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Protective Phase Converter for Three-Phase Systems Subjected to Powerful Single-Phase Loads

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Abstract—The contribution of this research is in suggesting the design and analysis of a protective phase converter consisting of static reactive elements. It protects and enables the symmetrical loading of all three phases in case a powerful single-phase load is connected to the system. The parameters of the converter elements are determined so that the source phase-currents stay symmetrical. The designed protective phase converter for different cases is incorporated in the three-phase system. Measurements completed for the cases of inductive or capacitive single-phase loads demonstrate considerable matching between the calculated and experimental results.

Keywords— Protective phase converter; three-phase systems; Single-phase loads; symmetrical; converter elements; converter parameters;

I. Introduction

A major factor for maintaining the quality of the three-phase voltage systems is the symmetrical loading of all three phases. It is relatively easy to maintain the balance between the phase currents when loads are three phase consumers [1]. But when a powerful single-phase load is connected to the system additional protective procedures should be introduced to enable symmetrical loading of all three phases [2]. Such powerful single-phase loads for example are the arc or resistance melting furnaces, electric traction supplies with AC contact grid etc [3].

A design of a Protective Phase Converter (PPC) consisting of static reactive elements is suggested in this research. It is to be connected between a three-phase voltage supply and a large single-phase load in order to enable symmetrical loading of the three phases. This paper describes the arrangement and the operation of a Protective Phase Converter (PPC) built of inductors and capacitors. The contribution of this research is the suggested method to determine the parameters of the converter elements so that the source phase-currents remain symmetrical. The paper describes the design and the operation of the suggested Protective Phase Converter (PPC) built of inductors and capacitors. In addition, contribution of the research is the development of a method for calculating the converter components by considering the load parameters and the requirement for symmetrical loading of the three phases.

II. General Protective Phase Converter Structure

The general circuit of the Protective Phase Converter (PPC) is presented in Fig.1. The source voltages V_R, V_S and V_T are of a symmetrical three-phase system. The single-phase powerful load has an impedance of Z and power factor of $cos\varphi$. The converter consists of reactive elements with impedances Z_1 and Z_2 respectively. Each one of them could be an inductor or a capacitor. Coordinating transformers could be used to match the consumer voltage to that of the source if necessary.

The analyzed is based on following assumptions:
- The system operates at steady state conditions;
- The three-phase source has unlimited power;
- The load and the converter elements are linear;
- All alternating quantities are sinusoidal;
- The elements of the PPC are ideal and are without resistive components.

The types and the parameters of the converter elements Z_1 and Z_2 are to be determined in such a way that the source phase-currents I_r, I_s and I_t are of a symmetrical three-phase system. In solving this task it is considered that the three-phase source is star connected and the phase voltages are:

$$V_R\,[0^o]\,,\ V_S\,[120^o],\ \ V_T\,[240^o] \qquad (1)$$

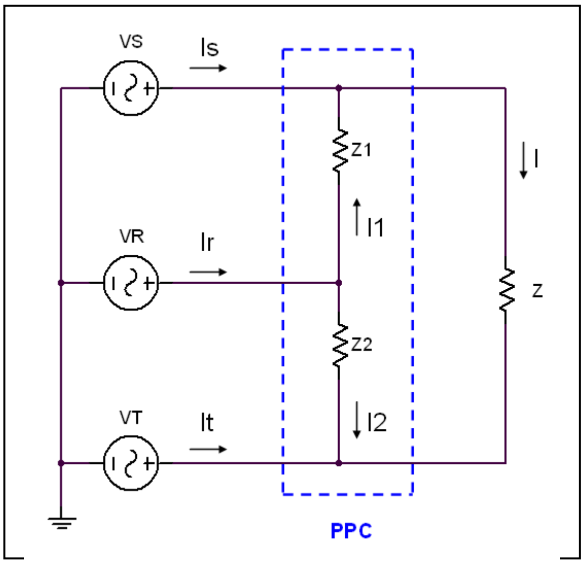

Figure 1: General electrical circuit showing the connection of the Protective Phase Converter (PPC)

