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ALTERNATIVE POWER STANDARD REALIZATION AT RADIO FREQUENCY

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Abstract – Modern ac-dc transfer equipments can operate up to 1 GHz at least. These equipments and the related ac-voltage measurements may be attractive for calibrating high frequency power sensors in term of ac-dc transfer difference instead of effective efficiency. Furthermore, below 30 MHz, the ac-voltage standard can be also used as powerful alternative and complement to the microcalorimeter technique for the realization of the RF power standard. In the paper experimental measurements and data analysis are presented that prove the previous assertions.

Keywords: ac-voltage, RF-power, standard.

1. INTRODUCTION

If an electrical system is conservative, the work to carry a unit charge from point *a* to point *b* is independent of the path followed and is assumed as voltage between *a*, *b*, i.e.:

$$V_{ab} = -\int_a^b \vec{E} \cdot d\vec{l} \ , \qquad (1)$$

where $\vec{E}$ is the electric field strength along the path and $\vec{l}$ the path unit vector. This happens in all electrostatic systems, of course, but applies also to all dynamic systems operating in TEM mode, provided that the integration is performed in a transverse plane [1].

Direct voltage measurements are significant and practicable on coaxial systems from dc to about 1 GHz. Above this threshold, measurement techniques and related standards have not been developed greatly, despite the initial enthusiasm reported in the historical literature [2]. Beyond 1 GHz, indeed, voltage measurement turned out to be easier if made indirectly trough power measurement, considering also the significant improvements obtained with the coaxial microcalorimeter technique [3].

Anyway, below 10 MHz the coaxial microcalorimeter fails completely if system uses the bolometric detection. Though it is possible to work around this inconvenient by using indirect heating thermoelectric sensors in the role of microcalorimeter thermal load [3], [4], [5], a lack of sensitivity persists below 10 MHz and this limits the power standard accuracy. Conversely, direct ac-voltage measurement becomes a more convenient way both to realize and to transfer the power standard. Therefore voltage standards and related transfer techniques assume noticeable importance in the radio frequency (RF) field, at least [6].

The basic principle of RF-voltage measurement is very simple. If a resistive element *R* is placed in a TEM transmission line in such a way that the spatial field is only negligibly altered, then *R* integrates the transverse electric field. This means that the resultant conduction current trough *R* renders the rms-voltage across it. The voltage can be measured by employing well known bolometric or thermoelectric detectors and, in this manner, an ac-dc voltage converter is realized that can be considered, under some assumption, a RF-voltage standard [7].

The RF-voltage standard can be used to calibrate another RF voltmeter trough a lossless coupling T-junction [8], that make possible a comparison, irrespective of the input impedances of the two devices, provided that the resulting T-branches have negligible electrical length with respect to the wavelength or, at least, the same electrical length.

We are using this technique to obtain the power standard from the RF-voltage at the RF frequencies, where the microcalorimeter starts to lack in sensitivity. The aim is to obtain an uncertainty of the same order of that obtainable with the last version of the coaxial microcalorimeter itself [4]. Furthermore, the same technique is used to calibrate a power sensor in term of ac-dc transfer difference with the advantage of extending the ac-dc transfer difference measurements beyond 1 MHz that is the current limit of the reference standard existing at INRIM at the moment.

The paper presents updated results concerning the realization and transfer of the RF power standard based on a coaxial thermoelectric power sensor of commercial type in the range of frequencies from dc up to 30 MHz.

2. POWER STANDARD RATIONALE

Thermoelectric power sensors used as thermal load in the coaxial microcalorimeter are devices identified as power transfer standards after the appropriate calibration in term of effective efficiency [4]. These devices have the same structure of the thermal voltage converters in coaxial lines (TVCs) used as RF voltage standards and calibrated in terms of ac-dc transfer difference [6], [7]. Therefore the mentioned power sensors can also be calibrated against other standard TVCs by comparison on an unmatched T-junction and in terms of transfer difference δ defined as follows:

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$$\delta = \frac{V_{\mathrm{RF}} - V_{\mathrm{dc}}}{V_{\mathrm{dc}}}, \qquad (2)$$

where V_{RF} is the RF-voltage at the reference plane of the input connector that produces the same TVC output of the dc-voltage V_{dc}.

