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Application of generalized non-active power theory for parallel hybrid compensation of periodic and non-periodic disturbances

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Abstract. A strategy of decomposition of detrimental current components in electric power systems is presented. The method is based on the non-active power theory with different averaging time intervals. These individual current components can be used as the reference signals for the devices compensating periodic as well as non-periodic and stochastic currents generated by non-linear unbalanced loads connected to an unsymmetrical non-sinusoidal voltage power source. The use of an appropriate set of parallel compensation devices for mitigating individual detrimental load current components with different dynamics can lead to the substantial reduction of the power rating and cost of such a hybrid compensator.

Key words

Generalized non-active power theory, detrimental current components, simulation, electric power system, parallel hybrid compensation.

1. Introduction

Although the electric power is produced with almost ideal parameters, the voltage shape may be influenced considerably by large, dynamic, and nonlinear loads, which are producing unbalanced, non-periodic, and even stochastic currents. Among these loads belong particularly: electric arc furnaces (EAF), big drives, welding machines, traction drives, etc. [1]. So, the compensation of concurrent undesirable phenomena represents a great challenge for engineers from the theoretical as well as practical point of view [2]-[7]. Thus, the extension of the existing power theories and perhaps the deduction of some new ones, having the potential to become the theoretical background for the compensation of the disturbances mentioned is of great importance.

The power theories have been mostly discussed, classified and compared in terms of their capabilities for the compensation of unwanted instantaneous power components in three-phase asymmetrical systems with non-sinusoidal voltages and currents.

The compensation of subharmonic, non-periodic, and stochastic disturbances in the electric power systems has emerged as a very serious problem to be solved now. The diversity of the features of these disturbances makes their compensation quite difficult.

A principal of usage of the generalized non-active power theory [10]-[17] for the parallel hybrid compensation of periodic and non-periodic disturbances is presented in the paper. A non-linear unbalanced load generating periodic as well as non-periodic and stochastic currents connected to an unsymmetrical non-sinusoidal voltage source is considered. Based on the so-called running quantities [9], [10] with different integration intervals, the non-active current of the non-linear load is separated into several characteristic components that can represent reference signals for different parts of the compensation system. According to different characters of the reference currents either compensators with slow dynamics or active devices based on fast electronic power converters can be used appropriately. The applied approach and presented formulas are verified by simulations in the Matlab/Simulink environment.

2. Overview of Generalized Non-active Power Theory

In the Fryze´s theory the active power P was calculated as the average value of $p = v\, i$ over one fundamental cycle $T = 1/f$. A serious limitation is that the calculation of i_a is characterized by the time delay T.

The original Fryze´s theory of the non-active current is extended in [10] by using a general averaging time interval T_C that can be chosen either one-half fundamental cycle, one full fundamental cycle T, that is the same as that in Fryze´s theory, or multiple fundamental cycles, depending on the character of the load current, compensation objectives and the energy storage capacity of power electronics-based compensator.

For the three-phase system, the voltage and current vectors may be expressed as follows

$$\boldsymbol{v} = \left[v_a, v_b, v_c\right]^T \qquad \boldsymbol{i} = \left[i_a, i_b, i_c\right]^T \tag{1}$$

The active current is defined in this generalized non-active power (GNP) theory by

$$\boldsymbol{i}_{\mathrm{a}}(t)=\frac{P(t)}{V_{\mathrm{P}}^{2}(t)}\boldsymbol{v}_{\mathrm{P}}(t) \quad (2)$$

$$P(t)=\frac{1}{T_{\mathrm{C}}}\int_{t-T_{\mathrm{C}}}^{t}\boldsymbol{v}^{\mathrm{T}}(\tau)\boldsymbol{i}(\tau)\,\mathrm{d}\tau \quad (3)$$

$$V_{\mathrm{P}}^{2}(t)=\frac{1}{T_{\mathrm{C}}}\int_{t-T_{\mathrm{C}}}^{t}\boldsymbol{v}_{\mathrm{P}}^{\mathrm{T}}(\tau)\boldsymbol{v}_{\mathrm{P}}(\tau)\,\mathrm{d}\tau \quad (4)$$

and $\boldsymbol{v}_{\mathrm{P}}$ (t) is the reference voltage vector that can be the voltage at the PCC (Point of Common Coupling), the fundamental positive sequence component of this voltage or something else, depending again on the type of a compensator and/or compensation objectives.

