The Monitoring of Energy Consumptions in a Urban Transportation System

Petre-Marian Nicolae[1], Ileana-Diana Nicolae[2]

[1]University of Craiova, Faculty of Electrotechnics, Craiova, Romania
pnicolae@elth.ucv.ro
[2] University of Craiova, Faculty of Automation, Computer Science and Electronics Craiova, Romania
nicolae_ileana@software.ucv.ro

Abstract

The paper presents a detailed analysis of the energy consumptions recorded in the distribution substations from a public transportation system. One presents the evolution of the energy consumptions at the level of the public transportation system and individually, at the level of transformation substations. One performs an analysis of the power factor at global level and respectively separately, for each transformation substation. There are presented aspects concerning the penalties applied to consumer due to the decreasing of the power factor from its own distribution network. The measuring process used the analogue apparatus and a quality analyzer from the distribution stations.

1. Introduction

The monitoring of energy consumptions represents one of the major objectives in order to improve the energy efficiency. On the other hand, the development of "clean" urban transportation systems, simultaneously with the obeying of the "environment friendly" character, assumes the permanent monitoring of energetic consumptions. Owing to the implementation of new solutions, based on Power Electronics, many connected technical problems appeared in urban transportation systems, whose solving is seen as a priority for the next coming years [1]. In order to be able to improve the energy efficiency in distribution stations for urban electric transportation systems one must firstly perform a detailed analysis of the present situation with respect to the energy consumptions from the rectifying substations that supply the contact line [2],[4]. In the same time, the continuous monitoring of energy consumptions allows the making of "real-time" decisions and allows the improvement of energy efficiency in the urban transportation lines and in the medium voltage networks from the distribution lines [5],[6],[8].

2. The Analysis of Active and Reactive Energies/Powers Consumptions at the Substation Level

To improve the energy efficiency from the rectifying substations of the analyzed consumer (RAT Craiova), for the beginning we made a one-year (September 2006 - August 2007) detailed monitoring of the energy consumptions at the level of electric energy distributions substations' level. This analysis also tries to identify the worst case as seen from the electric power distribution substations perspective. Today the supplying with electric energy from the rectifying substations for medium and low voltage assumes the use of 3 substations for the supplying with electric energy, namely:

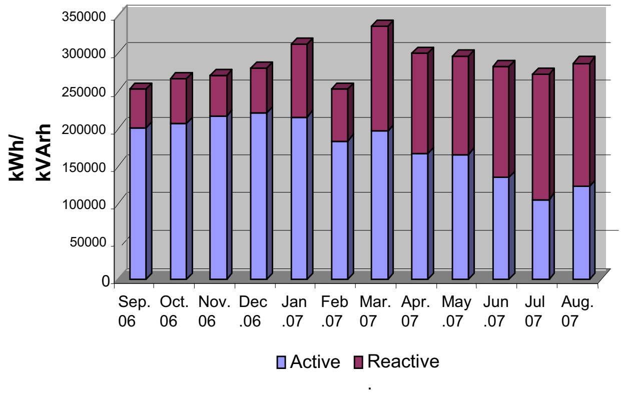


Fig. 1. Energies (active, reactive and total) consumed by all the rectifying substations.

- Substation 1 (Craiova-sud)
- Substation 2 (Craiova-Est)
- Substation 3 (Craiovita- Prefabricate).

Each of these substations supplies with electric energy a significant part from the line used for tram transportation. The recorded data correspond to the medium voltage level. The weight of the consumed reactive energy relative to the total consumed energy increased constantly during the analyzed interval. The total energy consumptions remained at a relative constant value during one year, with small season variations (slightly higher in winter time, owing to the light and heating equipment). Another explanation of the energy consumptions increase might be the increase of the number of operational trams (RAT purchased new trams) (Fig. 1).

The costs of the monthly energy consumptions as claimed by CEZ Oltenia along one year are depicted by Fig. 2.