Effective efficiency and transfer difference can be transformed one in the other. Indeed, the effective efficiency of a thermoelectric power sensors is defined as the ratio between a dc reference power P_{dc}, entering the sensor, to the RF power P_{RF} that produces the same sensor output (*U*=*const*) [4], [5]:

$$\eta_e = \left. \frac{P_{\mathrm{dc}}}{P_{\mathrm{RF}}} \right|_{U=const.} . \qquad (3)$$

If we now define a quantity called Power Transfer Difference Δ as:

$$\Delta = \frac{P_{\mathrm{RF}} - P_{\mathrm{dc}}}{P_{\mathrm{dc}}}, \qquad (4)$$

where P_{RF} and P_{dc} are the RF and dc power levels that give the same output response, using the relation given in (4), the definition (3) can be written in terms of the relative difference Δ between the two powers:

$$\eta_{\mathrm{e}} = \frac{1}{1+\Delta}. \qquad (5)$$

The Relative Power Difference defined in (4) cannot be directly measured but, since the devices used can be treated as thermal converters, they can also be calibrated in terms of the Voltage Transfer Difference defined in (2). So, by virtue of the Ohm's law, a first order approximation of (5) gives:

$$\eta_{\mathrm{e}} \cong \frac{R_{\mathrm{RF}}}{R_{\mathrm{dc}}} \frac{1}{1+2\delta}, \qquad (6)$$

where R_{RF} and R_{dc} are the RF and dc resistances respectively at the input reference plane of the thermoelectric power sensor. Measurements confirms that the use of the approximated relation (6) instead of the complete expression of the effective efficiency, gives negligible contribution with respect to the provided uncertainty (less than 400 ppm at 30 MHz). Equation (6) is used to complete the calibration of a power sensor in the frequency range dc – 30 MHz. This comprises both the frequencies where the microcalorimeter starts to lack in sensitivity and covers also a range in which it is possible to have good microcalorimetric results, so to perform a comparison between the two methods. It must be, however, noted that (6) is not interesting beyond 100 MHz because of the difficulty to establish an enough accurate value of $R_{\mathrm{HF.}}$

3. EXPERIMENTAL SET-UP

A measurement set-up suitable to calibrate a power sensor below 30 MHz is shown in Fig. 1. The system has the configuration typically used to compare ac-dc transfer difference standards [6], [7], [8]. The RF signal is provided by a synthesized generator, while the dc is provided by a calibrator. Both the outputs of the two instruments are sent to the input ports of a RF commercial electromechanical switch controlled by an external driver. This choice allows to reduce the possible noise signals coming from the electronic components because the external driver can be kept away from the measurement node.

The output port of the RF switch is directly connected to the input of a T-junction node used to supply the same voltage to both unknown and standard TVCs. This component is the most critical of the whole system: for this reason, the junction has been specifically realized so that the branches connected with TVCs have the minimum electrical length possible. This maximizes the frequency range of the device and minimizes the error due to the residual mismatch between standard and unknown TVCs.

Another critical component of the system is the RF-source that operates normally in quite bad mismatch conditions. The reflection coefficient of the generator does not enter explicitly into the comparison but the generator must be able to absorb well the relatively high standing wave that appears between its output port and the electrical centre of the T-junction.

Since the RF generator needs to work with a 50 Ω impedance at its output port, to maintain the symmetry also the DC calibrator is set to work in the same condition. The actual impedance, however, is never exactly 50 Ω, because it is the result of the impedances of the devices under test that are placed in parallel. Normally one of the devices used has a nominal impedance of 50 Ω, while the other one has an higher nominal impedance (such as 400 Ω), so the value resulting from the combination slightly differs from the required one. Anyway, to perform the measurements as close as possible to the desired voltage levels, a method has been implemented that uses a multimeter connected to the input port of the RF switch that lodges the DC Calibrator (Fig. 1).

This method search the actual DC value that must be set on the calibrator to have, at the centre of the node, the desired voltage level.

