? Moreover, what considerations should be taken into account for its development? This article aims to answer these questions, analyzing the most relevant scanners developments implemented for low-frequency electrical metrology. Hence, Section 2 describes the factors that affect the measurement results due to the scanner, present strategies to diminish their unwanted effects, and gives an overview of all types of scanners; at the end of the section, the scopes of all the scanners are defined, including commercial ones. Later, in Section 3, the methods to carry out a correct characterization of the scanners are explained. Additionally, Section 4 exposes a list of scanners design considerations for typical low-frequency electrical metrology applications.

2. Influence quantities and scanner implementations

In a measurement circuit, a perfect scanner would be one that can interconnect between different conductors without introducing any

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influencing quantity or without affecting the variables of the model that describes the measurement principle. For this reason, it is essential to analyze the influence quantities introduced by the scanner. Once the not negligible quantities are identified, their impact should be reduced.

2.1. Description of scanner influence quantities and the strategies to decrease their unwanted effects

2.1.1. Thermal EMFs

The presence of a scanner in a measurement system involves new interconnections. Depending on the contact materials of the interconnections, a voltage difference can occur due to the thermal EMFs [3]. The thermal EMF depends on the Seebeck coefficient of the contact materials and the temperature gradients between the electrical connection points [12]. If appropriate contact materials are not carefully chosen, voltage differences can be produced up to the microvolt range. These can cause significant errors when making low-level DC measurements, e.g., Zener-based voltage standard calibration [3,11,13,14], resistance calibration [4,5,9,15], resistors load coefficient calibration [11], and resistance thermometer calibration systems [16,17].

Two main actions must be done to minimize the scanner thermal EMF in the measurement circuit [3]. The first is to reduce the thermal gradients in the scanner contacts. Proper temperature control is not enough to achieve it. Temperature gradients because of the frictional heat from a high-speed rotary switch (angular velocity > 20°/s) [18], the heat from the current that drives a not-latching relay coil [3,7], the heat from a motor, or any other heat source near the contact terminals can cause thermal EMF that affect the results. The second is to avoid the use of contact materials with high-Seebeck coefficients [6]. For this reason, many of the articles reviewed in this research use gold, silver, or silver–gold plated terminals [1,3,5,11,15] due to their low-Seebeck coefficients ($\approx$ 1.5 μV/K at room temperature).

For relay-based scanners, latching relays that require only a short pulse to actuate can be used to avoid self-heating [1,3,5]. To achieve a lower thermal EMF in the relay terminals, [3] proposes a terminal selection and matching method. With it, ideal pairs can be matched except a few ones. Additionally, the relays can be placed inside a heat isolation structure to avoid the temperature gradients from any heat source in the switch device [7]. Besides, to elude the contact potential caused by the weld and the wires, Refs. [3,7] recommend the use of a U-shaped clamp terminal fixed in the relay board to support an acrylic screw that tightly clamps the terminal electrical connection point of the scanner. One way to reduce the effect of thermal EMFs is through a polarity reversal technique [11]. The proper use of this technique implies that there are no temperature gradients at the junctions during polarity changes.

2.1.2. Electromagnetic interference and leakage currents

Electromagnetic interference is a perturbation that affects measurement circuits by electromagnetic induction, capacitive coupling and/or leakage currents through dielectrics. To avoid them, a shield with conducting surfaces connected to a suitable potential needs to be implemented [19].

In DC measurements, a shield surrounding the conducting circuit wires isolates the measurements from external electric sources. However, the shield represents a new potential where leakage currents can appear. In general, leakage currents depend on isolation resistance, and the voltage difference between the central conductor and the shield or any other point with a different potential [20]. In resistance measurements above 100 MΩ, the potential of the shield should be driven to the same voltage as the central conductor to avoid leakage currents through the insulator [8]. Additionally, appropriate isolation between connectors, such as polytetrafluoroethylene (PTFE), is necessary.

Construction considerations should be taken into account to reduce the impact of leakage currents in a scanner. If the scanner is based on relays, the paths of the circuit board need to be surrounded by guard traces. In order to enhance the insulation among the circuit paths, an air gap can be introduced by a notch on the board. Also, the use of relays with shielding or modified relays to provide shielding ensures the complete surrounding of the circuit paths [1,5].