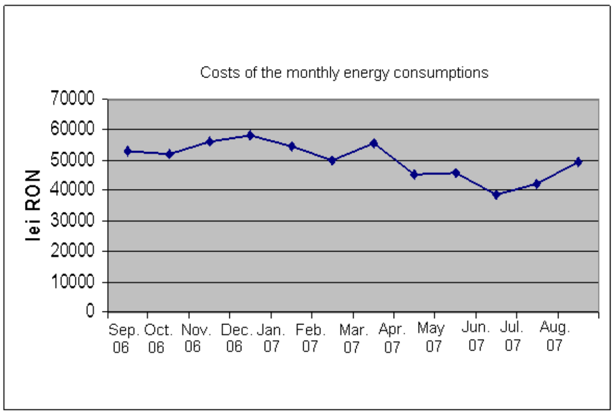


Fig. 2. The costs of the monthly energy consumptions along 1 year

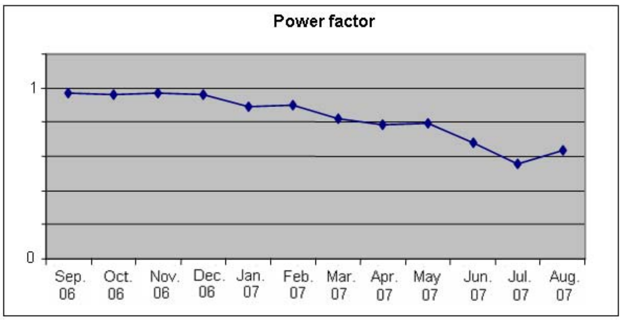


Fig. 3. Power Factor Variation

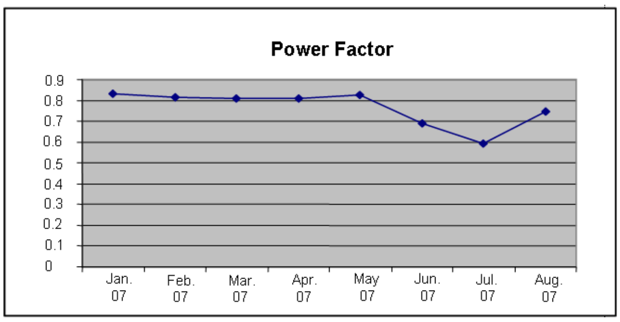
An analysis of costs evolution revealed their slight decay during the summer time, correlated with the previously discussed reduced energy consumptions. Yet in the last 2 months (July-August 2007) the costs presented a more visible raising slope, especially due to the reactive power consumption increase, simultaneously with the consumed active power decrease.

The power factor variation for the fundamental harmonic is depicted by Fig.3.

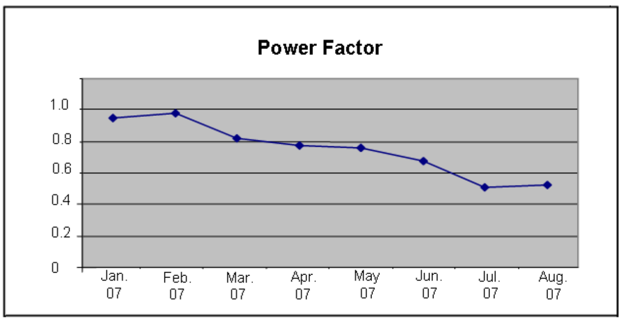
As one can see in Fig. 3, the fundamental power factor has constantly decreased, recording in the last 2 months values under the threshold of 0.65. Therefore the electric energy supplier imposed penalties to the consumer RAT Craiova, raising the per unit cost at the reactive energy from (0.043 RON+TVA) /kVArh to (0.13 RON+TVA) / kVArh. This might be a partial explanation for the significant costs rising revealed above.

3. The Analysis of (Re)active Energies/Powers Consumptions at the 2nd and 3rd Substation Level

For an accurate analysis of the causes that lead to the reactive energy consumptions increase, one performed a comparative study for two of the rectifying substations: Substation 2 (Craiova-Est) and respectively Substation 3 (Craiovita - Prefabricate).

