A novel measurement technique for DC voltage and current reducing the DMM loading effects

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Abstract— **A novel technique for the measurement of DC voltage and current that reduces the loading effects of a digital multimeter is presented in this work. When the variable of interest is a current (voltage), instead of connecting an ammeter (voltmeter) in series (parallel), it is proposed to connect a voltmeter (ammeter) and an ohmmeter in series (parallel) at the same two terminals conventionally employed. The application of this new measurement technique reduces the loading effects by a factor of at least 100 but up to 500, in comparison with those obtained in the conventional method.**

Keywords—current measurement, digital multimeter, loading effects, voltage measurement.

I. Introduction

After designing an electronic circuit, this has to be built and tested in order to guarantee that its performance corresponds to that expected. The testing phase, which can be implemented either manually or automatically, involves the measurement of the voltage at some representative nodes of the circuit and/or the current in some critical paths. These measurements are usually carried out by a digital multimeter (DMM) that is placed in parallel or in series to act as a voltmeter or an ammeter, respectively. However, when this instrument is connected to the circuit, the resulting equivalent circuit changes due to the input resistance (or impedance) of the voltmeter [1], [2] or the shunt resistance of the ammeter. The former should be ideally infinite, but it is generally equal to 10 MΩ and independent of the selected range, whereas the latter should be ideally zero, but its value increases with decreasing the range [3], [4]. Because of that, the measurement of the voltage or current of interest can be different to that expected due to the loading effects of the instrumentation on the circuit. Such effects are a clear example that the result of a digital measurement cannot always be trusted, as highlighted in [5].

The loading effects indicated before are especially critical when measuring: 1) current in circuits with low-value resistances, and 2) voltage in circuits with high-value resistances. An example of case #1 is the measurement of the current through a 100 Ω platinum thermal sensor that has to be lower than a certain limit to avoid self-heating effects. An example of case #2 is the measurement of the output voltage of a voltage divider (intended to provide a reference voltage for another stage of the circuit) implemented with high-value resistances to decrease the overall current consumption.

Different strategies can be applied to decrease the loading effects of instrumentation on the circuit under test. Some examples are given next. As for the voltage measurement, some bench-top DMMs offer the possibility to select an input resistance of 10 GΩ, instead of 10 MΩ, in low-value voltage ranges, but these DMMs are generally expensive models. On the other hand, as for the current measurement, the loading effects can be reduced by employing a current range higher than that required, which generally involves a lower shunt resistance but a higher measurement uncertainty. Therefore, there is a trade-off between loading effects and uncertainty. An alternative way to avoid loading effects in current measurements is the use of clamp-on current probes [6]-[8], but these generally have a limited accuracy.

Taking into account the previous limitations, this work aims to propose a novel technique for the measurement of DC voltage and current. This technique relies on a novel theorem [9] that was initially proposed for the analysis of circuits, but it can also be applied to the measurements field. According to the technique proposed herein, when the variable of interest is a current (voltage), instead of connecting an ammeter (voltmeter) in series (parallel), a voltmeter (ammeter) and then an ohmmeter are connected in series (parallel) at the same two terminals conventionally employed. The fact of connecting a voltmeter in series was already suggested in [10], but not with the aim of decreasing the loading effects of instrumentation. The experimental results presented later show that loading effects are reduced by a factor of at least 100 but up to 500 when applying the novel technique.

