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Virtual instrumentation control for evaluation and compensation of the three-phased grid's unbalanced operations

Controlul instrumentației virtuale pentru evaluarea și compensarea operațiunilor dezechilibrate ale rețelei trifazate

Robert Pecsi[1], Magdalena Culcea[1], Eleonora Darie[1] and Elena Sanda[1]

[1] Electric Engineering in Constructions and Building Services Department, Technical University of Civil Engineering in Bucharest, Romania

E-mail: robert.pecsi@utcb.ro; magdalena.culcea@utcb.ro; elena.sanda@utcb.ro

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Abstract. *The unbalanced operation of the three-phase grid has a large number of negative consequences. The solution to this problem of unbalance, problem that appears whenever an unbalanced or single-phase load is connected to the network can be based either on conversion, or on compensation. Compensation based methods are capable of compensating not only the unbalanced operations, but also the non-sinusoidal and reactive operations. Former papers of the authors study the compensations methods. In this paper there is developed a LabView virtual instrument capable to calculate the unbalance factor of the grid and to control the active power filter used for compensation. The developed virtual instrument enables the activation of the compensation depending on the values of the measured and calculated unbalance factor. The method compensates the non-sinusoidal, reactive and unbalanced operations of the three-phase grid. Measurements prove the instrument's efficient operation and the method's viability.*

Key words. *Virtual instrumentation, three phased grid*

1. Introduction

The three-phase grid was designed for an operation that should be sinusoidal, direct-sequenced, nonreactive and balanced. If these objectives were easy to be obtained and maintained at the beginnings of the three-phase grid, nowadays, due to the great diversity of the single-phase loads connected to the grid, the operation is mostly non-sinusoidal, reactive and / or unbalanced. For sinusoidal operation the loads should be linear, for non-reactive operation they should be resistive (or the power factor must be compensated), and for the balanced operation the loads on the grid's three phases have to be equal.

Any unbalanced three-phase load connected to the grid, leads to an unbalanced operation, that can be considered a superposition of an inverse and a homopolar symmetrical operation on the direct symmetrical operation. The non-sinusoidal, reactive and unbalanced operations have a lot of disadvantages, like the supplementary power losses in the grid's lines, differences from the voltage rating, the too fast aging of the grid's components and of the loads connected to it. The current knowledge about the studied matter through the analysis of similar or related published work is described by the author in the former papers on this topic [1-6].

The grid's unbalance is evaluated by some unbalance factors that can be calculated as proportions between the symmetrical components of the three-phase system. There are different types of unbalance factors:

- The dissymmetry factor, defined as:

$$\xi_d = \frac{V_i}{V_d} \tag{1}$$

- The inverse sequence factor:

$$\xi_i = \frac{V_i}{V_n} \tag{2}$$

- The total unbalance factor:

$$\xi_d = \frac{V_i}{V_d}, \tag{3}$$

where the homopolar and inverse components of the three phase voltage system can be determined by the symmetrical components' method, by the following equations:

$$\begin{cases} \underline{V}_d = \frac{1}{3} \cdot \left(\underline{V}_{10} + a \cdot \underline{V}_{20} + a^2 \cdot \underline{V}_{30} \right) \\ V_i = \frac{1}{3} \cdot \left(\underline{V}_{10} + a^2 \cdot \underline{V}_{20} + a \cdot \underline{V}_{30} \right), \\ \underline{V}_h = \frac{1}{3} \cdot \left(\underline{V}_{10} + \underline{V}_{20} + \underline{V}_{30} \right) \end{cases} \tag{4}$$

where $\underline{V}_{10}$, $\underline{V}_{20}$, $\underline{V}_{30}$ are the complex images of the phase voltages, and:

$$\begin{cases} a = \cos\left(2\pi/3\right) + j \cdot \sin\left(2\pi/3\right) = -1/2 + j \cdot \sqrt{3}/2 \\ a^2 == \cos\left(2\pi/3\right) - j \cdot \sin\left(2\pi/3\right) = -1/2 - j \cdot \sqrt{3}/2 \end{cases} \tag{5}$$

are the complex roots of the equation $\underline{z}^3 = 1$.

2. The principle and the physical unit used to compensate the unbalanced, reactive and/or non-sinusoidal operation

The authors have studied for some years and have a significant number of scientific paper and books written [1-6].