As in DC, in high-accuracy AC measurements, the electromagnetic interference can be avoided by a shield surrounding the conducting circuit wires. The shield should lead a current equal and opposite to the current in the central conductor [19]. Therefore, the scanner has to provide an appropriate connection of both inner and outer conductors, ensuring the coaxiality of the scanner-enabled channel. In AC measurement applications involving scanners, capacitive coupling causes crosstalk or unwanted capacitances among scanner inputs channels [2,4,21]. Connecting the input of the non-active channels to the shield of the active channel reduces the unwanted capacitances [4]. However, for applications where a short circuit is not feasible, increasing the isolation among channels is the best alternative [21,22]. Therefore, modular switches configured as a multiplexer can be implemented. Ref. [2] describes a scanner based on modular switches with three relays in series. In off-state, the middle relay can be shorted to the shield of the active channel to reduce the effect of the residual parasitic capacitances in the switch module. The relay control signals can introduce crosstalk between modules via capacitive coupling between relay coils and contacts. The effect of coupling can be reduced using optical control systems, such as the one presented in Ref. [2].

The scanners based on automatic XY or XYZ positioning systems can achieve excellent isolation between the circuit paths [8,9,15]. These connectors are usually Multiple Unit Steerable Array/Antenna (MUSA) connectors, which provide, in combination with coaxial cables, perfect shielding for the circuit's paths. Hence, if the shield is connected to the same potential of the circuit path, no leakage currents will be present. However, some considerations are necessary, like appropriate isolation among connectors, the length of the coaxial cables for the interconnections, which needs to be of low triboelectric noise, with low capacitance, and as short as possible [15].

2.1.3. Contact resistance

Although the resistance introduced by the scanner circuit path is typically less than 100 mΩ, it can considerably affect low-impedance measurements. The stability of the resistance may vary due to erosion and oxidation of the contact resistance. Oxidation increase the contact resistance; hence, silver-based or gold-based contact materials are typically used due to their excellent conductivity and high oxidation resistance. This problem is solved by measuring the scanner resistance path periodically to be later used in the measurement circuit model. Nevertheless, it is a parameter that needs to be considered during the search of the connectors, relays, or rotary switch. Another parameter to consider is their life-cycle. Depending on the applications, this parameter can be more or less critical. The closer to its life cycle, the more outstanding care must be taken in the repeatability of the contact resistance.

2.2. Overview of different types of scanner

There are three main types of scanners for high-accuracy electrical measurements: scanners based on relays, scanners based on motion systems, and scanners based on controlled rotating switches. Depending on the application, the inputs and outputs of any of the three types of scanners can be defined as two-terminal, three-terminal, two-terminal-pair, four-terminal, or four-terminal-pair [19,21].

2.2.1. Relay-based scanner

This type of scanner uses relays as a switch to connect or disconnect different inputs and outputs of the system. Relays allow interconnections to be controlled by low-current control signals. Typically, latching relays are used to avoid self-heating and reduce the effect

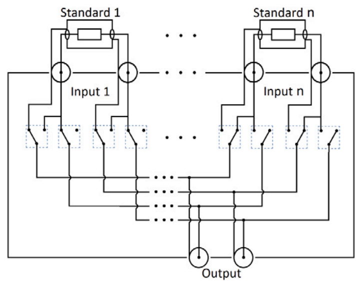

Fig. 1. Relay-based scanner to choose between n 2-pair terminals or three-terminal standards.

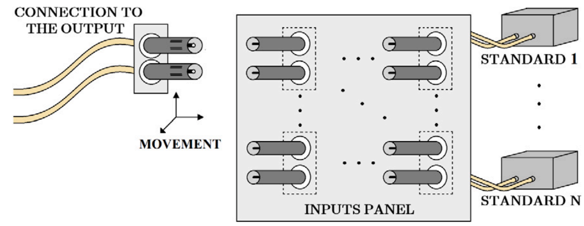

Fig. 2. Motion-system-based scanner to chose between N 2-pair terminal standards.

of thermal EMFs. The closed relay pads should bring a low and stable contact resistance. These can be achieved by gold-plated contact terminals [11].

Depending on the application, the scanner will need different relay arrangements. For systems that use coaxial connectors, at least one relay is required for the signal connection and another for the shield connection. Besides, it must be guaranteed that the channels not being used do not provide a potential that causes leakage currents [4]. Fig. 1 shows the principle of a relay-based scanner of n pair of coaxial inputs to one coaxial output pair. This does not mean that the relay-based scanners are limited to interconnect 2-pair terminals or 3 terminal standards. The inputs and outputs of the scanner can be set to interconnect any type of standards or signals.