II. Reverter's Theorem Behind the Novel Technique

Thevenin and Norton theorems were stated more than 100 years ago, but lately these have been re-explained and/or re-formulated [11]-[13]. These theorems have also been recently employed to prove a novel general-purpose theorem for the analysis of linear circuits [9], which was formulated by one of the authors of this work. This theorem, which establishes the basis of the novel measurement technique proposed herein, states the following:

1. Any current (for instance, I_A in Fig. 1a) can be determined as V_{eqA}/R_{eqA}, where V_{eqA} and R_{eqA} are an equivalent voltage and resistance, respectively. To calculate these parameters, the current path of I_A must be blocked through an open circuit and then:
   1.1. V_{eqA} is the open-circuit voltage between terminals 1 and 2 of the intended open circuit, as shown in Fig. 1b.
   1.2. R_{eqA} is the resistance between terminals 1 and 2 when turning off all the independent sources, as shown in Fig. 1c.
2. Any voltage (for instance, V_B in Fig. 2a) can be determined as $I_{eqB} \cdot R_{eqB}$, where I_{eqB} and R_{eqB} are an equivalent current and resistance, respectively. If the nodes of the voltage difference under study are identified as terminals 1 and 2, the previous parameters must be calculated as:

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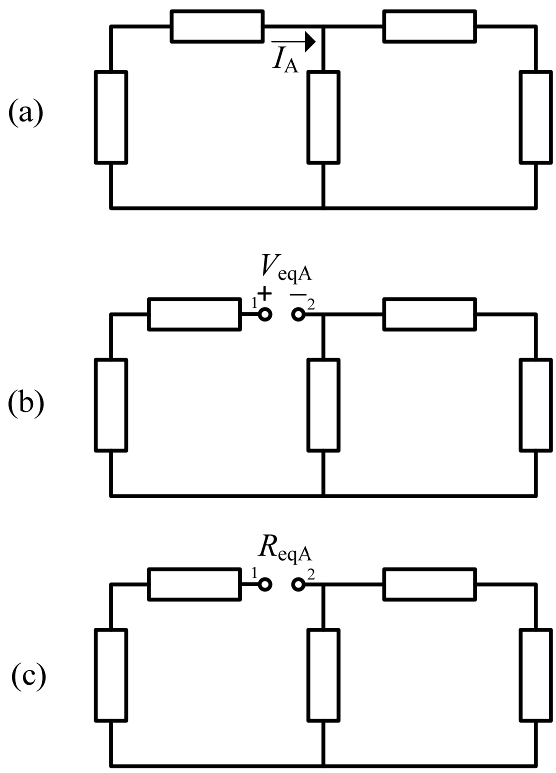

Fig. 1. Generic linear circuit explaining an alternative method to determine the current I_A; the rectangular symbol can be either a passive or an active two-terminal element.

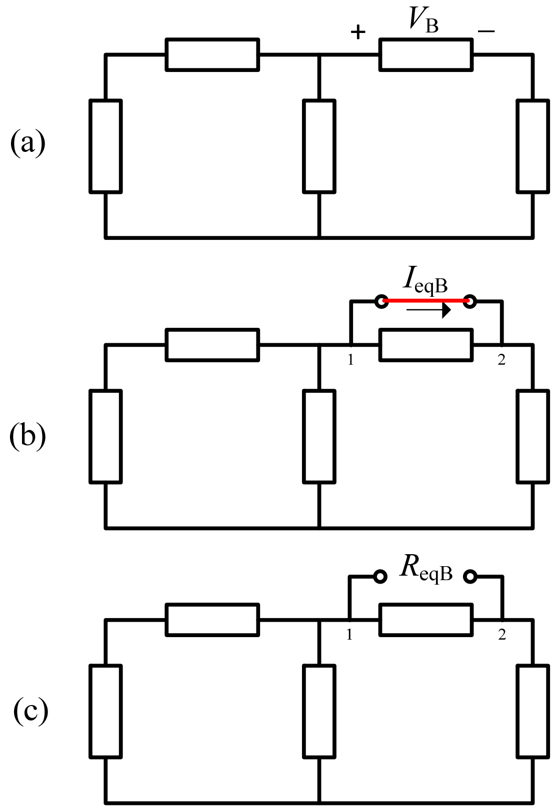

Fig. 2. Generic linear circuit explaining an alternative method to determine the voltage V_B.

2.1. I_{eqB} is the current flowing between terminals 1 and 2 when these are short-circuited, as shown in Fig. 2b.
2.2. R_{eqB} is the resistance between terminals 1 and 2 when turning off all the independent sources, as shown in Fig. 2c.

