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EMANUEL'S METHOD VERSUS ILIOVICI'S METHOD FOR REACTIVE POWER COMPENSATION IN PASSIVE–ACTIVE POWER CONDITIONING SCHEME. UNBALANCED CIRCUITS

Abstract: This paper briefly describes the most important definitions of reactive power (Iliovici, Budeanu, and Emanuel), and answers the question: which formula leads to minimization of the cost and size of hybrid power conditioning system for wide-spread use, with passive reactive power compensator and active power filter. The simulation results show that the Iliovici's formula is the best one in this respect and should be used in industrial applications. In this paper the simulation results are based on concept presented in [1] (accepted for presentation at CPE Conference, Ljubljana, Slovenia, June 2013).

1. Introduction [1]

In 2010 two fundamental publications [2], [3] brought the next step forward to describe power states in electrical circuits with non-sinusoidal voltage and current waveforms. Both publication were written by A. E. Emanuel. For almost hundred last years prominent scientists such a Bunet, Budeanu, Iliovici, Fryze, Bucholz, Kuster, Shepherd, Zakikhani, Depenbrock, Czarnecki, and Tenti, among others, proposed their own power definitions. However, these have not been universally accepted by electrical engineers and their organizations. Now, it is the time for Emanuel's proposal. Nowadays, various hybrid (passive-active) systems are commonly used for non-active power elimination in industry [4], [5]. Usually, a passive compensators are used to compensate reactive power, and an active power filter (APF) [4] to eliminate the remaining unwanted power components. The passive compensator was usually designed as a bank of, or a single Thyristor Switched Capacitor (TSC), where its control system dynamically calculates the total capacitance to be connected at a particular instant of time, in order to provide as complete compensation as possible. This calculation is based on the information about the reactive power of the load. Commonly, the Budeanu definition Q_B was utilized in such a systems, but since it was questioned, and his mathematical approach was claimed to not correspond to a perfect physical model [2], the new Emanuel's method has been proposed [3]. Based on the two mentioned publication the authors put a fundamental question: which of the proposed reactive power definitions leads to minimization of the APF current after a passive compensation? To get the answer to such a question the computer simulations of some circuits have been made with use of Emanuel's, Budeanu' s and Iliovici's method to describe the reactive power.

2. Short information about Emanuel's, Iliovici's and Budeanu's power definitions [1]

2.1 Emanuel's proposal

The idea of Emanuel's proposal of power factor compensation (called by Emanuel-"method") is based on separation of fundamental (50/60 Hz) active and reactive powers from the remaining apparent power components [2], [3]. In [2] Emanuel explained why he proposes this: "*The power frequency (50/60 or fundamental) apparent, active and reactive powers are the essential components among all the components of the apparent power. The electric energy is generated with nearly pure sinusoidal voltage and currents and the end-users, who buy the electric energy, expect a high quality product, i.e. the provider of electric energy is expected to deliver reasonable sinusoidal voltage waveforms that support the useful energy* P_1t. *The harmonic powers* P_h *are often considered electromagnetic pollution - a by-product of the energy conversion process that takes place within the nonlinear loads. Thus, it makes good sense to separate* P_1 *and* Q_1 *from the rest of the powers.*" Emanuel's proposal is based on the Fourier series as follows:

- the current is separated into fundamental and total harmonic current $i = i_1 + i_H$, where:

$$i_1 = I_1\sqrt{2}\sin(\omega t+\theta_1)\,,$$
$$i_{\mathrm{H}} = \sqrt{2}\sum_{h\neq 1} I_h \sin(h\omega t+\alpha_h)\,,$$

- the voltage is separated similarly with the current: $u = u_1 + u_{\mathrm{H}}$, where, $u_1 = U_1\sqrt{2}\sin(\omega t+\varphi_1)$ $u_{\mathrm{H}} = \sqrt{2}\sum_{h\neq 1} U_h \sin(h\omega t+\beta_h)$.

