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Improving Energy Efficiency through Electric Utility Unbalance and Reactive Power Compensation

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Abstract : *This paper presents some results proving that a compensation unit (an active power filter controlled by a core soft modified by the author) capable to balance the three-phase currents is also able to achieve the compensation of the reactive power from the three-phase grid.*
The three-phased systems have been designed for direct symmetrical sinusoidal operation, but any unbalanced three-phase load connected to the system leads to a non-symmetrical operation, that can be considered a superposition of an inverse and a homopolar symmetrical operation on the direct symmetrical operation. For each of these three operations, the active and reactive powers are separately conservative. Some of the disadvantages of the unbalanced operations is that the flow of non-symmetrical powers produces supplementary losses in the electric power systems and reduces their efficiency.
The compensation of the unbalanced utility currents is performed at a frequency of 10.800 Hz. The paper describes the necessary operations of the compensation unit at every 1/10.800 seconds in order to switch the power from a phase to the others.

Key words: Compensation unit; active power filter; reactive power; three-phased systems; balance; energy efficiency

Rezumat: *Acest articol prezintă unele rezultate ce dovedesc faptul că o unitate de compensare (un filtru activ de putere comandat de un soft modificat de autor) este capabilă să echilibreze sistemul trifazat al curenților de fază al unei rețele și să asigure compensarea puterii reactive din rețeaua trifazată. Sistemele trifazate au fost proiectate pentru regimuri de funcționare sinusoidale simetrice, dar orice sarcină trifazată dezechilibrată ce este conectată în sistem conduce la regimuri nesimetrice, ce pot fi considerate drept o superpoziție a unor regimuri de funcționare simetrice de succesiune inversă și omopolare peste regimul de funcționare simetric de succesiune directă. Pentru fiecare dintre aceste trei regimuri, puterile activă și reactivă se conservă separat. Unele dintre dezavantajele regimurilor dezechilibrate constau în faptul că fluxul puterilor nesimetrice generează pierderi suplimentare de putere în sistemele electrice și le reduce randamentul de funcționare. Compensarea rețelei de alimentare dezechilibrate se realizează la o frecvență de 10.800 Hz. Articolul descrie operațiile necesare a fi efectuate de unitatea de compensare la fiecare 1/10.800 secunde pentru a realiza schimbul de putere interfazic.*

1. Introduction

All three-phase systems have been designed for direct symmetrical sinusoidal operation. In order to achieve this, the power generators have to supply direct symmetrical e.m.f. and the loads must be balanced. Any unbalanced three-phase load connected to the system leads to a non-symmetrical operation, that can be considered a superposition of an inverse and a homopolar symmetrical operation on the direct symmetrical operation [1]. The unbalanced three-phase systems are characterizes not only by different currents on the three phase conductors, but, also by different voltages on the consumers connected to the three pases of the system. This has very negative effects also on the electric consumers and on the energy efficiency of the grid and the entire electrical system. In a former paper, the author proved that unbalanced operation of the three-phased grid increase at least three times the power losses in the grid conductors.

Because of these negative effects, the unbalanced operations are limited by the international regulations:

$$\epsilon_i = \frac{I_i}{I} \leq 5 - 15\%;\ \epsilon_u = \frac{U_i}{U_d} \leq 5 - 15\% \qquad (1)$$

As the author has previously proved [2], for each of these three operations, the active and reactive powers are separately conservative. Thus, an unbalanced three-phase load receives more direct power from the power system than it is necessary for itself and sends back into the system the difference as inverse and homopolar power. These power flows can be described by the non-symmetric active and reactive powers:

$$\begin{aligned} P_n &= P - P_d = 3U_i I_i \cos\varphi_i - 3U_0 I_0 \cos\varphi_0 \\ Q_n &= Q - Q_d = 3U_i I_i \sin\varphi_i - 3U_0 I_0 \sin\varphi_0 \end{aligned} \qquad (2)$$

As the generators are designed to supply power only in direct operation, we can consider the unbalanced loads themselves to be power sources for inverse and homopolar operations, though these loads are passive.