This theorem offers an alternative method for the circuit analysis that, in comparison with the classical node-voltage and mesh-current methods, is more straightforward. This is because the resulting circuit becomes simpler as a consequence of applying the open/short circuit indicated by the theorem.

III. Novel Measurement Technique

In a conventional approach, if the current I_A in the circuit shown Fig. 1a has to be measured, an ammeter is placed in series, as represented in Fig. 3a. Conversely, if the voltage V_B in Fig. 2a needs to be measured, a voltmeter is connected in parallel, as represented in Fig. 4a. However, using as a reference the Reverter's theorem explained in Section II, the measurement of a current or a voltage can be carried out in an alternative way. The proposal is the following:

1. Any current (for instance, I_A in Fig. 1a) can be determined as V_{eqA}/R_{eqA}, where:
   1.1. V_{eqA} is the voltage measured by a voltmeter connected in series, as shown in Fig. 3b.
   1.2. R_{eqA} is the resistance measured by an ohmmeter also connected in series, as shown in Fig. 3c, when the independent sources are turned off.

2. Any voltage (for instance, V_B in Fig. 2a) can be determined as $I_{eqB} \cdot R_{eqB}$, where:
   2.1. I_{eqB} is the current measured by an ammeter connected in parallel, as shown in Fig. 4b.
   2.2. R_{eqB} is the resistance measured by an ohmmeter also connected in parallel, as shown in Fig. 4c, when the independent sources are turned off.

In comparison with the classical methods shown in Figs. 3a and 4a, the measurement technique proposed herein has advantages and drawbacks. The main advantage is that the loading effect of the instrument is expected to much lower, especially when measuring 1) current in circuits with low-value resistances, and 2) voltage in circuits with high-value resistances. By cons, the main drawback is that two steps (or measurements) are required to determine the variable of interest. However, these two measurements are carried out between the same two terminals of the circuit, i.e. in series in Fig. 3 and in parallel in Fig. 4, as in the conventional approach represented in Figs. 3a and 4a. Another limitation is that the measurement setup must be able to turn off the independent sources while measuring the equivalent resistance. This, however, should not be a major issue in an automatic test equipment with digitally-controlled instrumentation.

IV. Materials and Method

As a proof-of-concept, the proposed technique has been applied to measure the current I_A and the voltage V_B of the simple DC voltage divider shown in Fig. 5. First, I_A and V_B were measured using the conventional configuration represented in Figs. 6a and 7a, respectively. Next, such variables were determined following the two-step methodology proposed in Section III. As for I_A, the voltmeter and ohmmeter were connected in series, as shown in Figs. 6b

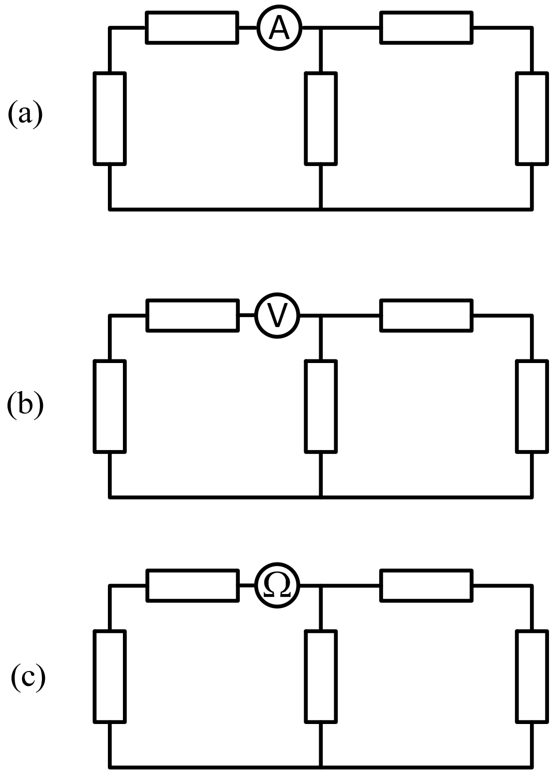

Fig. 3. Conventional (a) and novel (b and c) techniques applied to the measurement of a current.