For rms values:

$$I^2 = I_1^2 + I_{\mathrm{H}}^2\,,\ \text{where}\ I_{\mathrm{H}} = \sum_{h\neq 1} I_h^2 \qquad (1)$$

$$U^2 = U_1^2 + U_{\mathrm{H}}^2\,,\ \text{where}\ U_{\mathrm{H}} = \sum_{h\neq 1} U_h^2 \qquad (2)$$

apparent power squared has four terms [2]:

$$\begin{aligned} S^2 &= U^2 I^2 = (U_1^2 + U_{\mathrm{H}}^2)(I_1^2 + I_{\mathrm{H}}^2) = \\ &= (U_1 I_1)^2 + (U_1 I_{\mathrm{H}})^2 + (U_{\mathrm{H}} I_1)^2 + (U_{\mathrm{H}} I_{\mathrm{H}})^2 = \\ &= S_1^2 + D_{\mathrm{I}}^2 + D_{\mathrm{U}}^2 + S_{\mathrm{H}}^2 = S_1^2 + S_{\mathrm{N}}^2, \end{aligned} \qquad (3)$$

where: $S_1 = U_1 I_1 = \sqrt{P_1^2 + Q_1^2}$, is the fundamental apparent power, S_{N} is the non-fundamental apparent power, D_{I} is the current distortion power, D_{U} is the voltage distortion power, S_{H} is the harmonic apparent power, defined as:

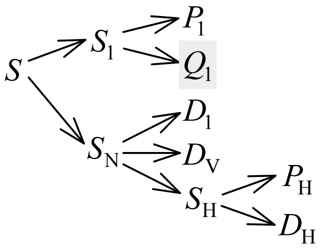

Fig. 1. Apparent power resolution according to Emanuel's proposal [1]

$$S_{\mathrm{H}} = U_{\mathrm{H}} I_{\mathrm{H}} = \sqrt{P_{\mathrm{H}}^2 + D_{\mathrm{H}}^2} \qquad (4)$$

The apparent power resolution according to Emanuel's proposal [2] is presented in Fig. 1. It is worth pointing out, that Emanuel's proposal does not strictly "compensate reactive power" but he proposes action called "power factor compensation". Because only quantity Q_1 has in its name the term "reactive power", the authors assume, that during hybrid filter action the following equations have to be satisfied:

- $Q_1 = 0$ by means of passive compensator action, and
- $S_{\mathrm{N}} = 0$ by means of active filter action.

2.2 Budeanu's proposal

Budeanu proposed the definitions of reactive power and, consequently, distortion power in the following forms:

$$Q_{\mathrm{B}} = \sum_{h=1}^{\infty} U_h I_h \sin\phi_h\ ,\ D_{\mathrm{B}} = \sqrt{S^2 - P^2 - Q_{\mathrm{B}}^2} \qquad (5)$$

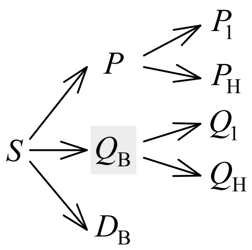

Fig. 2. Apparent power resolution according to Budeanu's proposal [1]

Apparent power resolution of power components that follows from this definition is presented in Fig. 2. Based on Fig. 2 resolution, the reactive power compensation (Q_{B}=0) can be done by a passive filter and D_{B} by an APF.

2.3 Iliovici's proposal

A quite different approach was proposed by Iliovici [6]. A new modified formula of his reactive power definition [7], [8] has the following form:

$$Q_{\mathrm{IL}} = -\frac{1}{4\pi}\int_0^T \left(u\frac{di}{dt} - i\frac{du}{dt}\right)dt \qquad (6)$$

Iliovici's reactive power is associated with electric and magnetic energy accumulated in circuits. The compensation of Iliovici's reactive power (Q_{IL}=0) can be done by a passive compensator action. It is worth mentioning, that the concepts proposed by Superti Furga [9] and by Tenti and Mattavelli, called Conservative Power Theory (CPT) [10] are originally developed based on the concept of Iliovici. It is worth reminding that reactive power defined by Budeanu was also aimed to represent phenomena that occur in loads with electric and magnetic intrinsic energy, i.e. nonactive energy of reactive loads. However unsuccessfully.