The non-active current is the remaining part of the current vector

$$\boldsymbol{i}_{\mathrm{n}}(t)=\boldsymbol{i}(t)-\boldsymbol{i}_{\mathrm{a}}(t) \quad (5)$$

If the current $\boldsymbol{i}$ (t) is the current of an unbalanced non-linear load, which may contain, in general, harmonic and also non-periodic stochastic components and the current $\boldsymbol{i}_{\mathrm{a}}$ (t) is the demanded source current, then $\boldsymbol{i}_{\mathrm{n}}$ (t) is the current that should be injected by a parallel compensator connected to the PCC, Fig. 1.

The non-periodic current means here a current whose frequency in not an integer multiple of the fundamental frequency. Thus, it may contain subharmonic, interharmonic, and stochastic components.

The GNP theory has been already successively used for the compensation of non-periodic disturbances by using parallel active filters [10] - [14], the STATCOM [15], a voltage and current parallel compensator [16], and the UPQC (Unified Power Quality Conditioner) [17] as well.

3. Principle of Decomposition of Detrimental Currents

The parallel hybrid compensation system shown in Fig. 1 can be composed of several parts.

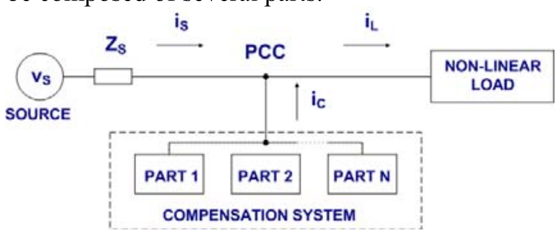

Fig.1 Configuration of parallel hybrid compensation

Some part can be a parallel APF (Active Power Filter) that is an electronic power converter-based compensator with high dynamics, while the other compensators can be only passive compensators or electronic power converters too, but with a lower switching frequency then the first one. This configuration can be more advantageous then a conventional universal electronic power compensator consisting of only one converter covering all compensation and filtration functions with respect to the necessary power rating and cost of the complete compensation device.

Let the active load current is

$$\boldsymbol{i}_{\mathrm{La}}(t)=\frac{P_{\mathrm{L}}(t)}{V_{\mathrm{LP}}^{2}(t)}\boldsymbol{v}_{\mathrm{LP}}(t) \quad (6)$$

where

$$P_{\mathrm{L}}(t)=\frac{1}{T_{\mathrm{C}}}\int_{t-T_{\mathrm{C}}}^{t}\boldsymbol{v}_{\mathrm{L}}^{\mathrm{T}}(\tau)\boldsymbol{i}_{\mathrm{L}}(\tau)\,\mathrm{d}\tau \quad (7)$$

$$V_{\mathrm{LP}}^{2}(t)=\frac{1}{T_{\mathrm{C}}}\int_{t-T_{\mathrm{C}}}^{t}\boldsymbol{v}_{\mathrm{LP}}^{\mathrm{T}}(\tau)\boldsymbol{v}_{\mathrm{LP}}(\tau)\,\mathrm{d}\tau \quad (8)$$

and $\boldsymbol{v}_{\mathrm{LP}}$ is the reference voltage vector. Let us take for this reference voltage the fundamental positive sequence component $\boldsymbol{v}_{\mathrm{Lf}}$ of the load voltage $\boldsymbol{v}_{\mathrm{L}}$. The current $\boldsymbol{i}_{\mathrm{La}}$ is then balanced and purely sinusoidal without any harmonics regardless the distorted and unbalanced voltage $\boldsymbol{v}_{\mathrm{L}}$ of the power system and a reactive and unbalanced load current $\boldsymbol{i}_{\mathrm{L}}$ with harmonic components. Even for a non-periodic load current $\boldsymbol{i}_{\mathrm{L}}$ the active current component $\boldsymbol{i}_{\mathrm{La}}$ then approaches a pure sine wave if the time averaging interval T_{C} is properly chosen. The non-active load current $\boldsymbol{i}_{\mathrm{Ln}}$ is then

$$\boldsymbol{i}_{\mathrm{Ln}}(t)=\boldsymbol{i}_{\mathrm{L}}(t)-\boldsymbol{i}_{\mathrm{La}}(t) \quad (9)$$