Instead of using only one relay to disconnect the scanner inputs, as shown in Fig. 1, each channel of the scanner can have various relays in series, placed on different screens. Then, for a non-active channel of the scanner, an intermediate relay can be connected to the shield of the active channel and thus decrease the parasitic capacitances between the not-active and the active to less than 0.5 aF [2]. In addition, this reduces the cross-talk between the scanner inputs. For scanners involving many inputs, the control signals of the relay must be conditioned, using the minimum amount of signals and avoiding self-heating in the system [3].

When choosing a relay, the contact material should be taken into account, seeking that they have low Seebeck coefficients to achieve low thermal EMFs, high conductivity, and high oxidation resistance to obtain a low and stable contact resistance (< 100 mΩ). The insulation resistance between the relay terminals should be as high as possible for high impedance measurements to avoid leakage currents. If the relay is going to be used continuously, its life expectancy should be high ($> 10^5$). Panasonic's TQ and TX series relays [23,24] have been used in high-accuracy scanners developments, obtaining excellent results [2,3]. These latching relays have Au + Ag clad on their contacts, contact resistance < 100 Ω, insulation resistance > 1 GΩ, and a life expectancy $> 10^5$. Other relays like the 3600 series from Coto Technology [25], which specifications indicate thermal EMFs < 5 μV with a stability of 50 nV, contact resistance < 50 mΩ, insulation resistance > 1 TΩ, and an electrical shield that covers the relay, have excellent specifications; however, as they are non-latching relays, considerable temperature gradients can be induced.

2.2.2. Scanner based on motion systems

This scanner uses a positioning system to connect the outputs to different inputs mounted on a plane panel. Fig. 2 shows an example of a scanner that interconnects the measurement system input among various inputs defined as two-terminal-pairs. The scanner output may vary depending on the application being define as one-terminal, two-terminal, three-terminal, two-terminal-pairs, etc. [26].

Depending on the number of input channels required, it will be necessary for the positioning system to have movement in two or three axis. The positioning can be carried out by means of low-noise motors [9] or by pneumatic systems [10]. In this type of design, it is common to use MUSA type coaxial connectors [8,10], which have PTFE insulation, and the contacts between their terminals have low-thermal EMFs due their gold plated or silver plated terminals [8]. Besides, the shield serves as a guide for a correct connection with the positioning system. If the application makes use of an active guard or an AC coaxial system, it will be necessary to place insulation between the shields of the terminals. Also, as described in Section 2.1.2, cables should be as short as possible, with low triboelectric noise and low capacitance, such as Belden 9224 cable [27]. With a small capacitance per meter increase, other cables such as PCB Piezoelectric 003 [28] or Belden 9423 [29] are also good options since they have a conductive layer added to the surface of the primary cable insulation to reduce the triboelectric noise. This increase in capacitance is an important factor in low capacitance measurements. For dc high resistance measurements, the impact is only reflected in the settling time when there are voltage changes and a ground shield system is used [30].

2.2.3. Controlled rotating switches scanner based

Rotary switches, coupled to a controlled motor, can be used as a scanner [11,18]. Fig. 3 shows the basic principle of this type of scanner. The scanner consists of a rotary switch coupled to a stepping motor through a good isolation material such as PTFE. The switch position can be controlled through an encoder that feeds back the signal that controls the motor. To reduce thermal EMFs, all the contact in a scanner should be of the same material or materials with low Seebeck coefficients [11]. Besides, instead of using welding, crimping and screws can be used to connect wires mechanically to the scanner terminals. Also, the switch should be made of high-isolating materials between their terminals to avoid leakage currents. Usually, an Oldham coupling is used to absorb the mechanical stress caused by errors in the alignment between the rotary switch and the motor [11,18]. Additionally, an aluminum enclosure containing the switch should be placed around the switch to prevent the heat and noise of the motor that can affect the measurement circuit.

In Ref. [11] the use of a C4 series rotary Electroswitch is reported. The datasheet for this switch [31] indicates that its terminals are made of Brass with silver plate and that the insulation between terminals is diallyl phthalate, which generates an insulation resistance > 10 GΩ. However, as part of the characterization, the authors of this reference measured insulation resistances of at least 10 TΩ on each switch. These features are desirable for developing a scanner based on controlled rotary switches whose purpose is to calibrate Zener voltage references.