3. Simulation results

Numerical simulations has been done to demonstrate the suitability of reactive power definitions, that is: Q_{IL}, Q_1, and Q_{B} for selecting

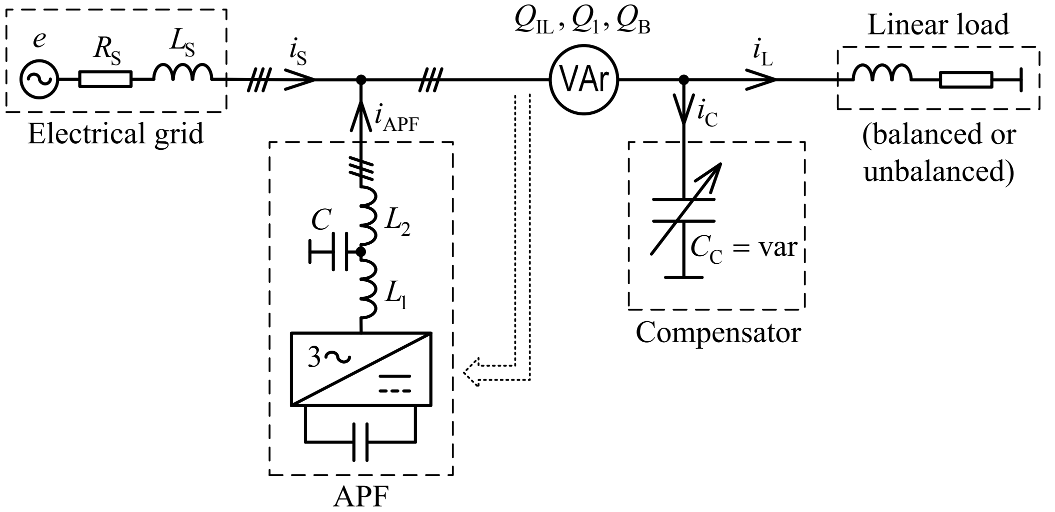

Fig. 3. Simulated supply system with linear load (balanced or unbalanced), compensated by using both active power filter and passive compensator.

the capacitance of a passive reactive power compensator. In order to validate the reactive power definitions there was simulated the three-phase supply system depicted in Fig. 3. The system comprises of the supply with its equivalent impedance (which has a resistive nature - common for distribution grids), the linear load with reactive current, both balanced and unbalanced, the passive reactive power compensator, which has been modeled as a variable capacitance, and the APF. The basic parameters of the system are given in Table II in the Appendix. The task of the APF [4] in each case was to fully compensate the supply current to be sinusoidal, and in phase with fundamental positive component of the supply voltage - regardless of its distortion or/and unbalance, and also regardless of the load and the passive compensator action. For such assumptions, the current injected by the APF depends only on the load and the reactive power passive compensator. Such a cooperative work of passive compensator and APF is often used in practical applications, and provides a complete power conditioning at a reduced cost compared to an only-active solution, i.e. with APF which acts also as a STATCOM (inverter based reactive power compensator). For that reason, the basic criteria to evaluate the suitability of the particular reactive power definition for such a system was the total cost of that system. This cost depends mainly on the rated power (rated rms current for a given supply voltage) of the APF, and also the capacitance of the passive compensator. The main goal of the simulations was to verify the effect of a passive compensation of reactive power (based on definitions Q_{IL}, Q_1 and Q_B), as well as the required rms current of the APF, as a function of the capacitance of the passive compensator. The full compensation of reactive power (for particular definition) is assumed to be done by the passive compensator, when the reactive power is compensated to zero value. It is evident, that for a given supply system there is always the capacitance of the passive compensator, which corresponds to the minimal APF current which is needed to fully compensate the supply current. It was verified, which definition of the reactive power provides passive compensation that gives the least current (thus the cost, volume, and mass as well) of an active filter. There are shown simulation results for three general cases:

- sinusoidal balanced supply, nonlinear load (Fig. 4, 5),
- sinusoidal unbalanced supply, linear balanced load (Fig. 6, 7),
- distorted balanced voltage, linear unbalanced load (Fig. 8, 9).