As already shown [2], the flow of these quantities can be followed and measured. Some of the disadvantages of these unbalanced operations is that the flow of non-symmetrical powers produces supplementary losses in the electric power systems and reduces their efficiency. Saverio Bolognani and Sandro Zampieri have analyzed in 2012 the problem of optimal reactive power compensation for the minimization of the power distribution losses in a smart microgrid [3]. They first proposed an approximate model for the power distribution network, a model that allowed the casting of the problem into „the class of convex quadratic, linearly constrained, optimization problems”. For achieving the optimal injection of reactive power by microgenerators connected to the microgrid, there has been designed a randomized, gossip-like optimization algorithm. For this algorithm, they provided convergence conditions and their analysis shows that, in radial networks, the best performance can be achieved by controlling those units that are neighbors in the electric topology. In their paper they included numerical simulations that do validate the proposed model.

Every non-symmetrical operation in the three-phase system has in fact a lot of disadvantages both for the system itself and for the other loads connected to it. Former papers of the author [1, 2, 4, 5] prove these disadvantages, providing ways of evaluating them and emphasizing the necessity of implementing balancing methods, and proposing methods and devices engineered to obtain a balanced operation for the power network, even if the load is mono-phased or is highly unbalanced. This paper presents some results of the researches conducting in order to prove that the compensation unit that has been proved to balance the three-phase currents is able to achieve this balance together with the compensation of the reactive power from the three-phase network. Some particular aspects of shunt power active filters control have been analyzed at the 9th International Conference on Optimization of Electrical and Electronic Equipment „Optim '04" by Prof. Răzvan Măgureanu et. al. [6].

2. The principle of compensation of unbalanced operations

When a load is an unbalanced three-phased load or a mono-phased load, the solution to integrate it in the three-phased grid and to maintain the grid's balanced operation can be either the conversion, or the compensation of the unbalanced three-phased electric energy, in such a way that the grid „feels" a balanced consumption, while the consumer is unbalanced. Conversation (whether it is rotational, electromagnetic or electronic) has the disadvantage that the entire power necessary for the unbalanced or mono-phased load must be handled by the conversion unit. Compensation units do not handle the entire power of the load, but only the consumed power's difference between the phase-loads. These are electronic active power filters that have been proved to be useful in compensating the unbalanced operations of the three-phased grid [4]. There are commonly known series or parallel topologies of compensation units. Parallel compensation units have the main advantage that only the compensation current flows through their components, therefore the power consumption and losses of such a device are very low. Parallel compensation units can be designed with voltage inverters and a capacitor for energy storage or with current inverters and an inductance as storage element. The author used a parallel active power filter with a voltage inverter, as illustrated in Figure 1, while changing the core soft to obtain the compensation of the unbalanced three-phased currents.

The compensation of the unbalanced utility currents is made by the compensation unit at a high frequency – the author used in his measurements the frequency of 10800 Hz. The passive filter has the role of cancelling the harmonics given by this high frequency command operation. The control unit of the compensation unit 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. The equipment used by the author for the measurements is described in more details in referred papers [1, 5, 6].

These necessary operations are the following:

- Measuring the actual currents of the utility (i_a, i_b, i_c), and the utility voltages (u_a, u_b, u_c);
- 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 of the utility current:

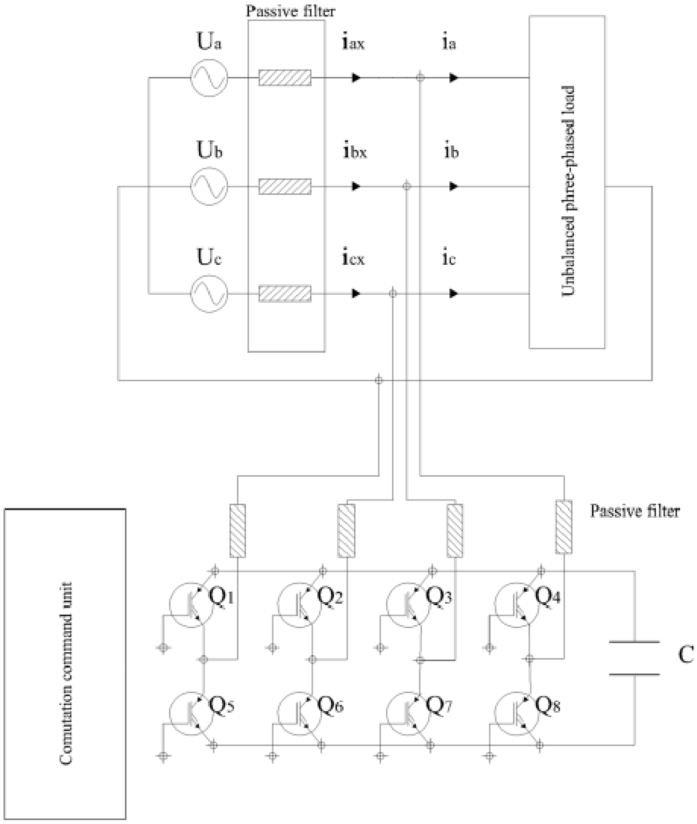

Fig. 1: The compensation unit used for the three-phased utility unbalance compensation

U_a, U_b, U_c – the voltages provided by the three-phased utility;
i_{ax}, i_{bx}, i_{cx} - the currents drawn from the utility lines by the system formed by the load and the compensation unit;
i_a, i_b, i_c - the currents drawn by the load;
Q_1-Q_8 – the IGBT transistors of the voltage inverter;
C - the capacitor that enables the inter-phase power transfer;

$$\bar{I}_{mean} = \frac{1}{3} \cdot (\bar{I}_a + \bar{I}_b + \bar{I}_c) \quad (3)$$

- Calculating the phases of the utility voltages:

$$\varphi_a = {}^{u_a}/_{\overline{U}_a}\ ;\ \varphi_b = {}^{u_b}/_{\overline{U}_b}\ ;\ \varphi_{ac} = {}^{u_c}/_{\overline{U}_c} \qquad (4)$$

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

$$i_{ax} = \overline{I}_{mean} \cdot \varphi_a;\ i_{bx} = \overline{I}_{mean} \cdot \varphi_b;\ i_{cx} = \overline{I}_{mean} \cdot \varphi_c \qquad (5)$$

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

3. Experimental results to compensate a mono-phased, strongly inductive load

The method of using a parallel compensation unit based on a voltage inverter was tested by the author. A lot of measurements were made for various unbalanced loads. In order to prove the ability of the compensation unit to compensate the reactive power, together with the unbalanced operation, a variable inductive mono-phased load has been chosen:

$$\underline{Z}_s = R_s + j \cdot X_s \qquad (6)$$

This load has been connected between a line of the utility and the neutral wire, the other two lines remaining unloaded. This paper will present the results of balancing the utility of 3 x 380 / 220 V AC, with the load (6) connected between line L3 and the neutral wire. Figure 2 shows the system used in measurements.