2.2.4. Scopes of different types of scanners

In this subsection, a comparison of the scopes of the different types of scanners, including some of the most used high-accuracy commercial scanners, is presented in Table 1. The influence quantities to be considered in this comparison are the thermal EMF, the isolation, the contact resistance, and some significant features of each scanner. It should be considered that the values in Table 1 are the highest or lowest values reported in the literature. The strategies described in Section 2.1 should be applied to achieve these levels of thermal EMFs, isolation, and contact resistance.

Table 1
Scope comparison between different types of scanners.

Scanner type	Thermal EMF	Isolation	Contact resistance	Life cycle	Special features
Based on relays [1,3–7]	< 20 nV	> 10^{13} Ω	Not indicated	It depends on the relay	High-switching speed; Easy expansion of channels.
Modular scanners based on relays [2]	Not indicated	> 10^{14} Ω (< 1 aF at 1 kHz)	< 0.1 Ω	> 10^5 cycles	Coaxial switch; High-switching speed; Easy expansion of channels.
Based on XY or XYZ systems [8,9,15]	< 10 nV	> 10^{14} Ω using MUSA connectors	< 0.04 Ω	> 10^5 cycles	Up to 30 four-terminal channels; their switching speed depends on the distance between the channels to be connected.
Base on pneumatic systems [10]	Not indicated	> 10^{14} Ω using MUSA connectors	< 0.0025 Ω	Not indicated	Developed for automatic measurements with an RLC meter.
Based on rotating switches [11,18]	< 1.5 nV	> 10^{14} Ω	< 0.02 Ω	Not indicated	Low-thermal EMF.
Guildline 6564 [32]	< 20 nV	> 10^{17} Ω	< 0.05 Ω	10^7 cycles	Based on relays; Ultra-high resistance scanners.
Data Proof 320B [33]	20 nV	$1.5x10^{12}$ Ω (not guarded)	< 0.05 Ω	10^7 cycles	Based on relays; Guarded.
Measurement International 42XX [34]	< 50 nV	> 10^{12} Ω	< 0.05 Ω	10^8 cycles	Based on relays; 10, 16 or 20 four-terminal channels.

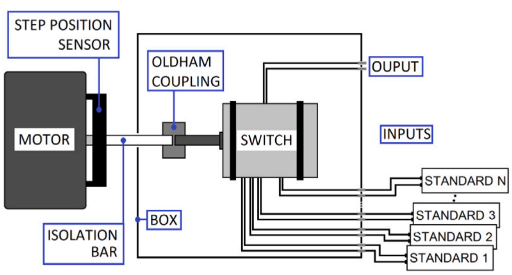

Fig. 3. Basic scheme of a scanner based on an electrical rotary switch.

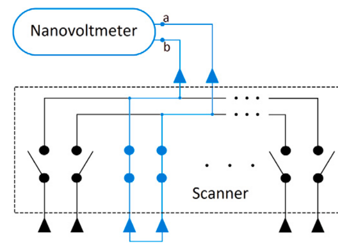

Fig. 4. Scanner thermal EMF measurement principle.

The different types of scanners can be used for various applications. The extent they can achieve will depend on the considerations that have been taken into account in their design. Table 2 shows some of the measurement results of each type of scanner, highlighting some of their special features.

3. Scanner characterization methods

Depending on the scanner's application, characterization has to be performed to ensure its incorporation into the measurement system does not affect the results. This section describes methods for characterizing the scanner. If the results characterization do not meet the requirements, the strategies described in Section 2.1 should be followed to reduce the unwanted effects.

3.1. Parasitic impedances

The contact impedances between the scanner's inputs and outputs can be measured in AC with an RLC bridge or in DC employing a resistance meter configured to 4 terminals. Usually, the value of the contact impedances is of the order of 100 mΩ. If impedances defined as 3 or 4 terminals will be measured, the scanner admittances between the conductor and the shield, as well as the contact impedances of each of their channels, must be measured with an RLC bridge and then corrected [4].

The insulation resistance between the scanner conductors and their shield can be measured directly using a high-resistance meter like a Keithley 6517B or an Keysight B2980. It can also be indirectly measured using a known voltage source and an electrometer that measures the current that it draws.

Factors like temperature, humidity, and triboelectric effects can cause a change in the value of the spurious impedances of the scanner. Hence, these factors must be measured during the characterization of the scanner and preferably controlled when the scanner is used.

3.2. Crosstalk between the scanner channels

Crosstalk can be determined using a lock-in amplifier [2]. The measurement process consists of connecting the output of the scanner to the lock-in. Subsequently, generating zero volts in the enabled channel, the signal in the lock-in amplifier is measured; then, a variation is made in the signal of some other not enabled channels, and the signal on the lock-in amplifier is measured again. Then, the ratio of the difference between the measured signals and the disabled channel signal variation can be calculated.