The general analysis of the PPC circuit is obtained by the use of the symmetrical components method [4]. The voltages of the three-phase symmetrical system are represented as follows:

$$V_R = V;\ V_S = a^2 V_R = a^2 V;\ V_T = aV_R = aV \qquad (2)$$

where: $a = (-0.5 + j\frac{\sqrt{3}}{2});\quad j = \sqrt{-1}$

The load impedance and the impedances of the converter elements can be described as follows:

$$Z = Z(\cos\varphi + j\sin\varphi),\quad Z_1 = jX_1,\quad Z_2 = jX_2 \qquad (3)$$

The currents of a symmetrical three-phase system have equal *r.m.s* values I, and are 120° displaced from each other. They are represented as:

$$I_r = I,\quad I_s = a^2 I,\quad I_t = aI \qquad (4)$$

Also, the following current equations are valid:

$$\left.\begin{aligned} I_r &= \left(\frac{1-a^2}{Z_1} + \frac{1-a}{Z_2}\right) V \\ I_s &= \left(\frac{1-a^2}{Z_1} + \frac{a^2-a}{Z}\right) V \\ I_t &= \left(\frac{a-1}{Z_2} + \frac{a-a^2}{Z}\right) V \end{aligned}\right\} \qquad (5)$$

From (2), (4) and (5) follows that:

$$\frac{a-1}{Z_2} + \frac{a-a^2}{Z} = \frac{a^2(1-a^2)}{Z_1} + \frac{a^2(a^2-a)}{Z} \qquad (6)$$

Taking into account equations (3) and (6) results in the following relationship:

$$Z = Z(\cos\varphi + j\sin\varphi) = = \frac{X_1 X_2}{2} \times \frac{(X_2 - X_1)\sqrt{3} + j(X_1 + X_2)}{X_1^2 + X_2^2 - X_1 X_2} \qquad (7)$$

Equation (7) can be represented in the following way:

$$\left.\begin{aligned} Z\cos\varphi &= \sqrt{3}\,\frac{X_1 X_2}{2} \times \frac{(X_2 - X_1)}{X_1^2 + X_2^2 - X_1 X_2} \\ Z\sin\varphi &= \frac{X_1 X_2}{2} \times \frac{X_1 + X_2}{X_1^2 + X_2^2 - X_1 X_2} \end{aligned}\right\} \qquad (8)$$

The solutions of (8) are:

$$\left.\begin{aligned} X_1 &= \delta Z \quad where \quad \delta = \frac{\sqrt{3}}{\sqrt{3}\sin\varphi + \cos\varphi} \\ X_2 &= \beta Z \quad where \quad \beta = \frac{-\sqrt{3}}{\cos\varphi - \sqrt{3}\sin\varphi} \end{aligned}\right\} \qquad (9)$$

As seen the reactances X_1 and X_2 are complex functions of *cosφ* and *sinφ*.

III. Analysis of the Protective Phase Converter with *R-L* Nature of the Load

The equivalent electrical circuits are presented in Figure 2 and Figure 3 respectively. The impedance of the (*R-L*) load is given by:

$$Z = Z_L(\cos\varphi_L + j\sin\varphi_L) \qquad (10)$$

where

$$tg\varphi_L = \frac{\omega L}{R};\ \omega = 2\pi f \qquad (11)$$

In this case, R and L are the resistance and inductance of the load and f is the frequency of the thee-phase source.

At ($0 < \varphi_L < \pi/2$) the parameter δ is positive and the reactance of the converter element is $X_1 = X_{1L} > 0$. The element $Z_1 = Z_{1L}$ is a reactor with inductance L_{1L} .

At ($0 < \varphi_L < \pi/6$) the parameter β is negative and the reactance of the converter element $X_2 = X_{2L} < 0$. The element $Z_2 = Z_{2L}$ is a capacitor with capacitance C_{2L} (Figure 2).

At ($\pi/6 < \varphi_L < \pi/2$) the parameter β is positive and the reactance of the converter element $X_2 = X_{2L} > 0$. The element $Z_2 = Z_{2L}$ is a reactor with inductance L_{2L} (Figure 3).