As detailed in [1], whenever connected to the grid there is an unbalanced three-phase load or a single-phase load, the balancing solution can be either the *conversion*, or the *compensation*, in such a way that the grid „feels" a balanced consumption, although the consumer is unbalanced. Conversion has the disadvantage that the entire unbalanced load-power must be handled by the conversion unit. Compensation units handle only the consumed power's difference between the phase-loads, the part of the unbalance from the entire power. These compensation unit are known as electronic active power filters. The active power filter can also be used to compensate the harmonics and the power factor of the three-phase grid.

The compensation of the unbalanced utility currents is performed by the active power filter at a really high frequency – the authors used in their measurements a frequency of 10800 Hz. The passive filter in figure 1 has the role of canceling the harmonics given by this high frequency command operation. The control unit of the active filter has to perform some operations of evaluating the unbalance, of calculating the necessary compensation currents and of building the command signal for the IGBT transistors of the voltage inverter. These necessary operations are the following:

- Measuring the actual currents of the utility (i_a, i_b, i_c), the utility voltages (u_a,u_b,u_c) and the load currents (i_{a_load},i_{b_load},i_{c_load});
- Calculating the rms values for the load currents ($\bar{I}_a$,$\bar{I}_b$,$\bar{I}_c$) and for the utility voltages ($\bar{U}_a$,$\bar{U}_b$,$\bar{U}_c$);
- Calculating the mean rms value of the utility current:

$$\bar{I}_{mean}=\frac{\bar{I}_a+\bar{I}_b+\bar{I}_c}{3} \quad (6)$$

- Calculating the phases of the utility voltages:

$$\phi_a=\frac{u_a}{\bar{U}_a},\phi_b=\frac{u_b}{\bar{U}_b},\phi_c=\frac{u_c}{\bar{U}_c} \quad (7)$$

- Calculating the reference currents of the utility, balanced currents in phase with the utility voltages that are to be obtained after the compensation:

$$i_{ax}=\bar{I}_{mean}\cdot\phi_a,i_{bx}=\bar{I}_{mean}\cdot\phi_b,i_{cx}=\bar{I}_{mean}\cdot\phi_c \quad (8)$$

- Calculating and building the command signals for the inverter transistors.

These compensation operations have already been performed and experimentally tested by the authors, what is new in this paper is the control of the compensation unit by a virtual instrument developed in LabView. The developed and tested virtual instrument allows the evaluation of the measured grid's unbalance factors, the activation of the compensation when the unbalance factor's value exceeds a certain threshold (usually the threshold values indicated by the valid and applicable regulations) and the effective control of the active power filter. The measurements performed through the virtual instrument connected to the grid were also verified by measurements with physical measurement devices.

The following figure illustrates the active power filter used for the compensation of the unbalanced, reactive and non-sinusoidal operations. The figure does not contain the components that form the power source and the physical connection to the grid. The meaning of the symbols from this figure is explained in the following equations, with the amendment that in the figure, for the voltage there is used „U" instead of „V".

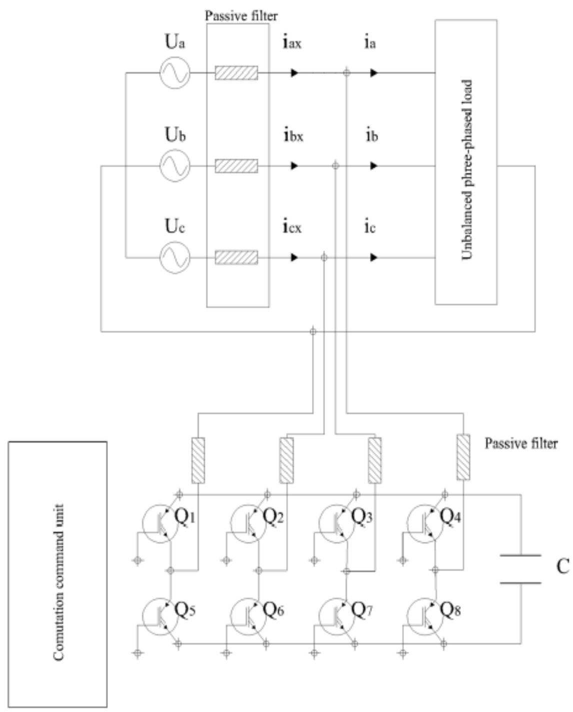

Figure 1: The active power filter used for the compensation of the unbalanced, reactive and non-sinusoidal operations.