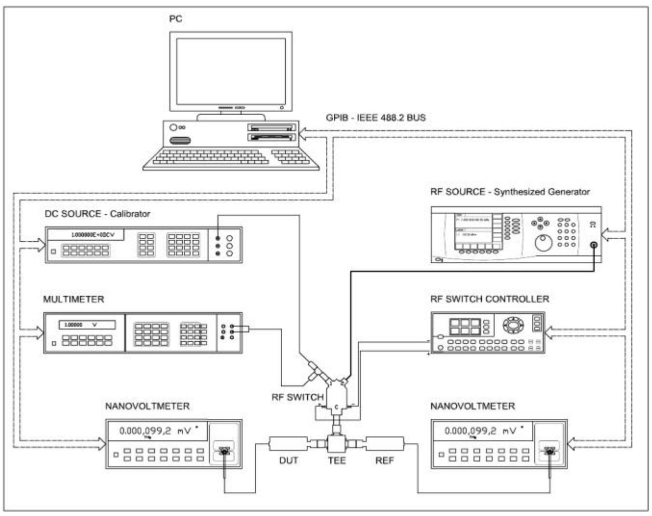

Fig. 1. Measurement set-up for calibrating ac-dc thermal voltage converters.

Once the value has been found, it is used to search the RF signal that provides the same output on the standard TVC.

Finally the output levels of the two devices are read through two twin nanovoltmeters to ensure the symmetry of the system. All the instruments are computer controlled through the IEEE 488.2 bus.

4. THERMAL VOLTAGE CONVERTERS CALIBRATION

Theoretically, the previous set-up is suitable to perform ac-dc transfer measurements from 10 kHz to 1 GHz and beyond but the real interest is to limit the range at 100 MHz at maximum, both because the microcalorimetric technique gives better results at higher frequencies and the ac-voltage measurements become less significant increasing the frequency itself.

4.1. Comparison with the ac Reference Standard

To validate the new system in the range of frequencies below 1 MHz, this set-up has been compared with the ac Voltage Reference Standard set-up actually present at INRIM [9].

The comparison involved one of the sensors normally calibrated inside the microcalorimeter in term of effective efficiency. The sensor is a commercial model modified by removing all active internal electronic, so that its thermoelectric output can be directly measured by means of a dc-nanovoltmeter. In this way, the sensor can be seen as a TVC and therefore it can be calibrated in term of transfer difference δ. The sensor used is fitted with Type-N connector. Measurements have been performed at the same frequencies and voltage levels on both the set-ups.

The set-up actually used to maintain the primary ac-voltage standard differs from the one described above mainly for three characteristics. First of all, the ac generator used is limited in frequency up to 1 MHz, and it is also for this reason that the new system has been implemented, so to be able to extend the frequency range of the ac-voltage measurements. Secondly, an electromotive force comparator is present to compensate the possible variations of the input voltages maintaining the ratio of the voltages constant independently of the value of the reference. The electromotive force comparator is not present in the new set-up: this choice does not affect the measurements results, as it can be demonstrated by the comparison performed described below; it is a solution used also in other NMIs [10], [11], [12]. Finally the switch used has been specifically designed for the scope and it is not a commercial type as the one cited above.

For all these reasons, the comparison is necessary, so to demonstrate that, despite the differences between the two measurement systems, both give the same results when the same sensor is calibrated against the same reference standard. The sensor assumed as unknown has been calibrated against the same INRIM ac-reference standard, a Multi Junction Thermal Converter designed at PTB [13], by using both the measurement set-ups.

To have a complete symmetry, both the set-ups use the same tee node, so that the comparison confirms the correct performance of the instruments used and of the program implemented. The results are shown in Fig. 2 and demonstrate a good behaviour of the new set-up.

The new set-up, together with the software program, implements a correct measurement procedure, giving results consistent with the reference system at least up to 1 MHz, the limit of the actual INRIM reference set-up. Anyway the comparison provides a first validation of the system, that, to be complete, must include also a comparison at higher frequency with the microcalorimeter.

As it can be seen from Fig. 2, the INRIM reference set-up provides better uncertainties at lower frequency. This is expected because the new set-up is optimized to work at higher frequencies.