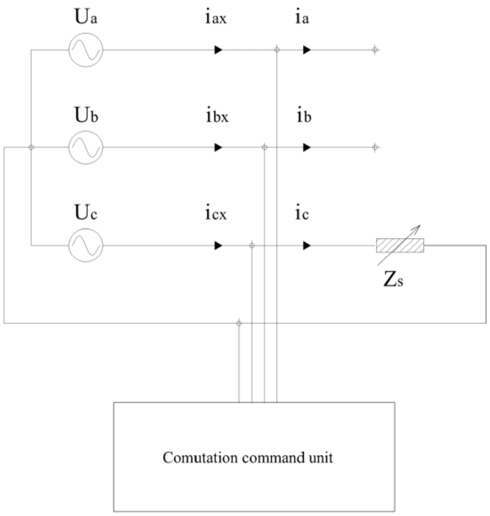

Fig. 2: The system used in measurements

The measurement tool used was composed of three identical mono-phased measurement blocks, S05127-1Z multimeters (Lucas Nüelle), as shown in the photo of Figure 3. These measurement blocks have been connected to measure the currents i_{ax}, i_{bx}, i_{cx} before and then after the compensation. The first two measurement values have been obtained for pure resistive loads, by keeping the inductivity at 0. The system proved once again its capability to compensate unbalances of the three-phased resistive loads. Then, the inductive coil has been modified to different values in order to verify the system's capability to compensate also the reactive power while compensating the unbalances of the load. Tables 1 and 2 show the results of the measurements – the first one indicates the values before starting the compensation unit, while the second one the results after starting the compensation process.

The obtained results of the measurements are not only validating the method and device proposed by the author in his former works ([3], [4]), but are also proving that the compensation unit is capable not only to balance the grid when a mono-phased or unbalanced load is present, but also to compensate the reactive operations given by the strongly inductive loads. After compensation, a symmetrical operation is obtained with a unity global power factor.

Fig. 3: The photo of the measurement tool used in measurements

	U_a	U_b	U_c	I_a	I_b	I_c	P_a	P_b	P_c	Q_a	Q_b	Q_c	$\cos\varphi_a$	$\cos\varphi_b$	$\cos\varphi_c$
	[V]	[V]	[V]	[A]	[A]	[A]	[W]	[W]	[W]	[VAR]	[VAR]	[VAR]	[-]	[-]	[-]
1	221	222	221	0	0	22,1	0	0	4862	0	0	0	-	-	1
2	221	222	221	0	0	11	0	0	2431	0	0	0	-	-	1
3	221	222	222	0	0	15,56	0	0	2421	0	0	2421	-	-	0,71
4	221	222	221	0	0	12,82	0	0	1643	0	0	3286	-	-	0,447
5	223	222	221	0	0	11,04	0	0	121,88	0	0	2437,6	-	-	0,05

Table *1*. The measurement results before starting the compensation

	U_a	U_b	U_c	I_a	I_b	I_c	P_a	P_b	P_c	Q_a	Q_b	Q_c	$\cos\varphi_a$	$\mathrm{Cos}\varphi_b$	$\mathrm{Cos}\varphi_c$
	[V]	[V]	[V]	[A]	[A]	[A]	[W]	[W]	[W]	[VAR]	[VAR]	[VAR]	[-]	[-]	[-]
1	221	222	221	7,35	7,36	7,35	1624,35	1633,92	1624,35	0	0	0	1	1	1
2	221	222	221	3,65	3,67	3,66	806,65	814,74	808,86	0	0	0	1	1	1
3	221	222	222	5,19	5,19	5,18	1147	1152,18	1149,9	0	0	0	1	1	1
4	221	222	221	4,27	4,28	4,27	943,67	944,5	943,67	0	0	0	1	1	1
5	223	222	221	3,69	3,68	3,68	822,8	817	820	0	0	0	1	1	1

Table *2*: The measurement results after starting the compensation

4. Conclusions

The experimental results do prove the successful compensation of the unbalanced and reactive operations of the electric utility by using a parallel compensation unit. These results show the cancellation of the reactive power, the compensated utility currents being of the same phase as the corresponding utility voltages.

The present paper continues the authors' researches regarding the applications of this method for the compensation of the unbalanced states of the three-phased electric utility [1-5]. Further experiments of the author prove that the same compensation unit compensates the current distortions too, being a complex compensation device, very effective in maintaining the electric energy quality. Good quality of the electric energy means lower power losses, which in turn involves less resources used to produce the same energy and consequently a better health of the environment we live in.

5. References

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