3. The virtual instrument developed for the calculation and display of the grid's unbalance factors

The developed virtual instrument includes a part of signal acquisition, for the acquisition - with a proper frequency - of the instantaneous values of the voltages and currents from the grid lines and performs the following steps:

- The acquisition of the three voltage signals from the three-phase grid (V_{10}, V_{20}, V_{30});
- The calculation of the true rms values for each phase voltage;
- The calculation of the complex images of the phase voltages, $\left(\underline{V}_{10}, \underline{V}_{20}, \underline{V}_{30}\right)$, by using the following definition:

$$\underline{V}_x = V_x \cdot (\cos\varphi + j \cdot \sin\varphi), \tag{9}$$

For the calculation of the initial phases of the acquired voltages, we used the fact that we have the freedom to define the value of one of them the significant part being their difference:

$$\begin{cases} \varphi_{10} \equiv 0 \\ \varphi_{20} = \varphi_2 - \varphi_1 = (\omega \cdot t + \varphi_{20}) - (\omega \cdot t + \varphi_{10}) \\ \varphi_{30} = \varphi_3 - \varphi_1 = (\omega \cdot t + \varphi_{30}) - (\omega \cdot t + \varphi_{10}) \end{cases} \quad (10)$$

- The calculation of the complex images of the symmetrical components, defined by equations (4);
- The calculation of the modulus for each symmetrical component, by using the equations:

$$V = \sqrt{\left[\mathrm{Real}(\underline{V})\right]^2 + \left[\mathrm{Im}(\underline{V})\right]^2} \quad (11)$$

- The calculation of the unbalance factors with equations (1)-(3).

That part of the virtual instrument, which performs the calculation of the rms values, the initial phases and the complex images for the three voltages is illustrated (as Block diagram) in figure 2.

The following figure, 3, illustrates the synthesis of the two complex numbers (the roots of the complex equation $\underline{z}^3 - 1$.

Figure 4 shows the calculation of the symmetrical components, and the following figure 5 shows the last part of the unbalance evaluation virtual instrument, that one of calculating the unbalance factors.

The figures 2-5 illustrate the evaluation of the voltage unbalance factors. In the same way the virtual instrument evaluates the current unbalance factors, too.