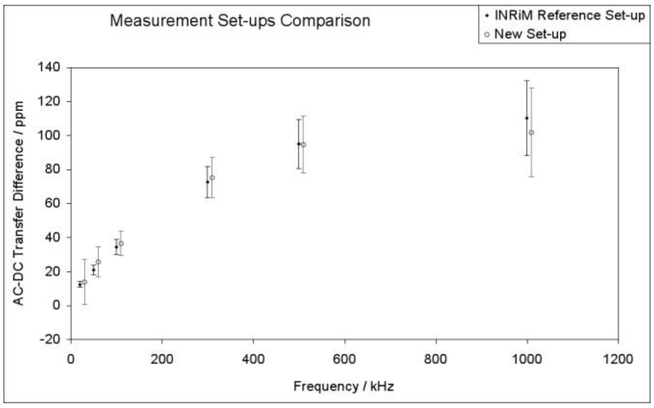

Fig. 2. Comparison between the new set-up and the INRIM Reference Standard set-up below 1 MHz. Data are slightly x-axis shifted for better reading.

The data have been compared also using the normalized deviation usually called Compatibility Index I_c and defined as [14]:

$$I_c = \frac{X_1 - X_2}{\sqrt{U_1^2 + U_2^2}}\ , \tag{7}$$

where X_1 and X_2 are the two values that have to be compared, while U_1 and U_2 are the extended uncertainties of the two quantities (coverage factor k = 2). The data show a good consistency if the absolute value of the Compatibility Index is less than the unity. The results of the comparison in terms of the Compatibility Indexes are shown in Table 1.

Table 1. Compatibility Indexes between the new set-up and the Reference Standard Set-up.

Frequency / kHz	Compatibility Index I_C
20	0.115
50	0.501
100	0.250
300	0.174
500	-0.018
1000	-0.247

4.2. Comparison with the microcalorimeter and the power measurement (on matched source) techniques

Since INRIM has not ac-dc transfer difference set-ups that can work above 1 MHz, to validate the new system at higher frequencies, a comparison is needed with other methods. As explained in Section 2, the proposal is to use ac-dc voltage transfer difference measurements to obtain indirectly, through (6), the effective efficiency η_e of a sensor up to the frequency of 30 MHz. Then the same sensor can be calibrated directly in terms of effective efficiency into the microcalorimeter and the results obtained can be compared to validate the new procedure at frequencies higher than 1 MHz. The sensor used is the same described before. After the calibration against the INRIM ac primary reference standard (Multi-Junction Thermal Converter designed at PTB [13]) in the range of frequencies up to 1 MHz it was measured against a device calibrated at VSL [15] in the range of frequencies from 3 to 30 MHz. Then the values of ac-dc transfer difference have been converted in effective efficiency using (6) and the results are shown in Fig. 3: this graph shows that it is possible to obtain effective efficiency values also below 10 MHz, that is the range of frequencies in which the microcalorimeter can not provide good sensitivity. The calibration accuracy increases with the frequency as expected because of the very low values of ac-dc transfer difference we are measuring below 10 MHz.

The choice of using a device calibrated at VSL for frequencies greater than 1 MHz is due to the fact that, at the moment, INRIM does not have an ac-voltage reference standard beyond that frequency value. In any case the project of a new Thermal Converter suitable to become a reference ac-voltage standard is under development.

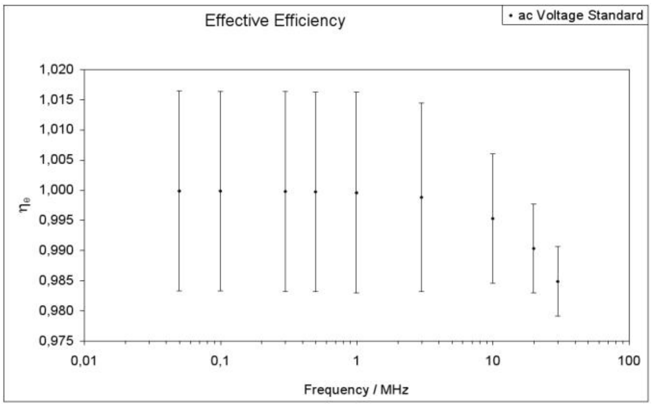

Fig. 3. Power sensor calibration against the ac-voltage standard in the frequency range 10 kHz – 30 MHz. X-axes is in logarithmic scale.

Since the microcalorimeter lacks in sensitivity under 10 MHz, the only data of Fig. 3 that can be used to make a comparison with the microcalorimetric technique are the one beyond 10 MHz. In Fig. 4 this comparison is shown. The effective efficiency η_e of the power sensor measured directly inside the microcalorimeter results to be more accurate than the value obtained indirectly from transfer difference δ measurement.