The current $\boldsymbol{i}_{\mathrm{Ln}}$ is just the current that should be generated by the parallel compensator in order that the source current was only active $\boldsymbol{i}_{\mathrm{S}}$ (t) = $\boldsymbol{i}_{\mathrm{La}}$ (t).

The so-called CRMS (Complex RMS) value $\boldsymbol{I}_{\mathrm{L1}}$ of the fundamental harmonic of the load current $\boldsymbol{i}_{\mathrm{L}}$ is

$$\boldsymbol{I}_{\mathrm{L1}}(t)=\frac{\sqrt{2}}{T}\int_{t-T}^{t}\boldsymbol{i}_{\mathrm{L}}e^{-\mathrm{j}\omega\tau}\,\mathrm{d}\tau \quad (10)$$

The CRMS value $\boldsymbol{I}_{\mathrm{L1}}$ is the quasi-instantaneous variable calculated over averaging interval $T = 1/f$, f is the fundamental frequency, $\omega = 2\pi f$.

The time response $\boldsymbol{i}_{\mathrm{L1}}$ can be calculated as

$$\boldsymbol{i}_{\mathrm{L1}}(t)=\sqrt{2}\,\mathrm{Re}\left\{\boldsymbol{I}_{\mathrm{L1}}e^{\mathrm{j}\omega t}\right\} \quad (11)$$

This current vector $\boldsymbol{i}_{\mathrm{L1}}$ is harmonic free, but generally not balanced, and may contain reactive and not-periodic parts (in the sense declared in the previous paragraph) if such components are present in $\boldsymbol{i}_{\mathrm{L}}$.

By applying equations (10), (11) on only the positive sequence components in the load current $\boldsymbol{i}_{\mathrm{L}}$ the current vectors $\boldsymbol{I}^{+}_{\mathrm{L1}}$ and $\boldsymbol{i}^{+}_{\mathrm{L1}}$ (t) are obtained. To eliminate the negative sequence components from the load current $\boldsymbol{i}_{\mathrm{L}}$ a proper positive/negative sequence detector, based e.g. on a type of the PLL (Phase Lock Loop) circuit, must be used, however.

In [8] the current $\boldsymbol{i}_{\mathrm{L}}$ of a non-linear load or a load with periodically – variant parameters was decomposed into five mutually orthogonal components: the generalized active current, scattered current, reactive current, unbalanced current, and current generated by a load with harmonics not present in the non-sinusoidal voltage source. We will not consider the scattered current appearing in systems with a changing equivalent conductance, e.g. due to the skin effect on transmission lines. However, we will suppose that the generated current contains also non-periodic components, in the sense declared before, produced e.g. by the EAFs (Electric Arc Furnace), which can be separated too. It is possible thanks to that, opposite to the CPC theory [9], the GNP theory is formulated in the time domain.

Thus, let us suppose that the load current in unbalanced non-sinusoidal systems with also non-periodic load current disturbances can be decomposed into the following components

$$\boldsymbol{i}_{\mathrm{L}}(t)=\boldsymbol{i}_{\mathrm{La}}(t)+\boldsymbol{i}_{\mathrm{Ln}}(t)=\boldsymbol{i}_{\mathrm{La}}(t)+\boldsymbol{i}_{\mathrm{L1r}}(t)+\boldsymbol{i}_{\mathrm{L1u}}(t)+\boldsymbol{i}_{\mathrm{Lh}}(t)+\boldsymbol{i}_{\mathrm{Lnp}}(t) \quad (12)$$

where $\boldsymbol{i}_{L1r}$ is the reactive current associated with the fundamental harmonic only, $\boldsymbol{i}_{L1u}$ is the fundamental harmonic unbalanced current, $\boldsymbol{i}_{Lh}$ is the harmonic current, and $\boldsymbol{i}_{Lnp}$ is the non-periodic current containing all remaining non-active disturbances (subharmonics, interharmonics, stochastic).