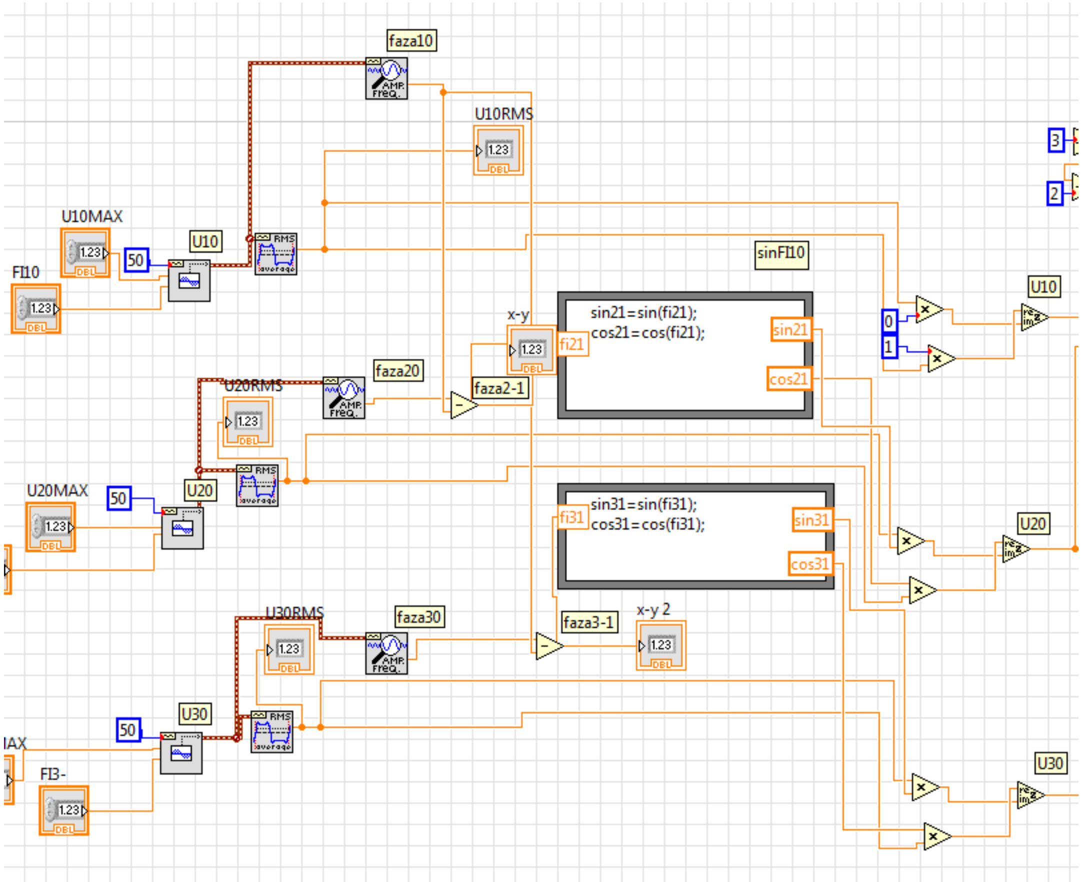

Figure 2: A first part of the unbalance evaluation virtual instrument.

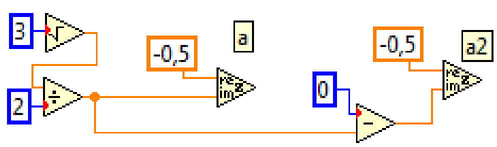

Figure 3: The synthesis of the two complex numbers a and a^2.

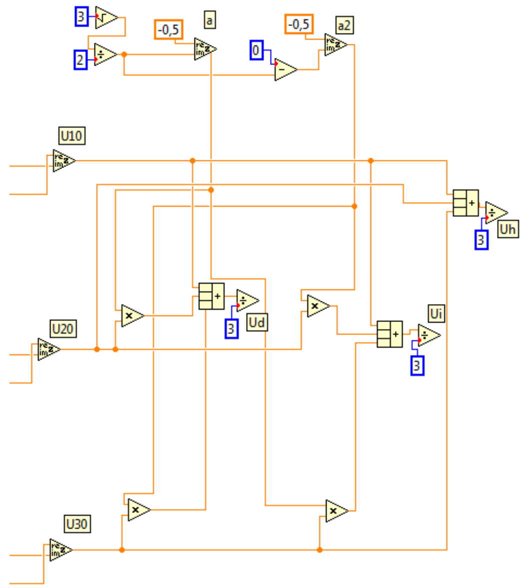

Figure 4: The calculation of the symmetrical components.

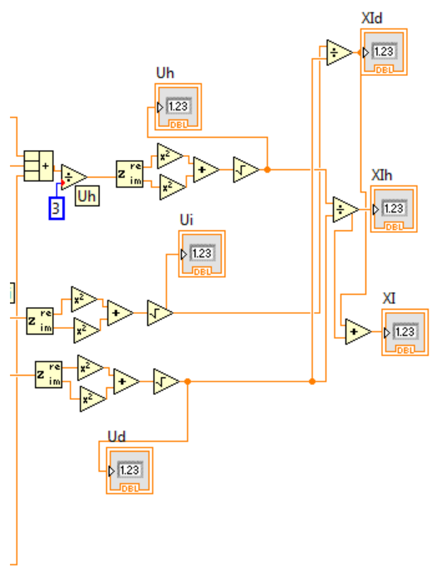

Figure 5: The last part of the unbalance evaluation virtual instrument.

4. The virtual instrument for the control of the compensation unit

This part of the virtual instrument has been developed in order to implement the steps described under point 2. After the signal acquisition of the phase lines' voltages and currents, their rms values are determined, then, the currents' mean rms value, the voltages phases and the equivalent balanced, non-reactive, sinusoidal currents are calculated. The difference between these perfect currents and the load currents form the signal that will control the active power filter.

Although the first part – the evaluation part – of the virtual instrument performs a lot of the required operations, for the sake of modularity and of the better understanding, this control part of the virtual instrument is developed by the authors as an independent virtual instrument. Consequently, it will contain the following parts. Figure 6 illustrates the control virtual instrument – its block diagram.