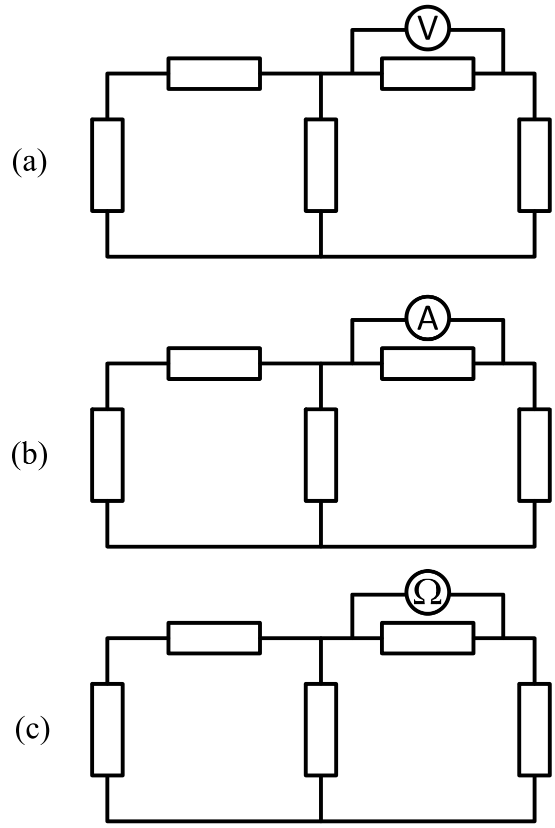

Fig. 4. Conventional (a) and novel (b and c) techniques applied to the measurement of a voltage.

an 6c, respectively. As for V_B, the ammeter and ohmmeter were connected in parallel, as represented in Figs. 7b an 7c, respectively. In addition, for the cases shown in Figs. 6c and 7c, the independent voltage source (V_s) was turned off, as indicated through the red dashed line. The results obtained with the conventional and novel measurement techniques were then compared.

The following instrumentation was used during the experimental tests. A DC power supply (Keysight E3631A) provided the independent voltage source (V_s) of the circuit. A DMM (Agilent 34410A) was employed as a voltmeter, ammeter, and ohmmeter to measure the required voltage, current, and resistance, respectively, shown in Figs. 6 and 7. For the DC voltage measurement, this DMM offers an input resistance of 10 MΩ in the range of interest, whereas for the DC current measurement, it has a shunt resistance of 200 Ω if the current is lower than 1 mA. The DMM was set with an integration time of 100 NPLC (Number of Power Line Cycles) so as to have more precise measurements.

For the case represented in Fig. 6, we selected V_s = 100 mV and $R_1 = R_2$ with (nominal) values ranging from 270 Ω to 560 Ω, which are similar to the shunt resistance of the DMM. On the other hand, for the case represented in Fig. 7, we selected V_s = 25 V and $R_1 = R_2$ with (nominal) values ranging from 1 MΩ to 10 MΩ, which are similar to the input resistance of the DMM. The actual values of V_s, R_1, and R_2 were measured by the same DMM. These values were employed to calculate the ideal values of I_A and V_B in a scenario with ideal instrumentation. For both the conventional and the novel measurement techniques, the relative error in percentage with respect to the previous ideal value was computed.

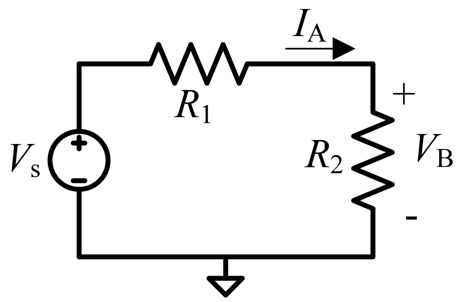

Fig. 5. Voltage divider employed to prove the proposed technique for the measurement of I_A and V_B.