The question is whether the non-periodic load current components can be detected with reasonable accuracy by using the GNP theory.

It was theoretically as well as in some experiments proofed [12]-[17] that the precision of the calculation of the currents $\boldsymbol{i}_{La}$, $\boldsymbol{i}_{Ln}$ by using (6), (9) in unbalanced non-sinusoidal systems with non-periodic load currents is sufficient if T_C is chosen to be 5–10 times that of the fundamental period. Contrary to that, for T_C decreasing under 5 times that of the fundamental period (T_c=T/2 is the lowest possible value), the non-periodic component of the load current is more and more pronounced in the current $\boldsymbol{i}_{La}$.

Thus, let us introduce

$$\boldsymbol{i}_{\mathrm{Lnp}}(t)=\boldsymbol{i}_{\mathrm{La}}(t)\Big|_{T_C=T}-\boldsymbol{i}_{\mathrm{La}}(t)\Big|_{T_{\mathrm{Cnp}}=T_C>>T} \quad (13)$$

where $\boldsymbol{i}_{La}$(t), T_{Cnp}>>T will be calculated by (6) with T_{Cnp} = (5–10)T in the following analysis.

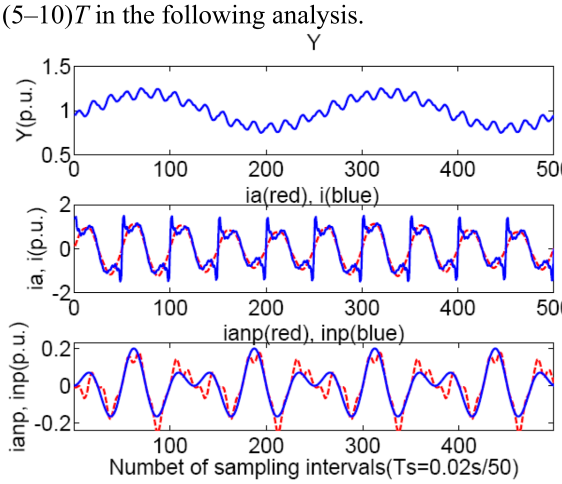

Fig. 2 Waveforms of admittance Y and phase current responses i, i_a, i_{np}, i_{anp} in the time domain for T_C = T/2, T_{Cnp} = 5T

Fig. 2 shows the waveforms of the admittance Y, and the current responses i, i_a, i_{np}, i_{anp} in the time domain for T_C = T/2, i is the load current in any phase, i_a is the calculated active current, i_{np}, i_{anp} being currents in the same phase with superscript "a" denoting the non-periodic current calculated using (13). The subharmonic component of the frequency 10 Hz and the set of the most important twelve harmonic components (h=2-13, the amplitude law I_h=1/h p.u.) are present in the current i. Due to high content of even harmonics, especially the second one, the current i is highly distorted and very different from a sinusoidal waveform. We see that the estimated current i_{anp} follows its actual waveform i_{np} well, but some residual harmonic components in the current i_{anp} remain.

In general, we can say that the choices T_C = T/2, T_C = T provide us with similar results in the estimation of the non-periodic current component i_{anp} by using (13). Nevertheless, for the currents i with high content of harmonics we could give a preference to the option T_C = T where all harmonics are eliminated, which is not the case of Fig. 2.