Fig. 4, contain the selected transients in phase A for cases when the reactive powers, Q_{IL}, Q_1 and Q_B, respectively, are fully compensated by the passive compensator, whereas Fig. 6, and 8 show a similar transients in all the phases for case when the reactive power Q_{IL} is fully compensated by TSC. Fig. 5, 7, and 9 show the corresponding characteristics of the reactive power values and APF's rms current as a function of the capacitance of the compensator C_C. All the notations in the figures are consistent with those in Fig. 3. For the sinusoidal supply voltage, regardless if balanced or unbalanced, (Fig. 4 to 7), for any type of load the reactive powers Q_{IL}, Q_1 and Q_B are almost equivalent. Although, in case of distorted supply voltage, there are significant differences between the obtained results, regardless of the load, linear [1], nonlinear [1] or unbalanced (Fig. 8, and 9). The results clearly show, that the passive compensation of the reactive power based on Iliovici definition (Q_{IL}) provides:

- the minimal value of rated power (current) of APF,
- the lowest capacitance of the TSC,

in case of distorted supply voltage. The results are summarized in Table I. The table shows both the physical and relative percentage values of APF current ($I_{APF,RMS}$) and compensator capacitance (C_C) for the reactive power compensation based on the Q_{IL}, Q_1 and Q_B definitions, and for all the studied cases. Based on these results it is evident, that the passive compensation of reactive power based on Iliovici definition Q_{IL} substantially minimizes the total cost of the compensation system, by both minimizing the rated current of the APF, and reducing the capacitance of passive compensator. For that reason, this definition is highly recommended to be used in all passive reactive power compensators (TSCs, SVCs) instead of Budeanu definition Q_B, or even instead of recently introduced Emanuel's method, based on which only the fundamental reactive power has to be compensated.

4. Summary

The paper presents the results of simulation studies of a hybrid power conditioning scheme which is common in the industry, i.e. passive-active solution, where the passive part is constituted by the capacitor bank for reactive power compensation and APF compensates the remaining unwanted current components (only its distortion). The aim of the work was to complement the results given in [1] with the studies of unbalanced system, both in terms of the supply voltage and the load. The results clearly show, that the Iliovici's formula (6) is the best one for the TSC control also in unbalanced supply system. It leads to minimum current of APF and the smallest capacitance of the TSC in case of distorted voltage - regardless of the load: balanced [1] or unbalanced. Therefore, this formula should be used in all the practical applications of the APF-TSC active-passive compensation system.

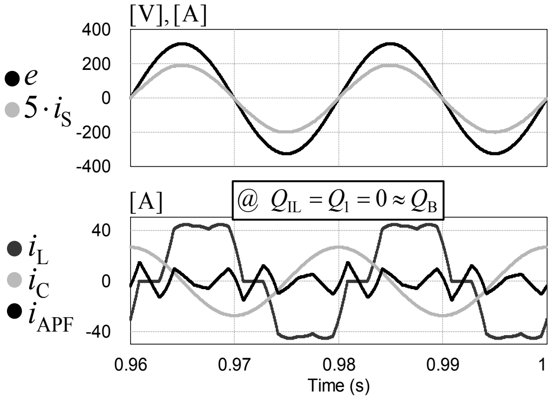

Fig. 4. Current compensation of nonlinear load operating under sinusoidal, balanced supply voltage. Transients for $Q_{IL}=Q_1=0\approx Q_B$ (phase A), of supply voltage, and the currents of: supply, load, passive compensator, and APF [1].