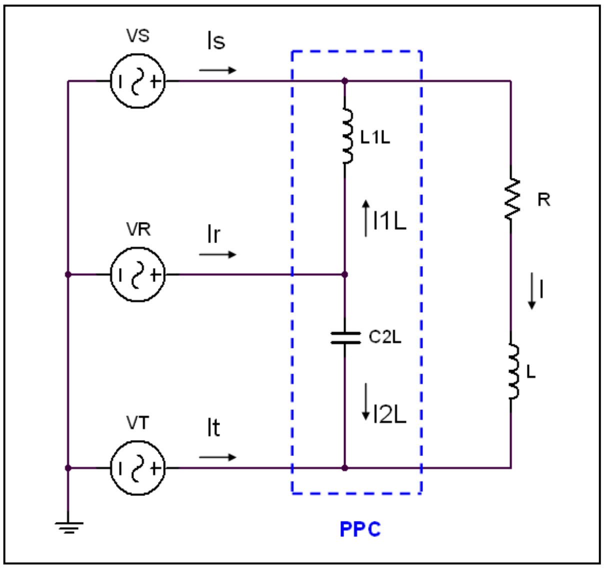

Figure 2: Electrical circuit showing the connection of the Protective Phase Converter (PPC) at (0 < φ_L < π/6)

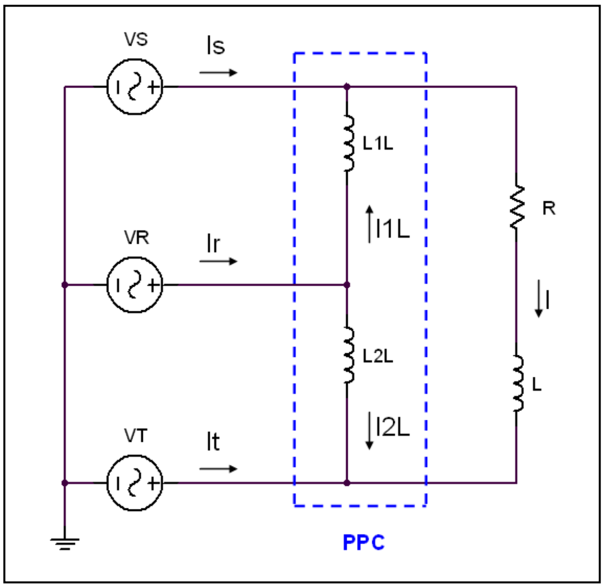

Figure 3: Electrical circuit showing the connection of the Protective Phase Converter (PPC) at (π/6 < φ_L < π/2)

At ($\varphi_L = \pi/6$) the parameter $\beta \to \infty$ and the converter consists of element X_{1L} only.

The parameters L_{1L}, C_{2L} and L_{2L} are accordingly determined:

$$\left.\begin{aligned} &\text{At } (0 < \varphi_L < \pi/2), \quad L_{1L} = \frac{\delta_L Z_{1L}}{\omega} \\ &\text{At } (0 < \varphi_L < \pi/6), \quad C_{2L} = \frac{1}{\beta_L \, \omega \, Z_{2L}} \\ &\text{At } (\pi/6 < \varphi_L < \pi/2), \quad L_{2L} = \frac{\beta_L Z_{2L}}{\omega} \end{aligned}\right\} \quad (12)$$

IV. Analysis of the Protective Phase Converter with *R-C* Nature of the Load

The equivalent electrical circuits are presented in Figure 4 and Figure 5 accordingly. The load has a capacitive nature. Therefore, the impedance of the (*R-C*) load can be represented as:

$$Z = Z_C (\cos \varphi_C + j \sin \varphi_C) \quad (13)$$

where

$$tg\varphi_C = \frac{1}{\omega CR} \quad (14)$$

At ($-\pi/2 < \varphi_C < 0$) the parameter β is negative as seen from equations (9), the converter reactance is $X_2 = X_{2C} < 0$ and the converter element $Z_2 = Z_{2C}$ is a capacitor with capacitance C_{2C} as shown in Figure 4 and Figure 5.