The remaining three non-active current components in (12) can be determined as follows

$$\boldsymbol{i}_{\mathrm{L1r}}(t)=\boldsymbol{i}^{+}_{\mathrm{L1}}(t)-\boldsymbol{i}_{\mathrm{La}}(t)-\boldsymbol{i}_{\mathrm{Lnp}}(t) \quad (14)$$

$$\boldsymbol{i}_{\mathrm{L1u}}(t)=\boldsymbol{i}_{\mathrm{L1}}(t)-\boldsymbol{i}^{+}_{\mathrm{L1}}(t) \quad (15)$$

$$\boldsymbol{i}_{\mathrm{Lh}}(t)=\boldsymbol{i}_{\mathrm{L}}(t)-\boldsymbol{i}_{\mathrm{L1}}(t) \quad (16)$$

By summing these three components we obtain

$$\boldsymbol{i}_{\mathrm{L1r}}(t)+\boldsymbol{i}_{\mathrm{L1u}}(t)+\boldsymbol{i}_{\mathrm{Lh}}(t)=\boldsymbol{i}_{\mathrm{L}}(t)-\boldsymbol{i}_{\mathrm{La}}(t)-\boldsymbol{i}_{\mathrm{Lnp}}(t) \quad (17)$$

which is in agreement with (12).

So, all the load current components can be determined by calculating $\boldsymbol{i}_{La}$, $\boldsymbol{i}_{L1}$, $\boldsymbol{i}^{+}_{L1}$, and $\boldsymbol{i}_{Lnp}$ (6), (11), (11) for $\boldsymbol{I}^{+}_{L1}$, (13). However, it should be emphasized that the calculation of $\boldsymbol{i}_{Lnp}$ by using (13) is only an approximation whose accuracy depends on the character of the non-periodic current disturbances and a respective choice of the averaging interval T_{Cnp}>>T.

If the non-active load current i_{Ln} (9) is completely compensated for by a parallel hybrid compensator, only the active load current $\boldsymbol{i}_{La}$ (6) is provided by the source, i.e. $\boldsymbol{i}_S$ = $\boldsymbol{i}_{La}$. We can see that the four components (13)-(16) of the non-active current $\boldsymbol{i}_{Ln}$ require different dynamics of their compensation. The compensation of the harmonic component $\boldsymbol{i}_{Lh}$ requires a higher switching frequency of the respective PWM (Pulse Width Modulated) converter then the compensation of the remaining three components. Sometimes, the reactive $\boldsymbol{i}_{Lr}$ and unbalanced $\boldsymbol{i}_{Lu}$ current can be major detrimental currents of the load. A SVC (Static VAr Compensator) based on three thyristor-controlled susceptances, whose parameters are updated only twice a fundamental voltage cycle, is a proper device for the compensation of these two components. On the other side, some selected harmonics can be compensated for by using PFs (Passive Filter) tuned to some orders or a range of harmonics.

Thus, it is evident that in different concrete situations, compensation objectives are different too and the use of an appropriate set of compensation devices for mitigating individual detrimental current components can lead to the substantial reduction of the power rating and cost of such a hybrid compensator.

4. Simulation of Decomposition of Detrimental Load Current Components

Let us demonstrate the strategy presented above on an example of the three phase unbalanced non-sinusoidal system with the load current $\boldsymbol{i}_L$ that contains, in addition to the active current $\boldsymbol{i}_{La}$, also the reactive current $\boldsymbol{i}_{L1r}$ associated with the fundamental harmonic only, the fundamental harmonic unbalanced current $\boldsymbol{i}_{L1u}$, the harmonic current $\boldsymbol{i}_{Lh}$, and the non-periodic current containing all remaining non-active disturbances $\boldsymbol{i}_{Lnp}$.

Figs. 3-5 show the results of the simulation of a model based on (6)-(11), (13)-(16) with $\boldsymbol{v}_{LP}= \boldsymbol{v}^{+}_{L1}$ ($\boldsymbol{v}_{LP}$ is selected as the fundamental positive sequence component), $T_{Cnp} = 5T$, and with the parameters of the fundamental positive sequence components $\boldsymbol{v}^{+}_{L1}$, $\boldsymbol{i}^{+}_{L1}$, fundamental negative sequence component $\boldsymbol{i}^{-}_{L1}$, and the fifth harmonic current $\boldsymbol{i}_{L5}$ declared in Tab. I.