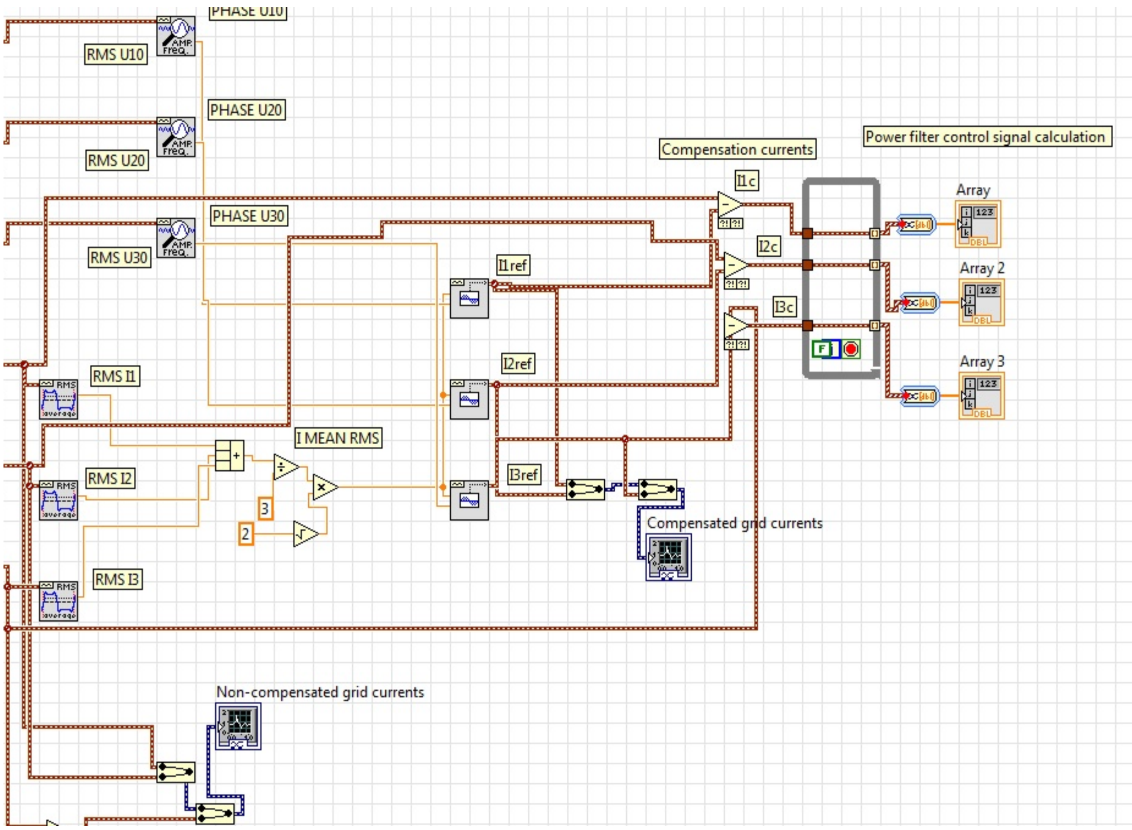

Figure 6: The compensation-control virtual instrument.

The sub-VI (virtual instrumentation subroutine) from figure 6 is integrated in the unbalance evaluation and compensation control virtual instrument inside a case structure activated by the positive result of the comparison between the unbalance factor calculated by the sub-VI presented in figure 5 and the threshold value, which can be introduced and modified by the virtual instrument's operator. For further development of this evaluation and compensation virtual instrument, it can be extended to:

- to evaluate also the power factor and to activate the compensation sub-Vi also for the exceeding of certain threshold values by this power factor (the evaluation of the non-reactive operations and the consequent activation of the compensation unit) and
- to evaluate the sinusoidal waveform of the grid's currents, by the comparison between the true rms, calculated by the evaluation sub-Vi through integration

method and the rms of the sinusoidal waveform ($I = I_{max}/\sqrt{2}$). For any significant difference between these two rms values of the same current, we can consider that there is a corresponding significant deviation from the sinusoidal waveform and that there is necessary to activate the compensation sub-VI

The active power filter controlled by this virtual instrument was tested in various load conditions and in all the measurements the results were excellent. The authors used unbalanced, reactive, non-linear loads and all the combinations between them. In every case the obtained phase currents were sinusoidal, non-reactive and balanced. Figure 7 illustrates some of the compensation results obtained with this evaluation and compensation virtual instrument.