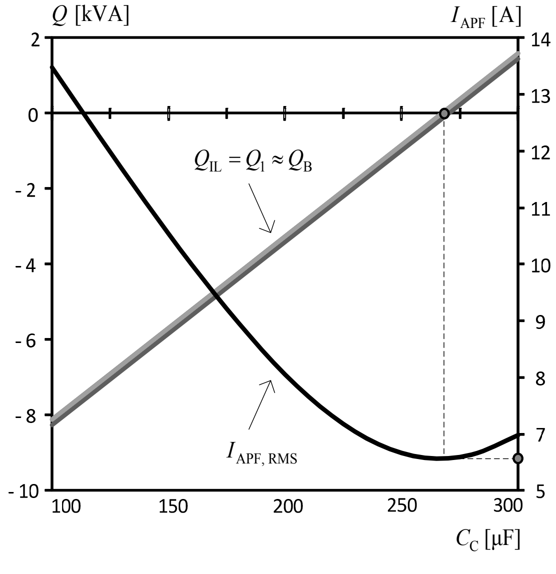

Fig. 5. Current compensation of nonlinear load operating under sinusoidal, balanced supply voltage. Reactive powers and APF current as a function of capacitance C_c of the compensator [1].

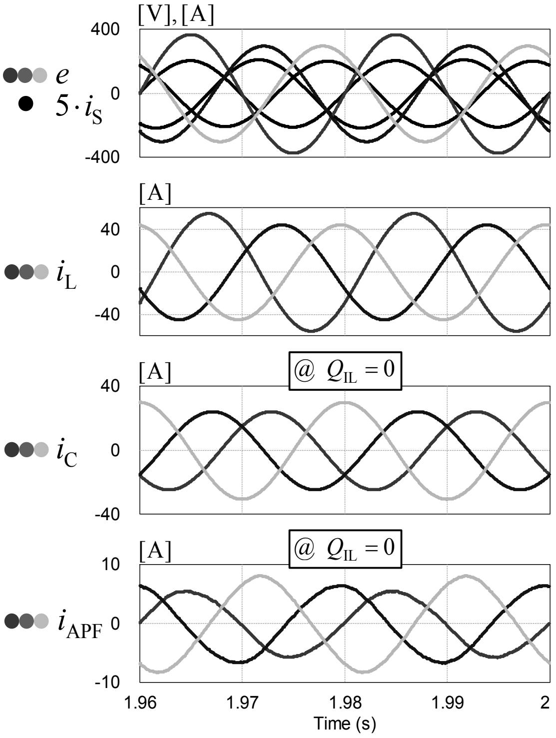

Fig. 6. Current compensation of linear load operating under sinusoidal, unbalanced supply voltage (rms of negative sequence equal to 35 V). Transients for Q_{IL}=0 of supply voltage, and currents of: supply, load, passive compensator, and APF.

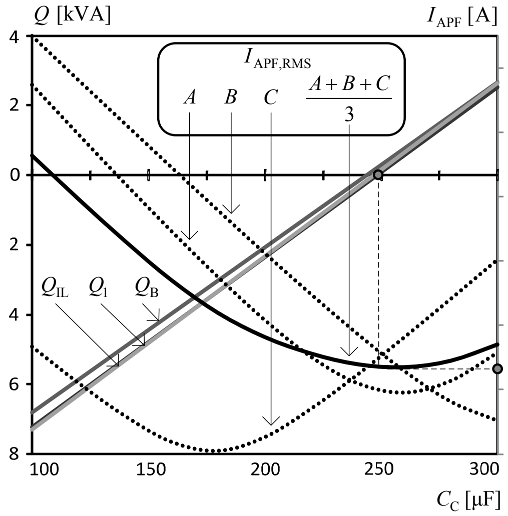

Fig. 7. Current compensation of linear load operating under sinusoidal, unbalanced supply voltage. Reactive powers and rms currents of APF (in phases A, B, C, and the value averaged from three phases) as a function of capacitance C_c of the compensator.