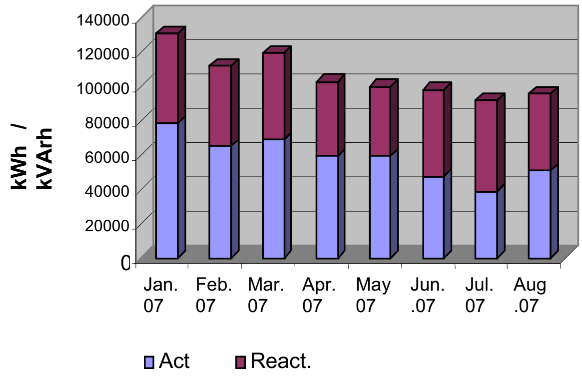


(a) Substation 3 Craiovița-Prefabricate

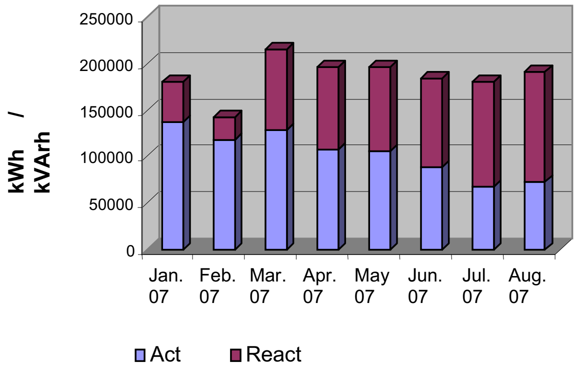


(b) Substation 2 Centru-Est

Fig. 4. Energies consumed by the 2nd and 3rd substations.



(a) Substation 3 Craiovița-Prefabricate



(b) Substation 2 Centru-Est

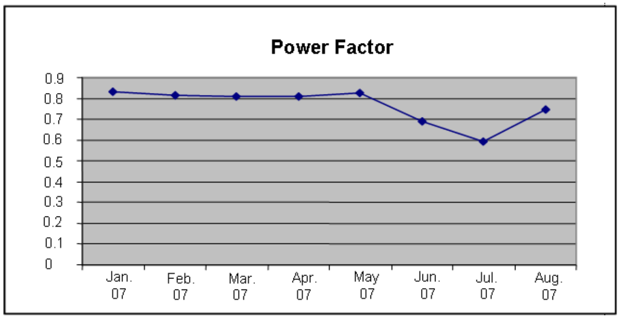
Fig. 4. Energies ((re)active and total) consumed by the 2nd and 3rd

Significant energy consumptions were noticed at the substation no. 2 and 3 (Fig. 4).

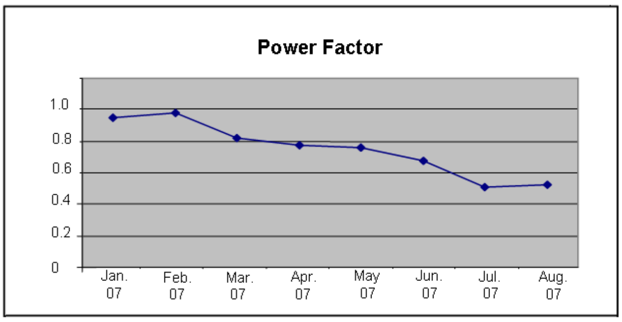
The analysis accomplished separately for the substations 2 and 3 revealed that the power factor falling for the substations level was greater for the 2nd substation, which is also more important from the energy consumptions point of view (the energy consumptions at the 2nd substation level are almost twice those from the 3rd substation level).

The graphical representation of the power factor evolution for both substations (Fig. 5) revealed its falling for both substations , being more significant for the 2nd substation, where its value falls under 0.6 and causing the increase of the coasts for reactive (and total) energy of this substation. A comparative analysis of the costs for the consumed active and reactive energy for every substation revealed that in the 3rd substation the costs for the reactive energy is almost constant. On the contrary, for the 2nd substation, the costs for the reactive energy increased constantly in the last two months of the analyzed period. It exceeded the value of the consumed active energy up to a weight of 57% of the total consumed energy.

One can notice after a detailed analysis a problematic operation at both substations where one can see a relatively significant consumption of reactive energy. Because this energy is absorbed from the system, the energy consumptions are higher and consequently the costs are increased. Therefore it is compulsory to take measures in order to reduce the consumptions through the reactive power compensation. Firstly one must take measures with the rectifying substation 2, that



(a) Substation 3 Craiovița-Prefabricate



(b) Substation 2 Centru-Est

Fig. 5. Power factor variation in the 2[rd] and 3[nd] substations

records the highest consumptions of total and respectively of reactive energy.