V. Experimental Results and Discussion

The experimental relative error when measuring I_A and V_B with the application of the conventional method (Figs. 6a and 7a) is represented in Figs. 8 and 9, respectively. In Fig. 8, the lower the value of R_1 (or R_2), the higher (in absolute terms) the relative error (from -15% to -32%), due to the fact that the shunt resistance of the DMM has more effects on the measurement. Secondly, in Fig. 9, the higher the value of R_1 (or R_2), the higher the relative error (from -5% to -30%), because the external resistance becomes more similar to the input resistance of the DMM. The experimental results in Figs. 8 and 9 agree with those expected theoretically taking into account the loading effects of the instrumentation.

As for the novel measurement technique proposed in Section III, Figs. 10 and 11 show the experimental relative error when measuring I_A and V_B, respectively. In the former case (Fig. 10), the error is quite independent of the value of R_1 and remains below -0.1 %, which is a very remarkable value taking into account the scenario under test. In comparison with Fig. 8, the relative error in Fig. 10 is between 190 and 543

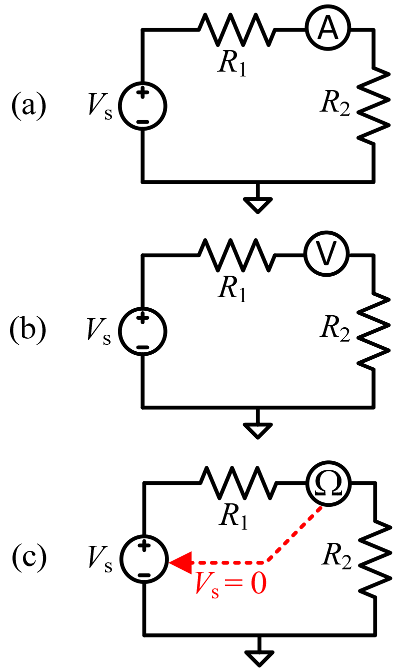

Fig. 6. Conventional (a) and novel (b and c) techniques applied to the measurement of the current I_A in Fig. 5.

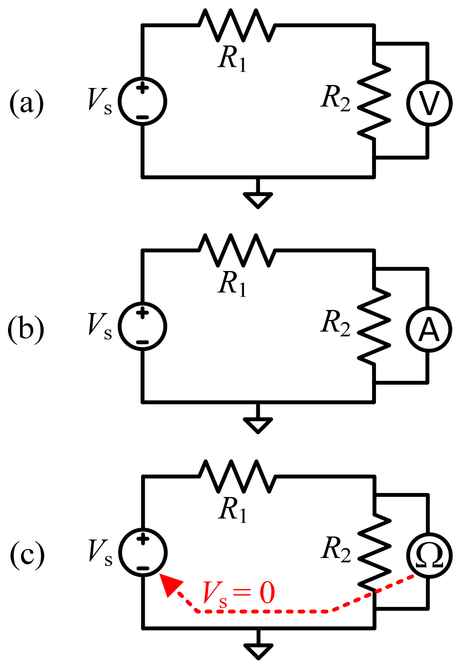

Fig. 7. Conventional (a) and novel (b and c) techniques applied to the measurement of the voltage V_B in Fig. 5.

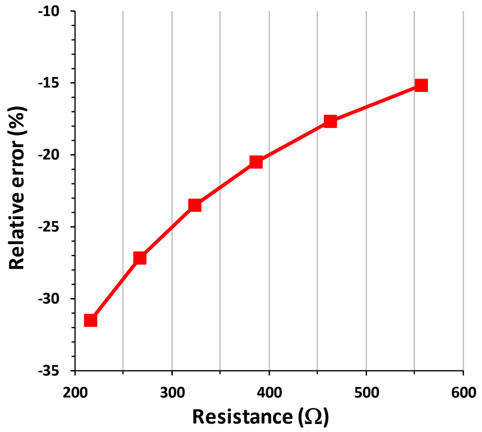

Fig. 8. Relative error in the conventional measurement of I_A in Fig. 5.