Grid current waveforms without compensation | **Grid current waveforms after compensation**

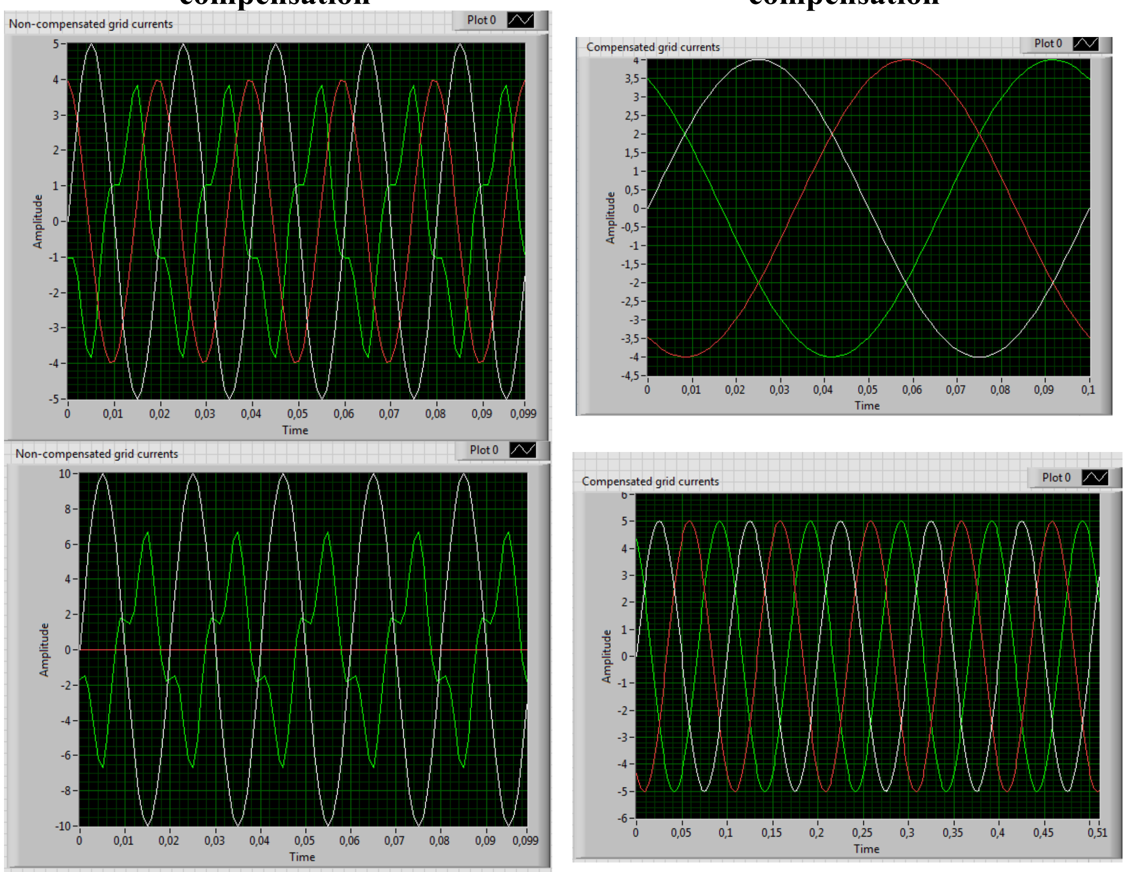

Figure 7: Some experimental results with the evaluation and compensation virtual instrument.

5. Conclusions

In conclusion we can state that the developed virtual instrument is a precise and elegant, flexible tool for the evaluation and the compensation of the unwanted operations of the three phase grid: unbalanced, nonlinear, reactive operations. Together with the active power filter used by the authors in many measurements and balancing experiments, with the electronic control circuits and with the signal acquisition boards, the developed virtual instrument is a valuable tool [1] – [6].

The results of the measurements performed with the active power filter controlled by this virtual instrument proved very good compensation parameters. The virtual instrument enables the control al an active filter with results that are similar, identical with any other control device, physical of virtual. In fact, the results themselves prove that compensation is performed well enough, so the control of the active power filter can be done by using such a virtual instrument.

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