A similar analysis performed on this occasion revealed that for the 1[st] substation the reactive energy consumptions are lower as compared with that from the 2[nd] substation.

4. The Analysis of Active and Reactive Powers Consumptions Using a Quality Analyzer

The analysis presented in the previous section emphasized that a condition to take measures for the energy efficiency consists in the use of quality analyzers for the determination of electric energy quality, able to offer a detailed analysis with respect to the distorting and non-symmetrical regimes. In this way one can determine the voltage and current harmonics superposed over the fundamental harmonic. The waveforms distortions can result into the apparition of supplementary powers, with drawbacks over the substations from the analyzed consumer [7]. They can also cause the propagation of these effects at other consumers from system [9],[10],[11],[13].

As an example we present the case when in the supplying line, on the a.c. side, a current with an approximate RMS value of 165 A a.c. was revealed.

The analyzed substation is depicted by Fig. 6. It is submitted to the haviest electric stress owing to its placement (between the other 2 substations that supply the d.c. line) and respectively to the length of the line conductors.

The waveforms of the three-phase voltages and currents absorbed from the network (before the rectifier with diodes) as they were recorded with the quality analyzer are depicted by Fig. 7.

In this figure the substation supplying is made from a three-phase system of medium voltage (3x20 kV). The substation consists of an a.c. equipment for medium voltage (that includes the primary three-phase line, the three-phase bars for medium voltage, the breakers and separators for the protection of the

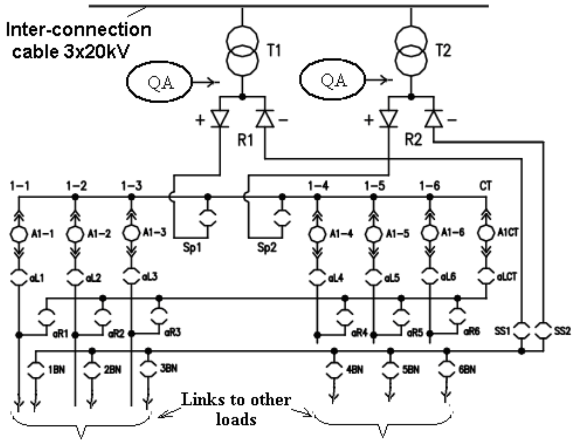


Fig. 6. Single phase electric schema of the analyzed transformation substation

transformer-rectifier group), the voltage lowering transformers T1 and T2, the rectifying groups R1 and R2 as well as a d.c. installation with the rated voltage of 600V (formed from the d.c. separators and the ultra-fast d.c. breakers). To provide the continuity of the voltage supplying to the traction d.c. line, the substation benefits of a double supplying system from the medium voltage network through the lowering transformers T1 and T2.

The lowering transformers are meant to reduce the RMS voltage of the three-phase voltage from the level of medium voltage of 20 kV a.c. to a three-phase voltage of 480 V a.c. The transformer has a Δ/Y connection. The three-phase line voltage of 3x480 V a.c. (or phase voltages 3x278 V a.c.) is rectified by means of the three-phase rectifiers with diodes (R1 and R2) into d.c. voltage of 600V.

The harmonic decomposition of the voltages and currents waveforms was performed using the Fast Fourier transform (FFT). The harmonic decomposition allows the determination of the total harmonic distortions using the relations:

$$THDX = \frac{X_d}{X_1} \cdot 100 \ \ [\%] \qquad (1)$$

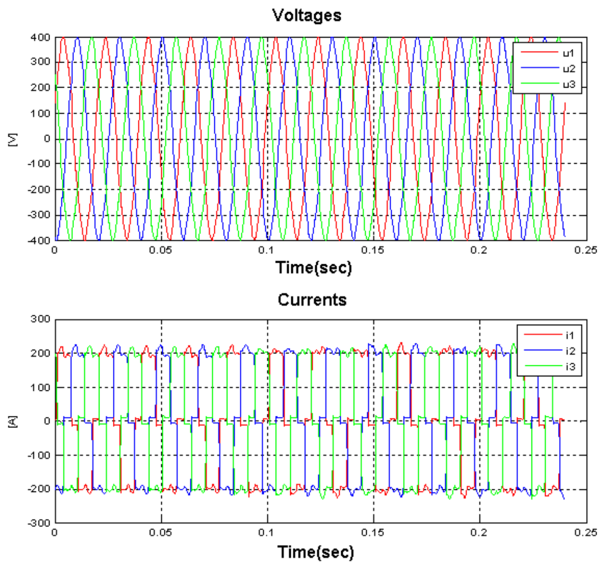


Fig. 7. Voltages and currents waveforms recorded

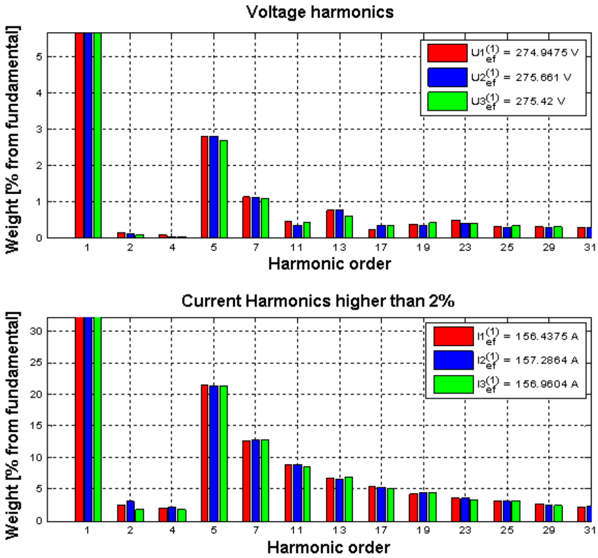


Fig. 8. Voltages and currents decomposition

where X represents a voltage or a current, X_1 is the RMS value of the fundamental harmonic, and X_d represents the distorting residue of the quantity with a non-sinusoidal periodic variation:

$$X_d = \sqrt{\sum_{k=2}^{N} X_k^2} \qquad (2)$$

(X_k represents the RMS value of the k-th harmonic). For the accomplished analysis we considered 40 harmonics (according to the EU standard).

For the analysed case, with the waveforms depicted by Fig. 7, we obtained the results presented below for the total harmonic distortions of the phase voltages and respectively of the currents absorbed from the network that supplies the distribution station (see also Fig. 8):

$THDU_1 = 3.38$ %	$THDI_1 = 28.11$ %
$THDU_2 = 3.32$ %	$THDI_2 = 28.22$ %
$THDU_3 = 3.21$ %	$THDI_3 = 27.89$ %

The RMS values of the phase voltages and currents were:

$U_{1RMS} = 275.12$ V	$I_{1RMS} = 163.35$ A
$U_{2RMS} = 275.85$ V	$I_{2RMS} = 163.87$ A
$U_{3RMS} = 275.56$ V	$I_{3RMS} = 163.45$ A

The distorting residuum of the phase voltages and currents, using eq. (2), were:

$U_{1d} = 9.29$ V	$I_{1d} = 45.79$ A
$U_{2d} = 9.16$ V	$I_{2d} = 45.98$ A
$U_{3d} = 8.83$ V	$I_{3d} = 45.60$ A

The harmonic decomposition of phase voltages and currents make the determination of the powers that flow through the substation supplying network possible. In order to determine these powers we used the equations:

- for the phase powers:
  - for a phase active power:

$$P\alpha = \sum_{k=1}^{N} P_k = \sum_{k=1}^{N} U_k I_k \cos\varphi_k;\ k = 1,...,N;\ \alpha = 1,2,3 \qquad (3)$$

  - for a phase reactive power:

$$Q\alpha = \sum_{k=1}^{N} Q_k = \sum_{k=1}^{N} U_k I_k \sin\varphi_k;\ k = 1,...,N; \alpha = 1,2,3 \qquad (4)$$

where φ_k represents the phase-difference between homologous harmonics of voltage and current for the same order.