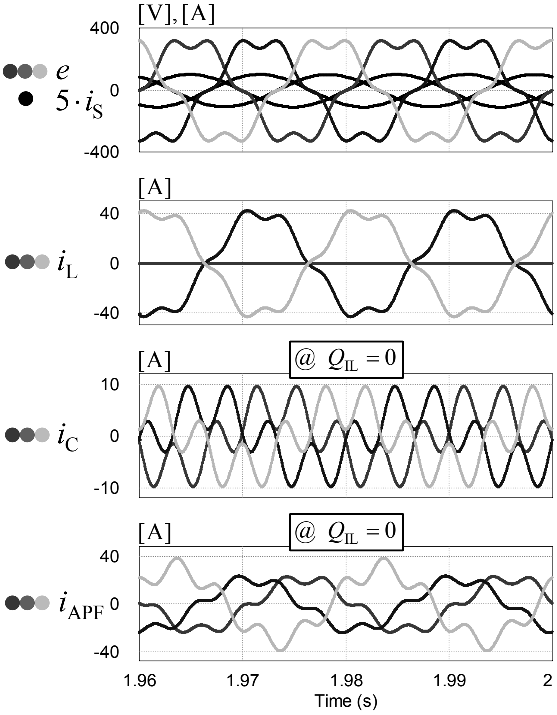

Fig. 8. Current compensation of linear, unbalanced load operating under distorted, balanced supply voltage Transients for Q_{IL}=0 of supply voltage, and currents of: supply, load, passive compensator, and APF.

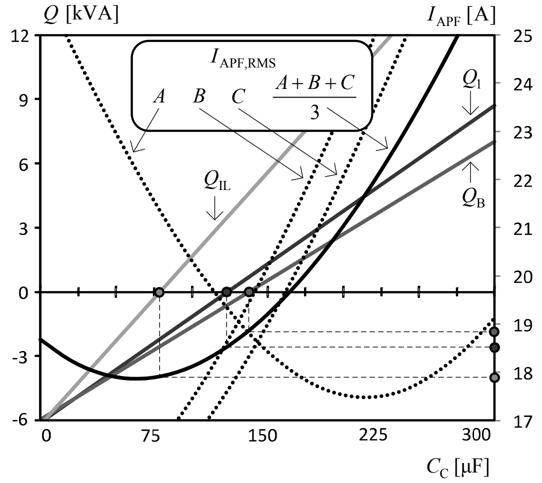

Fig. 9. Current compensation of linear, unbalanced load operating under distorted, balanced supply voltage. Reactive powers and rms currents of APF (in phases A, B, C, and the value averaged from three phases) as a function of capacitance C_c of the compensator.

Table 1. Summary of the simulation results.

Quantity	@ Q_{IL}=0	@ Q_1=0	@ Q_B=0
BALANCED SUPPLY, NONLINEAR LOAD (Fig. 4, 5)			
C_C	267μF (100%)	267μF (100%)	270μF (101%)
I_{APF}	6.49 A (100%)	6.49 A (100%)	6.50 A (100%)
UNBALANCED SUPPLY, LINEAR LOAD (Fig. 6, 7)			
C_C	249μF (100%)	249μF (100%)	245μF (98%)
I_{APF}	4.71 A (100%)	4.71 A (100%)	4.78 A (101%)
DISTORTED SUPPLY, UNBALANCED LOAD (Fig. 8, 9)			
C_C	76 μF (100%)	124 μF (163%)	133 μF (175%)
I_{APF}	17.8 A (100%)	18.6 A (104%)	18.8 A (106%)

5. Appendix

Table 2. Basic parameters of the supply and the APF.

Quantity	Value
SUPPLY	
Supply voltage, 1st harmonic (RMS)	230 V
Supply voltage, 5th harmonic (RMS)	35 V
Supply voltage frequency	50 Hz
Equivalent resistance of the supply R_S	0.1 Ω
Equivalent inductance of the supply L_S	0.0 μH
APF	
APF inverter DC voltage	750 V
Inductances L_1 of the LCL circuit	2.0 mH
Inductances L_2 of the LCL circuit	1.4 mH
Capacitances C of the LCL circuit	10 μF
PWM carrier frequency	10 kHz
Sampling frequency	20 kHz
LOAD (BOTH LINEAR AND NONLINEAR)	
Active power	20 kW
Reactive power (Iliovici definition)	-12 kVAr

7. Bibliography

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