The results are, anyway, compatible, as the superimposition of the error bars shows. The bias that appears in Fig. 4 between the two calibration methods was not expected. The hypothesis is that it can be due to the presence of a standing wave on the branches of the tee, caused by the asymmetry of the system, since the two devices connected have a different electrical length. Indeed, this acts as an error source which a correction is not yet provided for.

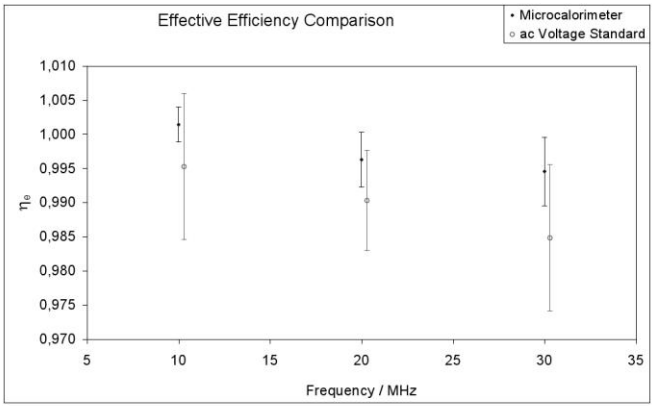

Fig. 4. Comparison between two power sensor calibrations (microcalorimeter and ac-dc transfer difference) in the range 10 MHz – 30 MHz. Data are slightly x-axis shifted for better reading.

In Table 2 the resulting Compatibility Indexes of the comparison described are presented, showing an agreement that confirms the superimposition of the error bars presented in the graph.

The calibration transfer is interesting between two power sensors of the same type, when it is made with the set-up of Fig. 1. In this case the system is forcibly symmetric and the mismatch between the two sensors is minimum, therefore the systematic error sources mentioned before are minimized.

Fig. 5 shows a comparison between a calibration of the same device made through two different methods: using the set-up of Fig. 1, in terms of ac-dc transfer difference converted subsequently in *effective efficiency* through (6) and by means of the more common comparison on the same matched source, whose measurement set-up is presented in Fig. 6. This method consists in the comparison of the unknown device with a reference standard on the same matched generator. As it can be seen in Fig. 6, the generator is connected to a sensor (alternatively the unknown and the reference) through a 10 dB attenuator pad and the output is directly read using a nanovoltmeter.

Table 2. Compatibility Indexes for the comparison between the microcalorimeter and the ac-dc transfer difference method.

Frequency / MHz	Compatibility Index I_C
10	-0.558
20	-0.714
30	-0.823

The output of the two devices are then compared to compute the Calibration Factor K of the device under calibration that is defined as follows [16]:

$$K_{X} = K_{R} \frac{P_{IR}}{P_{IX}}, \qquad (7)$$

where P_{IR} is the incident power at the reference frequency of 50 MHz, P_{IX} is the incident power at the calibration frequency under the condition that both incident powers give equal sensor response and K_R is the reference calibration factor. The calibration factor of a sensor is then linked to its effective efficiency by the following relation:

$$K = \eta_{e}(1-|\Gamma|^{2}), \qquad (8)$$

where η_e is the effective efficiency and Γ is the reflection coefficient of the sensor measured with a Vector Network Analyzer.

Reversing (8) it is possible to obtain the effective efficiency η_e from the Calibration Factor K as follows:

$$\eta_{e} = \frac{K}{1-|\Gamma|^{2}}. \qquad (9)$$

In other words we are comparing the measurement method based on ac-voltage measurements with the method based on power measurements.

Even if both the methods allow to obtain the desired quantity, that is the effective efficiency η_e, the method implemented through the ac-dc transfer difference results a little bit more accurate than the one based on the substitution on a matched generator, because voltage measurements are independent of the RF-generator mismatch [2].

As it can also be seen from Fig. 5 and Table 3, the agreement between the power measurement and the RF voltage measurement is greater than the one obtained with the microcalorimeter (see Fig. 4) even if a bias is still present.