- for the total powers:
  - total active power:

$$P = \sum_{\alpha=1}^{3} P_\alpha \qquad (5)$$

  - total reactive power:

$$Q = \sum_{\alpha=1}^{3} Q_\alpha \qquad (6)$$

Using the equations (3)…(6) we determined the powers corresponding to harmonics and on each phase, as well as the total active and reactive powers. Fig. 9 and Fig. 10 depict these powers. From Fig. 9 and Fig. 10 one can see that for certain harmonic orders the power flow is from the distribution station toward

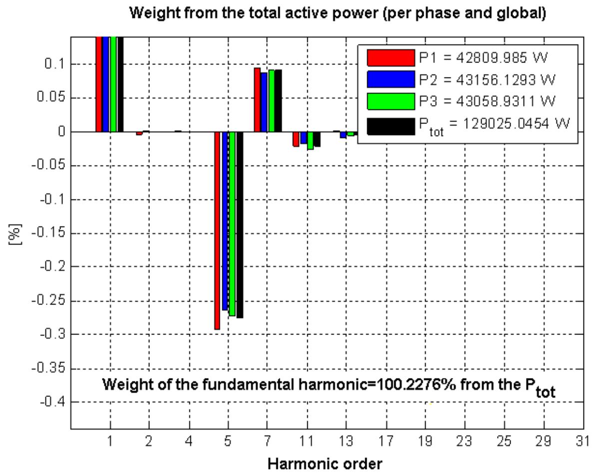


Fig. 9. Active powers for the dominant harmonics, for the single phase case and the total active power

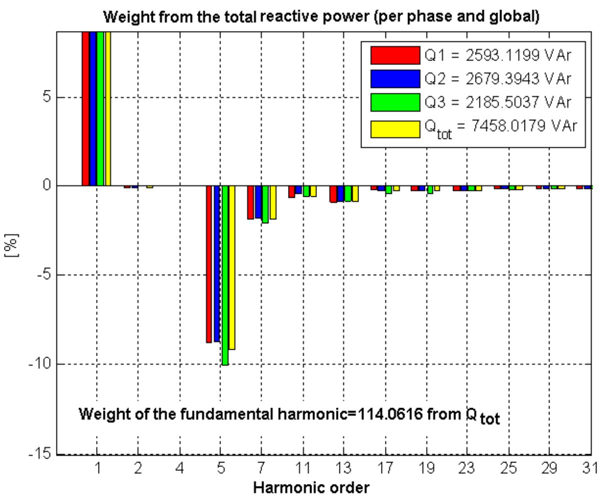


Fig. 10. Reactive powers for the dominant harmonics, for single phase case and the total reactive power

the electric energy supplying system. The total active power is slightly higher than the active power of the fundamental harmonic (0.2276%). Still the active power of the fundamental harmonic is close to the total active power specially because there is a flow of active powers along the superior harmonics, whose sense is variable.

From Fig. 9 one can notice that the active power along the 5-th harmonic is negative, revealing a reversed power flow, from the network toward source. Practically a part of the superior harmonics active power is negative, providing an explanation for the small difference between the fundamental active power and the total active power. Fig. 10 reveals that the total reactive power generated by the superior harmonics is smaller than the fundamental reactive power. Moreover the reactive power on each of the superior harmonics is negative, thus explaining the great difference between the total reactive power and the fundamental's reactive power. In this case practically the reactive power is received by the supplying network at low voltage along the fundamental harmonic, and the low voltage network returns a part of the received reactive power to the main network through the rectifier with diodes that supplies the electric driving network.

5. Conclusions

A comparative analysis of the costs for the consumed active and reactive energy for every substation revealed that in the 3-rd substation the costs for the reactive energy is almost constant. On the contrary, for the 2nd substation, the costs for the reactive energy increased constantly in the last two months of the analyzed period.

One can notice after a detailed analysis a problematic operation at both substations where one can see a relatively significant consumption of reactive energy.

A similar analysis performed on this occasion revealed that for the 1-st substation the reactive energy consumptions are lower as compared with that from the 2nd substation.

The use of a quality analyser can provide significant information on the complete system used for the monitoring of the substation for energy transformation (20 kV a.c./480 Va.c.). The preliminary analysis reveals that at a small load of the substation (as in the case analysed at Section 4), the distorting is not significant at the three phase system of supplying voltages, whereas is important at the absorbed currents. In this situation the reactive power flow is significant along the superior harmonics from the supplying network toward the transformation substation. This provides an explanation for the penalties supported by the consumer (the local transportation society) at the recordings made with analogue test apparatus (see sections 2-3).