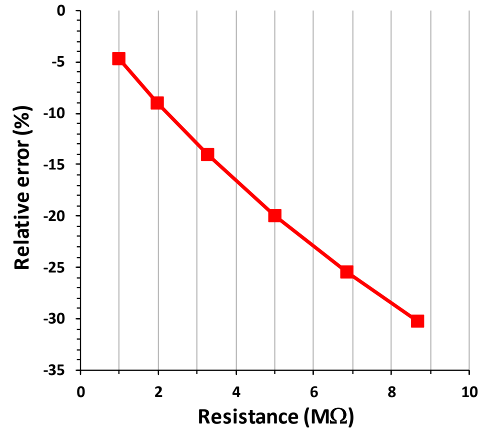

Fig. 9. Relative error in the conventional measurement of V_B in Fig. 5.

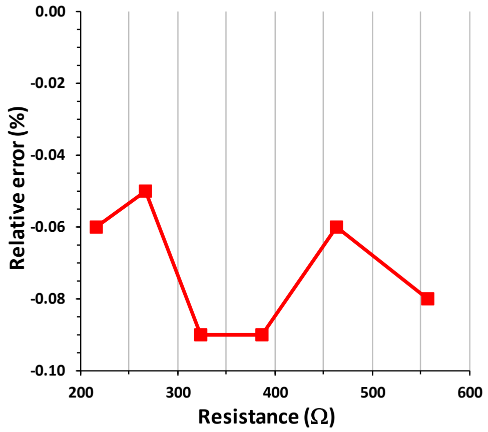

Fig. 10. Relative error in the novel measurement of I_A in Fig. 5.

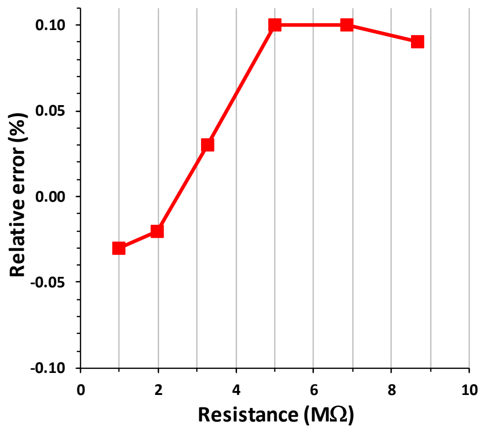

Fig. 11. Relative error in the novel measurement of V_B in Fig. 5.

times lower. In the latter case (Fig. 11), similar conclusions can be extracted. The relative error ranges from -0.03% to 0.1%, which is between 156 and 467 times lower than that represented in Fig. 9. Therefore, the proposed technique clearly offers an improvement factor higher than 100. In addition, the error shown in Figs. 10 and 11 seems to be more related to the limitations of the DMM (especially when measuring high-value resistances), rather than the limitations of the method itself.

According to the experimental results reported before, the measurement technique proposed herein seems to be very effective to reduce the loading effects of the instrumentation. Actually, the lower the resistance of the circuit when measuring a DC current or the higher the resistance of the circuit when measuring a DC voltage, the better the performance of the proposed technique, which is the opposite that happens in the conventional method.

VI. Conclusions

With the aim of reducing the loading effects of instrumentation, a novel technique for the measurement of DC voltage and current has been proposed. This technique relies on a novel theorem that was initially proposed for the analysis of circuits, but it can also be applied to the measurements field. The application of such a new technique has shown that the relative error when measuring a current (voltage) in a circuit with low-value (high-value) resistances is reduced by a factor of at least 100 but up to 500, in comparison with that obtained when applying the conventional method.

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