Tab. I Parameters of the three phase load voltage and current used in simulation

Variable	Magnitude (p.u.)	Phase
$\boldsymbol{v}_L= \boldsymbol{v}_{L1}= \boldsymbol{v}^{+}_{L1}= \boldsymbol{v}_{LP}$	1	0
$\boldsymbol{i}^{+}_{L1}$	1	$-\pi/2$
$\boldsymbol{i}^{-}_{L1}$	0.5	0
$\boldsymbol{i}_{L5}$	0.2	0

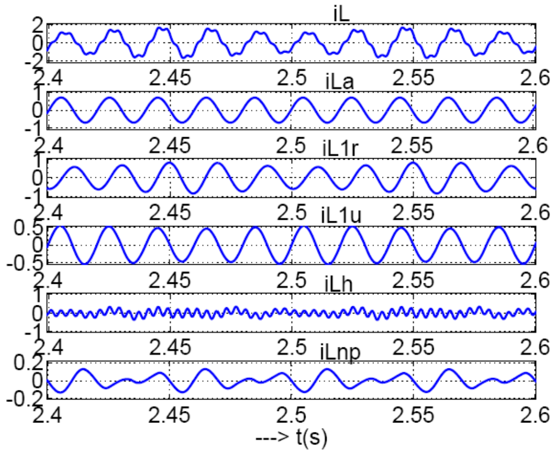

Fig. 3 Decomposition of load current $\boldsymbol{i}_L$ modulated by the subharmonic signal

In Fig. 3 we can see the decomposition of the load current $\boldsymbol{i}_L$ in one phase into the components $\boldsymbol{i}_{La}$, $\boldsymbol{i}_{L1r}$, $\boldsymbol{i}_{L1u}$, $\boldsymbol{i}_{Lh}$, $\boldsymbol{i}_{Lnp}$ when the magnitude of the load current $\boldsymbol{i}_L$ specified by Tab. 1 is modulated by the subharmonic signal with the magnitude ΔI_L=0.2 p.u. and frequency 10 Hz. Due to the phase shift $-\pi/2$ between $\boldsymbol{v}_{L1}$ and $\boldsymbol{i}^{+}_{L1}$ the current components $\boldsymbol{i}_{La}$, $\boldsymbol{i}_{L1r}$ should have in ideal case the magnitudes $\sqrt{2}$ p.u. (without subharmonic modulation of the load current) and the current $\boldsymbol{i}_{L1u}$ should replicate $\boldsymbol{i}^{-}_{L1}$. We see in Fig. 3 that the waveforms of the separated current components $\boldsymbol{i}_{L1r}$, $\boldsymbol{i}_{L1u}$ are partially influenced by the subharmonic modulation, but exhibit the expected responses. The same is valid for the component $\boldsymbol{i}_{Lh}$. It is evident as well that the maximum amplitudes of the components $\boldsymbol{i}_{Lh}$, $\boldsymbol{i}_{Lnp}$ are somewhat lower than those of these components contained originally in the load current $\boldsymbol{i}_L$, namely 0.2.

In Fig. 4 we can see the decomposition of the load current $\boldsymbol{i}_L$ in one phase into the components $\boldsymbol{i}_{La}$, $\boldsymbol{i}_{L1r}$, $\boldsymbol{i}_{L1u}$, $\boldsymbol{i}_{Lh}$, $\boldsymbol{i}_{Lnp}$ when the magnitude of the load current $\boldsymbol{i}_L$ is modulated by the white noise signal. We see that the load current imitates fairly a waveform with a non-periodic stochastic character like that produced for example by an EAF.