The accomplished analysis revealed the necessity of designing and realization of a complex system for the analysis and monitoring of energy consumptions, which should also perform the monitoring, processing and analysis of non-sinusoidal and/or unbalanced regimes both for the side of medium voltage (in three-phase systems) and respectively for the side of low voltage – for a.c. and d.c. current components (separately). The realisation of the real-time monitoring system becomes compulsory in this case [12],[13].

Practically one must make a complex monitoring of the energy consumptions for the substation input and also inside it, including the outputs that supply the 2nd part of the tram line.

ACKNOWLEDGMENT

The authors thank to ANCS who supported this research through the 4th Program – "Partnership in priorities domains" under the Contract 71-145/2007 and "IDEI" Program under the Contract 695/2008.

6. References

[1] H.M. Suryawanshi, A.K. Kulwal, M.A. Chaudhari, V.B. Borghate, "High Power Factor Operation of a Three-Phase Rectifier for an Adjustable-Speed Drive", IEEE Trans. on Industrial Electronics, vol. 55, No. 4, April 2008, pp. 1637-1646

[2] Katsaprakakis D. A. et all, A Power Quality measure, IEEE Transactions on Power Delivery Vol 23, April 2008. pp. 553-561.

[3] V. Leon-Martinez, J. Montanana-Romeu, J. Giner-Garcia, A. Cazorla-Navarro, J. Roger-Folch, M.A. Grana-Lopez, "Power quality effects on the measurement of reactive power in three-phase power systems in the light of the IEEE Standard 1459–2000", 9th International Conference on Electrical Power Quality and Utilisation, EPQU 2007, pp.1-6, 9-11 Oct. 2007

[4] Auler L.F., d'Amore R., Power Quality Monitoring Controlled Trough Low-Cost Modules, IEEE Transactions on Instrumentation and Measurement Vol 58, March 2009, pp. 557-562.

[5] P. Pinato, D. Zaninelli, "Harmonic disturbances in electric traction system overhead lines", 10th International Conference on Harmonics and Quality of Power, 2002, vol.2, pp. 748-753

[6] Lian K. L., Perkins B. K., Leh. P.W., Harmonic Analysis of a Three-Phase Diode Bridge Rectifier Based on Sampled-Data Model, IEEE Transactions on Power Delivery Vol 23, April 2008. pp. 1088-1096.

[7] P.M. Nicolae, I.D. Nicolae, L. Mandache, I.G. Sîrbu, "Improved Technological Solution For Urban Transportation System By Tram", Proceedings of the International Symposium on Power Electronics, Electrical Drives, Automation and Motion - SPEEDAM, Taormina, Italy, 23-26 May, 2006, IEEE Catalog Number 06EX1320C

[8] Horn, R.H. Wilkinson, T.H.R. Enslin, "Evaluation of converter topologies for improved power quality in DC traction substations", Proceedings of the IEEE International Symposium on Industrial Electronics, ISIE 1996, pp.802-807

[9] M. A. Hannan, and A. Mohamed, "PSCAD/EMTDC Simulation of Unified Series-Shunt Compensator for Power Quality Improvement," IEEE Transaction on Power Delivery, vol. 20, pp. 1650–1656, April. 2005.

[10] E. Gholipour, and S. Saadate, "Improving of Transient Stability of Power Systems Using UPFC," IEEE Transaction on Power Delivery, vol. 20, pp. 1677–1682, April. 2005.

[11] S. Orts, "Achieving Maximum Efficiency in Three-Phase Systems With a Shunt Active Power Compensator Based on IEEE Std. 1459", IEEE Trans. on Power Delivery, vol.23, pp. 812-821, Apr. 2008.

[12] Pietro Vincenzo Barbaro, Antonio Cataliotti, Valentina Cosentino, and Salvatore Nccio, A Novel Approach based on Nonactive Power for the Identification of Disturging Loads Systems, IEEE Trans. On Power Delivery, July 2007 Vol 22, Nr.3 pp. 1782-1789.

[13] A.. Ţugulea, Criteria for the Definitions of the Electric Power Quality and its Measurement Systems, ETEP, vol.6, no.5/1996, p.357-363