3.3. Thermal EMFs

As described in [13,16], the thermal EMFs measurement can be performed depending on how the scanner is used. Nevertheless, the measurement principle is the same. As shown in Fig. 4, by shorting the enabled channel's inputs and connecting a nanovoltmeter on the output terminals, a reading of the thermal EMFs of that set of conductors connected in series can be obtained. The polarity inversion method can be done to eliminate the thermal EMFs of the nanovoltmeter [3,11].

The stability of the scanner thermals EMFs is necessary if the measurement process takes a long time, as in the calibration of the load coefficient [3]. This is done by taking continuous measurements, equally spaced in time (≈ 30 s), for long periods and evaluating them using the Allan deviation [35].

Table 2
Measurement results of different types of scanners.

Scanner type	Special features	Measurement results
Relay-based scanner [2].	The scanner consists of modular switches; each module comprises three relays in series, which allows it to have shielded chambers that, in off mode, reduces parasitic capacitance between the input and output of the module by connecting the central relay to the output shield.	Off-state isolation between channels of -185 dB at 1 kHz. Contact resistance less than 90 mΩ. A difference between the measurements, with and without the scanner, of 1 part in 10^6 in the ratio of a High frequency 4-TP coaxial bridge at 1 MHz.
Relay-based scanner [3].	Uses a terminal selection and matching method to reduce thermal EMFs. It uses a thermal insulation structure to balance the temperature field around the electrical connection point. It uses U-shaped clamp terminals fixed in the relay board to support an acrylic screw that tightly clamps the terminal electrical connection point of the scanner.	Thermal EMFs of all the scanner channels range from −11 to 17 nV, with Type A uncertainties varying from 1 to 2 nV.
Scanner based on motion systems [10].	The positioning system is based on pneumatic actuators. It uses MUSA connectors. Interconnects four-terminal-pair standards.	The contact resistance of the connectors is below 2.5 mΩ, with a repeatability better than 50 μΩ and a difference among contacts below 200 μΩ.
Scanner based on motion systems [15].	The positioning system is based on servo-controlled motors. The scanners have 16 sets of inputs of two-terminal-pair or four-terminal-pair. Use gold-plated, crimped-type BNC connectors.	Differences with and without the scanner of less than 4 parts in 10^9 on measurements of standard resistors with nominal values of 1 Ω to 10 kΩ and less than 4 parts in 10^7 with nominal values of 10 MΩ to 100 GΩ. Differences with and without the scanner of 5 parts in 10^9 on measurements of standard capacitors of 10 pF at 1 kHz, 2 parts on 10^9 at 1,592 kHz, 0.012 μrad on its loss angle 1 kHz, and of 0.017 μrad at 1,592 kHz.
Scanner based on controlled rotating switches [11].	All the electrical connections of the inputs and outputs are thermally anchored on an Al (95%)/ Cu (4%)/ Mg (1%) alloy plate. A Nylon screw is crewed into the plate at each connection spot. A beryllium oxide washer ensures a high level of isolation resistance and thermal contact between the aluminum plate and the copper nut where the electrical wire is screwed through a crimped spade.	Eleven of the twelve scanner positions show voltage offset values between −15 and +25 nV with an associated Type A uncertainty varying from 2 to 7 nV. The twelfth scanner position shows a voltage offset of 60 nV with a Type A uncertainty of 7 nV.
Scanner based on controlled rotating switches [18].	All the contact parts are made of silver–copper alloy materials. Crimps and screws are used to connect lead wires mechanically to terminals. All the switch parts are attached to s Diflon plate to achieve high leakage resistance. The rotation of the switch is smooth and slow (about 30∘/s) to keep thermal EMFs reproducible.	Settling time within 2 s after changing the switch contact position. An overall reproducibility of the thermal EMF at the contacts is better than 1.5 nV.

4. Scanner design considerations for typical low-frequency applications

Depending on the use, different design considerations will have to be taken so that the scanner causes the minimum possible changes in the measurement results. Table 3 lists the most critical design considerations and the possible types of scanners that can be used in some typical low-frequency electrical metrology applications. The applications chosen for this analysis are calibration of intermediate nominal resistance values (1 Ω to 1 MΩ) [36], calibration of high nominal resistance values (10 MΩ to 10 TΩ) [37], calibration of Zener reference standards [3,13,14], impedance calibrations with an RLC meter [2,4,10], and measurement of low voltage values (< 1μV) to achieve balances on a digitally-assisted impedance bridge or a fully-digital impedance bridge [21]. Applications such as the calibration of resistance thermometers [17] are contained in the analysis of resistors calibration of intermediate nominal values. Several design considerations apply to different uses, such as avoiding thermal EMFs, which should be taken into account in all the direct current measurements.