At ($-\pi/6 < \varphi_C < 0$), the parameter δ is positive as seen from equations (9), the Protective Phase Converter (PPC) reactance is $X_1 = X_{1C} > 0$, and the converter element $Z_1 = Z_{1C}$ is a reactor with inductance L_{1C}. This is reflected in Figure 4.

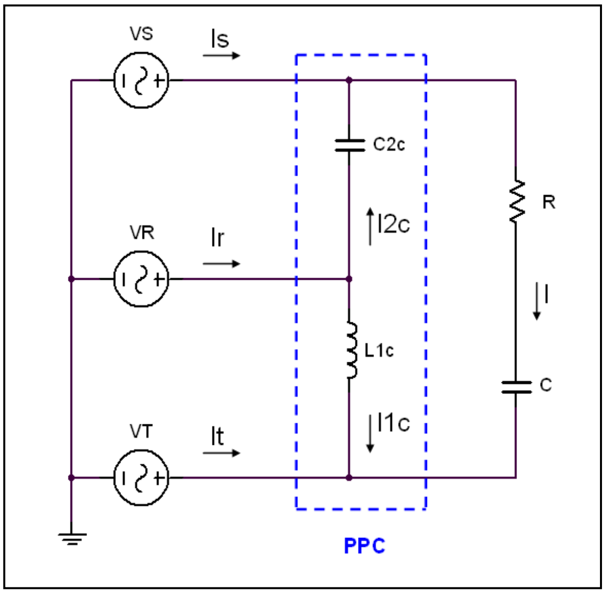

Figure 4: Electrical circuit showing the connection of the Protective Phase Converter (PPC) at (-π/6 < φ_C < 0)

At ($-\pi/2 < \varphi_C < -\pi/6$), the parameter δ is negative as seen from equations (9), the converter reactance is $X_{2C} < 0$, and the element $Z_1 = Z_{1C}$ is a capacitor with capacitance C_{1C} (Figure 5).

At $\varphi_C = -\pi/6$), the parameter $\beta \to \infty$ and the converter is without element Z_{1C}.

It is obvious that the nature of the Protective Phase Converter (PPC) elements depend considerably on the nature of the load.

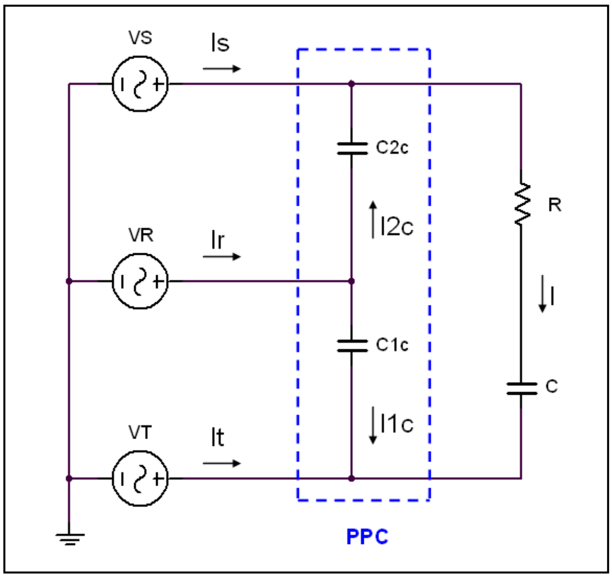

Figure 5: Electrical circuit showing the connection of the Protective Phase Converter (PPC) at (-π/2 <φ_C < -π/6)

Further, the parameters C_{1C}, C_{2C} and L_{1C} are determined accordingly:

$$\left.\begin{aligned} &\text{At } (-\pi/2 < \varphi_C < 0), && C_{2C} = \frac{1}{\beta_C Z_C \, \omega} \\ &\text{At } (-\pi/6 < \varphi_C < 0), && L_{1C} = \frac{\delta_C Z_C}{\omega} \\ &\text{At } (-\pi/2 < \varphi_C < -\pi/6), && C_{1C} = \frac{1}{\delta_C \, \omega \, Z_C} \end{aligned}\right\} \qquad (15)$$

For single-phase loads with other combinations of inductive or capacitive parameters there is need to adjust the converter elements Z_{1L} and Z_{2L} or Z_{1C} and Z_{2C} respectively. This is achieved by implementing the equations (9), (12) and (15) that represent the converter static characteristic.