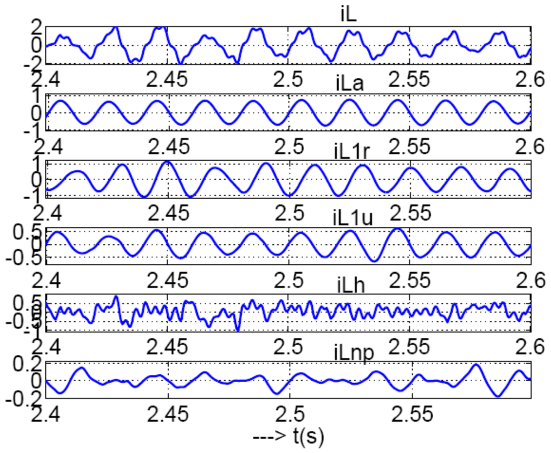

Fig. 4 Decomposition of load current $\boldsymbol{i}_L$ modulated by white noise signal

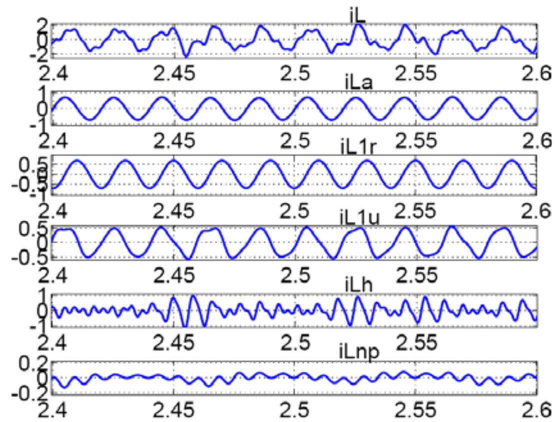

Fig. 5 Decomposition of load current $\boldsymbol{i}_L$ with superimposed interharmonics

The separated current components $\boldsymbol{i}_{L1r}$, $\boldsymbol{i}_{L1u}$ are again partially influenced by the non-periodic stochastic modulation of the load current. The component $\boldsymbol{i}_{Lh}$ contains not only the fifth harmonic, but also a part of disturbances introduced into the load current by the white noise signal.

Figs. 3, 4 showed the results of the decomposition of the load current $\boldsymbol{i}_L$ into its components under the sinusoidal voltage $\boldsymbol{v}_L= \boldsymbol{v}^{+}_{L1}$ (Tab. I). When the voltage involves also a negative sequence component $\boldsymbol{v}^{-}_{L1}$ and the fifth harmonic $\boldsymbol{v}_{L5}$, both of the magnitude of 0.2 p.u., we can not recognize any important difference. So, the method presented is not significantly affected by load voltage distortions.

Finally, Fig. 5 presents the results of the decomposition of the load current $\boldsymbol{i}_L$ into its components when to the components of the load current characterized by Tab. I the additional current interharmonics (104, 117, 134, and 147 Hz) specified by [18] and used in [17] are superimposed. Again, this stochastic non-periodic current $\boldsymbol{i}_L$ imitates a current waveform produced for example by the EAF. We see that the current components $\boldsymbol{i}_{L1u}$, $\boldsymbol{i}_{Lnp}$ are partially influenced by the imposed interharmonics, while the Fourier analysis of the current ($\boldsymbol{i}_{Lh}$+$\boldsymbol{i}_{Lnp}$) has confirmed that this current contains the interharmonic (104, 117, 134, and 147 Hz) and harmonic (250 Hz) components with very similar magnitudes as those injected in the load current $\boldsymbol{i}_L$.

5. Conclusion

The presented method of decomposition of the three phase current with non-periodic components is based on the generalized non-active power theory working with different averaging time intervals T_C. The current can be decomposed into the active current, reactive current associated with the fundamental harmonic only, fundamental harmonic unbalanced current, harmonic current, and non-periodic current containing all remaining non-active disturbances (subharmonics, interharmonics, stochastic). The injected non-periodic current component has been decomposed from the load current with a good precision for all analyzed examples (subharmonic, stochastic, and interharmonic disturbances). The individual decomposed current components can be used as the reference signals for the devices compensating periodic as well as non-periodic stochastic current components generated by non-linear unbalanced loads connected to an unsymmetrical non-sinusoidal voltage power source. The use of an appropriate set of compensation devices for mitigating individual detrimental current components with different dynamics can lead to the substantial reduction of the power rating and cost of such a hybrid compensator.

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