The switching speed is important for Zener standard calibrations because polarity reversal to reduce thermal EMFs is usually done with the scanner [3,13,14]. This does not happen with resistor calibration since the measurement system itself performs the polarity reversal [37]. On the other hand, scanner switching speed is also an important consideration for fully digital impedance or digitally-assisted impedance bridges [21]. The balances of various bridge paths are evaluated through the scanner along with a lock-in amplifier, used as a null detector, to achieve the 4-terminal pair definition of the measured impedances. So if the switch between channels takes several seconds, the bridge measurement process could take several tens of minutes.

The use of a short for the non-enabled channels of the scanner avoids parasitic capacitances or resistances in parallel to the impedance connected in the enabled channel. This mainly affects capacitance calibrations below 10 pF and resistance calibrations with values greater than 1 GΩ.

5. Conclusions

Knowing the different types of scanners for electrical metrology, as well as the influence quantities that limit their performance and the methods to characterize them, it is possible to develop a scanner that allows automating the measurement system without degrading its uncertainty and eliminating human error.

The choice among the types of scanners described depends on the application in which it will be used. Since there are relays that can switch in up to 5 ms [23,24], a relay-based scanner can be used in applications that need to make quick changes between different inputs. A scanner based on a positioning system can achieve excellent isolation among the various inputs. Since all contact parts of a motor-automated rotary switch-based scanner can be chosen to be of the same material and crimps and screws can be used to connect mechanically the wires to its terminals, these types of scanners have proven to be a perfect choice for achieving low thermal EMFs.

If switching speed is not a factor that impacts the results, scanners based on motion systems are an excellent alternative since it simulates the manual connection made if the scanner was not available, but without the human errors generated in the process. On the other hand, relay-based scanners are the most dynamic alternative as they can be applied for various low-frequency electrical measurement applications.

Table 3
Design considerations and scanner types for low-frequency electrical metrology applications.

Applications	Design considerations	Scanner types
Calibration of resistance of intermediate nominal values (1 Ω to 1 MΩ) [8,36]	Avoid thermal EMFs; avoid temperature gradients; have terminals with low Seebeck coefficient materials; avoid the effects of electromagnetic interference in the environment.	Scanners based on relays; Scanners based on controlled rotating switches; Scanners based on motion systems.
Calibration of resistance of high nominal values (10 MΩ to 10 TΩ) [1,5,9,37]	Avoid thermal EMFs; avoid temperature gradients; avoid the effects of electromagnetic interference in the environment; avoid the generation of leakage currents; have terminals with low Seebeck coefficient materials; shielding along each channel; high isolation between channels and other potentials; short circuit on the not-enabled channels.	Scanners based on relays; Scanners based on motion systems.
Calibration of Zener reference standards [3,6,11,13,14].	Avoid thermal EMFs; switching speed; avoid temperature gradients; avoid the generation of leakage currents; have terminals with low Seebeck coefficient materials.	Scanners based on relays, Scanners based on controlled rotating switches
Calibration of impedance with an RLC bridge [2,4,10]	Avoid the effects of electromagnetic interference in the environment; avoid the generation of leakage currents; avoid the effects of electromagnetic interference between the scanner channels; coaxiality; low and stable impedance values in the channels; shielding along each channel; short circuit on the not-enabled channels.	Scanners based on relays; Scanners based on motion systems.
Measurement of low voltage values (< 1μV) to achieve balances on a digitally-assisted impedance bridge or a fully-digital impedance bridge [2,21]	Switching speed; avoid the effects of electromagnetic interference in the environment; avoid the generation of leakage currents; avoid the effects of electromagnetic interference between the scanner channels; coaxiality; low and stable impedance values in the channels; shielding along each channel.	Scanners based on relays.

Regardless of the type of scanner, it is necessary to analyze the influence variables that the scanner could introduce to the measurement system. This paper describes the influencing variables that typically affect results and defines a list of design considerations for some of the typical low-frequency electrical measurement applications. This information serves as the basis for the choice or development of a scanner.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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