V. Currents of the Circuit Incorporating the Protective Phase Converter

The load voltage V_Z, being the line voltage of the three-phase system and the load current I can be specified as:

$$V_Z = V\sqrt{3}, \quad I = \frac{V_Z}{Z} = \frac{V\sqrt{3}}{Z} \qquad (16)$$

A. *Determination of the source phase currents and the load current*

In case of *R-L* nature of the load, the r.m.s values of the source phase currents and the load current can be represented as follows:

$$\left.\begin{aligned} I_r &= \frac{V}{Z_L}(\cos\varphi_L - j3\sin\varphi_L) \\ I_s &= a^2 I_r = a^2\frac{V}{Z_L}(\cos\varphi_L - j3\sin\varphi_L) \\ I_t &= a I_r = a\frac{V}{Z_L}(\cos\varphi_L - j3\sin\varphi_L) \\ I &= \frac{V}{Z_L}\sqrt{9 - 8\cos\varphi_L} \end{aligned}\right\} \qquad (17)$$

In case of *R-C* nature of the load, the r.m.s values of the source phase currents and the load current can be represented as follows:

$$\left.\begin{aligned} I_r &= \frac{V}{Z_C}(\cos\varphi_C + j3\sin\varphi_C) \\ I_s &= a^2 I_r = a^2\frac{V}{Z_C}(\cos\varphi_C + j3\sin\varphi_C) \\ I_t &= a I_r = a\frac{V}{Z_C}(\cos\varphi_C + j3\sin\varphi_C) \\ I &= \frac{V}{Z_C}\sqrt{9 - 8\cos^2\varphi_C} \end{aligned}\right\} \qquad (18)$$

B. *Determination of the r.m.s. values of the currents via the (PPC) elements Z_1 and Z_2*

In case of *R-L* Load Z_L, the r.m.s. values of the voltage and the current via the (PPC) element Z_1 can be calculated as follows:

$$\left.\begin{aligned} V_{Z1} &= V\sqrt{3} \\ I_{1L} &= \frac{V\sqrt{3}}{X_{1L}} = \frac{V}{Z_L}(\cos\varphi_L - \sqrt{3}\sin\varphi_L) \end{aligned}\right\} \qquad (19)$$

In case of *R-C* Load Z_C, the r.m.s. values of the voltage and the current via the (PPC) element Z_1 can be calculated accordingly:

$$\left.\begin{aligned} V_{Z1} &= V\sqrt{3} \\ I_{1C} &= \frac{V\sqrt{3}}{X_{1C}} = \frac{V}{Z_C}(\cos\varphi_C + \sqrt{3}\sin\varphi_C) \end{aligned}\right\} \qquad (20)$$

Similarly, in case of *R-L* Load Z_L, the r.m.s. values of the voltage and the current via the (PPC) element Z_2 can be calculated respectively:

$$\left.\begin{aligned} V_{Z2} &= V\sqrt{3} \\ I_{2L} &= \frac{V\sqrt{3}}{X_{2L}} = \frac{V}{Z_L}(\cos\varphi_L + \sqrt{3}\sin\varphi_L) \end{aligned}\right\} \quad (21)$$

Likewise, in case of *R-C* Load Z_C, the r.m.s. values of the voltage and the current via the (PPC) element Z_2 can be calculated as follows:

$$\left.\begin{aligned} V_{Z2} &= V\sqrt{3} \\ I_{2C} &= \frac{V\sqrt{3}}{X_{2C}} = \frac{V}{Z_C}(\cos\varphi_C - \sqrt{3}\sin\varphi_C) \end{aligned}\right\} \quad (22)$$

The power factor $cos\varphi_S$ of the three-phase system can be determined as:

$$\cos\varphi_S = \frac{\cos\varphi_L}{\sqrt{9-8\cos^2\varphi_L}} = \frac{\cos\varphi_C}{\sqrt{9-8\cos^2\varphi_C}} \quad (23)$$

VI. Discussion on the Theoretical Results

The application of a Protective Phase Converter (PPC) makes it possible to load a three-phase system with any kind of powerful single-phase loading, at the same time maintaining symmetrical phase currents. The suggested Protective Phase Converter (PPC) contains only reactive elements – capacitors and/or inductors.