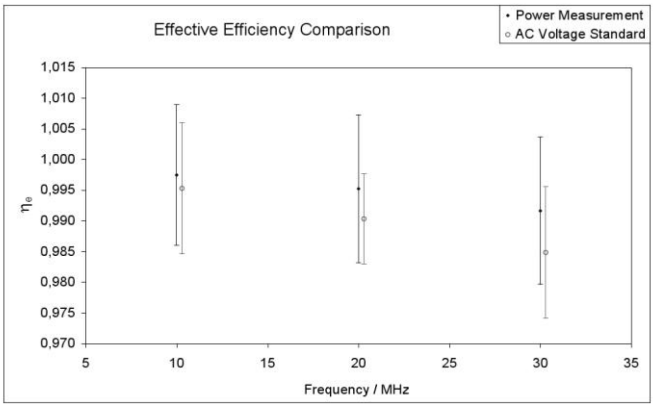

Fig. 5. Comparison between two power sensor calibrations (comparison on the same matched source and ac-dc transfer difference) in the range 3 MHz – 30 MHz. Data are slightly x-axis shifted for better reading.

Finally, the microcalorimeter uncertainty is the smaller achievable, so it can be concluded that this technique still remains the more precise, at the state of the art, in the range of frequencies beyond 10 MHz. The ac-dc transfer difference method results to be more precise than the substitution on a matched generator, but less precise than the microcalorimeter.

Anyway, since the new calibration proposed (power versus RF voltage) shows better results than the ones obtainable with the classical power method (power versus power), it could become a good alternative, mainly at low frequencies. In fact the new technique allows to obtain actual measurements of the effective efficiency below 10 MHz in a totally independent way, that is, it could be eligible as an alternative to the traditional techniques in order to extend the calibration capabilities downward.

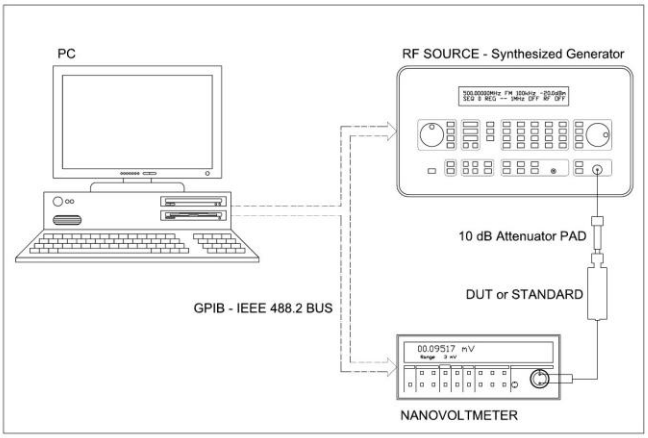

Fig. 6. Measurement set-up of the comparison on the same matched source method.

Also in this case the results have been compared using the Compatibility Index, whose results are presented in Table 3. The values are very low demonstrating a high consistency of the data.

Table 3. Compatibility Indexes for the comparison between direct power measurement (on matched source) and the ac-dc transfer difference method.

Frequency / MHz	Compatibility Index I_C
10	-0.139
20	-0.348
30	-0.422

Accuracy improvement of the method based on ac-voltage is possible. For this purpose a project of a calculable TVC, as already said, is in progress that will allow to obtain a more accurate ac-voltage reference, hopefully up to 100 MHz, to extend the comparison with the microcalorimeter.

5. CONCLUSIONS

In this paper we proposed an hybrid method to realize the RF-power standard. Microcalorimetric technique is, of course, recommended for frequencies beyond 10 MHz because of its superior performance in terms of accuracy. At lower frequencies, the power standard is realized indirectly through ac-voltage measurement so to workaround the limitation of the microcalorimeter.

The measurement of ac-voltage appears to be more convenient with respect to the power measurement when a calibration transfer is requested because it is faster and less sensitive to the source mismatch. The data presented are limited up to 30 MHz but a project of a new TVC is in progress which will allow to extend the measurements up to 100 MHz at least. The improvements that will be made to extend the measurements up to 100 MHz should also allow a reduction of the uncertainty that, at the moment, is better than the one obtained with the direct substitution on a matched generator but still grater than the one obtainable with the microcalorimeter. The aim is to reach the same uncertainty levels obtainable both with the last version of the microcalorimeter and with the new method proposed.

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