The power factor of the three-phase source is unity at purely active single-phase load. At resistive-inductive (*R-L*) or resistive-capacitive (*R-C*) loads the source power factor decreases and remains lower than that of the load.

At resistive-inductive (*R-L*) loads the source power factor is capacitive. At resistive-capacitive (*R-C*) load the source power factor is inductive. This phenomenon is well demonstrated in the discussed circuits with the different nature of the load.

At unity power factor of the load the source phase currents are $\sqrt{3}$ times less than the load current. At lower power factors the phase currents increase significantly, which may damage the source. In such cases it is advisable to improve the power factor and depending upon the load, shunt capacitors or series inductors could be used.

The Protective Phase Converter (PPC) can be easily controlled automatically [5], [6]. It is necessary to follow up the symmetry of the source phase currents by the use of filters for symmetrical components or any other suitable method [7]. In case of unbalance, the controlling circuit will initiate signals for appropriate changes in the parameters of the reactances X_1 and X_2 leading to symmetry of the source phase currents.

VII. Simulation and Experimental Results

The circuits of Figure 2, Figure 3, Figure 4 and Figure 5 were simulated by the aid of the software MULTISIM. Loads with different power factors were examined. The simulation results match the results obtained from the theoretical considerations.

Further, the ideal reactive inductive and capacitive elements of the Protective Phase Converter (PPC) were replaced with real elements, containing some small resistive components. It was accepted that the resistive component values could be not more than 10% of the corresponding inductive or capacitive impedances of the converter elements. The effects of these resistances over the experimental results are negligible.

The theoretical and experimental results are shown in Table 1 and Table 2. In both cases the tree-phase voltages are as follows:

$V_R = 220\angle 0^o$, $V_S = 220\angle 120^o$, $V_T = 220\angle 240^o$

$f = 50\ Hz$

The load impedance and the load current are accordingly:

$Z_L = 38\Omega$, $I_L = 10A$

TABLE I CASE OF (*R-L*) LOAD

cosφ	1.0	0.95	0.9	0.87	0.6	0.3
R, Ω	38	36.1	34.2	32.9	22.8	11.4
L,mH	0	37.8	52.7	60.5	96.8	115
L_{1L},mH	210	141	126	121	106	107
R_{1L}, Ω	6.58	4.41	3.98	3.8	3.31	3.37
C_{2L}, μF	48.4	19.8	7.02	-	-	-
R_{2L}, Ω	6.58	16.1	45.4	-	-	-
L_{2L},mH	-	-	-	~	267	155
R_{2L}, Ω	-	-	-	~	8.38	4.87
I_m, A	**10**	**10**	**10**	**10**	**10**	**10**
$I_{r,s,tth}$, A	5.77	7.72	9 .19	10	14.32	16.6
I_{rm}, A	**6.7**	**8.14**	**9.27**	**10**	**14.24**	**16.57**
I_{sm}, A	**6.32**	**8.53**	**10**	**10.8**	**15.05**	**17.24**
I_{tm}, A	**6.32**	**7.81**	**9.20**	**10**	**14.15**	**16.27**
I_{1Lth}, A	5.79	8.63	9.58	10	11.5	11.3
I_{1Lm}, A	**5.76**	**8.60**	**9.52**	**10**	**11.43**	**11.24**
I_{2Lth}, A	5.79	2.36	0.83	0	4.55	7.80
I_{2Lm}, A	**5.76**	**2.36**	**0.83**	**0**	**4.50**	**7.80**
$cos\varphi_{s\ th}$	1.0	0.71	0.57	0.50	0.24	0.104
$cos\varphi_{s\ m}$	1.0	0.75	0.61	0.54	0. 30	0. 17

The Index (th) corresponds to the theoretical and simulation data. The Index (m) corresponds to the data obtained by measurement. All data obtained by measurement are highlighted.

TABLE II CASE OF (*R-C*) LOAD

cosφ	1.0	0.95	0.9	0.87	0.6	0.3
R, Ω	38	36.1	34.2	32.9	22.8	11.4
C, μ F	~	268	192	167	104	88
C_{1C}, μF	-	-	-	0	38.1	65.6
R_{1C}, Ω	-	-	-	~	8.5	4.9
L_{1C}, mH	210	510	1440	~	-	-
R_{2C}, Ω	6.6	16	45	~	-	-
C_{2C}, μF	48.4	72.2	80.1	83.8	96.1	94.5
R_{2C}, Ω	6.6	4.4	4.0	3.8	3.3	3.3
I_m, A	**10**	**10**	**10**	**10**	**10**	**10**
$I_{r,s,t\ th}$, **A**	5.77	7.72	9.19	10	14.32	16.6
I_{rm}, A	**6.72**	**8.15**	**9.31**	**9.98**	**14.30**	**16.6**
I_{sm}, A	**6.23**	**7.80**	**9.19**	**10**	**14.14**	**16.3**
I_{tm}, A	**6.4**	**8.54**	**10**	**10.8**	**15.06**	**17.3**
I_{1Cth}, A	5.75	2.37	0.83	0	4.54	7.83
I_{1Cm}, A	**5.75**	**2.37**	**0.84**	**0**	**4.54**	**7.81**
I_{2Cth}, A	5.79	8.63	9.55	10	11.45	11.3
I_{2Cm}, A	**5.76**	**8.59**	**9.54**	**9.98**	**11.46**	**11.2**
Cos$\varphi_{s\ th}$	1.0	0.71	0.57	0.50	0.24	0.10
Cos$\varphi_{s\ m}$	1.0	0.75	0.61	0.54	0.30	0.17

There is a close match between the phase currents determined theoretically and experimentally. A difference of about 10% between the theoretically obtained and measured currents is observed only at load power factors close to unity.

Typical graphs for (R-L) load are given in Figure 6, showing clearly the trends of changes in the source phase currents and in the converter branches.

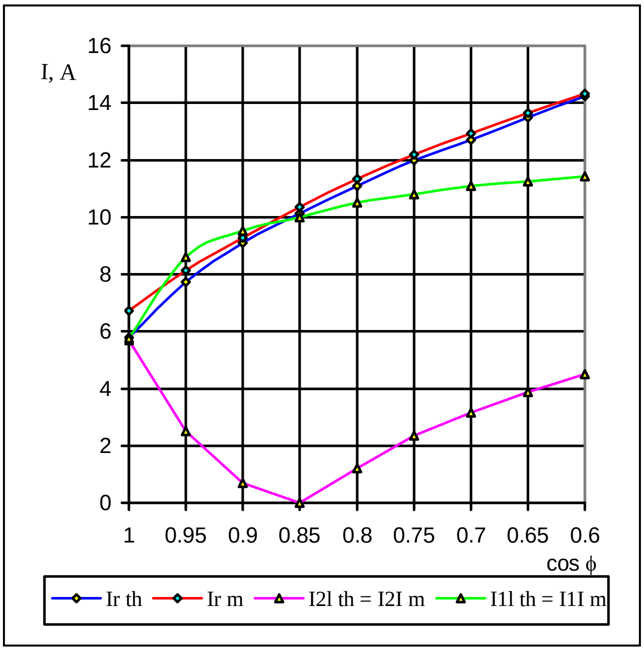

Figure 6: Currents as functions of the load power factor; (R-L) load

VIII. Conclusions

A Protective Phase Converter (PPC) consisting of reactive elements, is suggested and analyzed in this paper. Such converters could be used successfully in case of loading of three-phase voltage systems with powerful single-phase loads, in this way keeping the symmetry of the supply source.

The contribution of the paper is the theoretical analysis of the converter performance in case of different nature of the load. Another contribution is the method of determining the values of the converter components. Theoretical and experimental results match closely as seen from Figure 6. The source-currents establish a three-phase symmetrical system at any change of the single-phase load parameters by keeping the same load current.

The negligible differences between the theoretical results and the results obtained by measurement, appear due to the nonlinear characteristics of the inductors and capacitors and the ignored losses in their resistive components.

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