ENVIROMENTAL IMPACT OF DIFFERENT TECHNOLOGY TYPES OF PRIMARY CIRCUITS

Assoc. Prof. Eng. **Cezar POPA** PhD[1], Prof. Eng. **Radu PENTIUC** PhD[1], Eng. **Alexandru MIRON** PhD[2]

[1] „Ştefan cel Mare" University of Suceava
[2] CNTEE Transelectrica SA, Bacău

REZUMAT. Lucrarea analizează principalele tehnologii utilizate în realizarea circuitelor primare din staţiile electrice în corelaţie cu preţul de cost şi impactul asupra mediului ambiant în ceea ce priveşte: spaţiul necesar pentru instalare, emisiile echivalente de CO_2 şi alţi poluanţi. Aprecierea corectă din faza de proiectare a riscurilor şi avantajelor de utilizarea a unei soluţii tehnico - economice poate reprezenta un factor decisiv în strategia adoptată pentru realizarea de noi staţii electrice sau retehnologizarea celor existente.

Cuvinte cheie: impact mediu ambiant, echivalenţă emisii CO_2, circuite primare, tehnologii echipamente comutaţie

ABSTRACT. The paper examines the main technologies used for the production of primary circuits for substations correlated with the cost price and the environmental impact in terms of space required for installation, CO2- equivalent emissions and other pollutants. An accurate assessment during the design stage of the risks and benefits of using a technical-economical solution can be a decisive factor in the strategy adopted to construct new substations or revamp the existing ones.

Keywords: environmental impact, CO_2 equivalent emissions, primary circuits, switchgear equipments/technology

1. INTRODUCTION

The natural greenhouse effect produced by the gases that naturally exist in the atmosphere (water vapors, nitrogen, carbon dioxide, methane etc) provide temperature control of earth by balancing the energy received from the sun, accumulated energy and the one reflected back into the space. Industrial activities and the various growing needs of population are factors that determine changes in the natural atmospheric concentrations of greenhouse gases (GHG): carbon dioxide, methane, nitrous dioxide, plus the contribution of some synthesis gases from the category of high greenhouse gases (HGHG): HFCs, PFC/PFPEs, SF_6 [1]. Increasing concentrations of gases in the atmosphere cause amplification of the reflection effect of heat radiated from the earth which will be transmitted in a much smaller degree into space. Change of the energy balance leads in time to radical climate changes [2-4]. Electric energy production, transport and distribution systems are the largest users and consumers (70…80 % of world production) of Sulphur Hexafluoride (SF_6) gas. Use, storage and handling of SF_6 is strictly followed by national environment protection agencies due to the global warming potential (GWP) which is 23,900 times higher than that of CO_2 and to the extreme stability over time, estimated at 3200 years [4]. Research results have ensured decreased gas quantities per equipments and per annual volume of leakages by redesign and led to measure plans to limit handling losses by monitoring equipment, adopting strict procedures and personnel training [5-6]. Information collected in the early period between 1990 and 2000 from the operating companies has allowed development of researches and, subsequently, a relevant data base to assist substation owners in formulating new strategies on short and long term in regard to:

- opportunity of new substations and technology;
- opportunity to change existing technologies (oil, SF_6) taking into consideration the investment costs against the prospect of reducing operating costs and the impact on the environment.

2. PRIMARY CIRCUITS TECHNOLOGIES

Modern solution for the production of electrical equipments in substations aim at increasing function safety, decreasing occupied surfaces, execution times, total investment, operating and maintenance costs and damage downtime. An important role in developing modern solutions for outdoor substations is played by performances obtained in the manufacture of electrical equipments. In designing modern solutions one must have in view that their application should be easy when modernizing existing substations, considering the large number of substations whose life cycle has expired. High voltage substations ($U_n \geq 110\,kV$), depending on the technology used, can be divided into four generations.

The first generation Air Insulated Switchgear-AIS is that of outdoor substations conventionally equipped with oil circuit breakers or SF_6 (two working pressures or auto compression) and air insulated equipments. Depending on the equipment, this technology can be used up to 400kV (oil) and 800kV (SF6), at a rated current of 1.6...4 kA and a breaking current of 63 kA. As SF_6 breakers are made as closed pressure systems, they require periodic inspection of gas quality and must be re-filled periodically. The average gas quantity contained by the circuit breaker considered in this study (110 kV with auto compression) is 30 kg. Annual average leakage reported by users varies widely depending on the technology and equipment age and is 12...5 % [2] and [7].

The second generation is represented by substations with Compact (configurable modules) Air Insulated Switchgear-MAIS equipped with SF_6 circuit breakers, surrounded by the rest of the equipment arranged vertically in compact formation. The conventional disconnector is integrated into the new disconnector circuit-breaker led to a simplified circuit diagram, increased reliability, decreased assembling area and total costs. The average quantity of SF_6 used by modern self-expansion breakers of 110kV is 28.5kg and annual leakages guaranteed by the producers are 1% [7] and [8].

The third generation Hybrid Insulated Switchgear-HIS is represented by hybrid high voltage substations comprising air insulated devices and encapsulated modules containing pressurized SF_6-insulated switching devices. As they were designed to combine the advantages of an open system that can be developed (AIS) with the very good reliability of sealed pressure systems (GIS), which are much more difficult to develop. Hybrid modules, providing compact size and superior performance, are a less expensive technical solution for modernizing old AIS technology (oil). Outstanding performances recommend this technology for a range voltage of 72.5 ... 550 kV. The amount of SF_6 contained by the encapsulated module for a voltage of 110 kV is 36 kg and guaranteed gas losses are only 0.5% per year.

The fourth generation Gas Insulated Switchgear-GIS, and the most performing, is made up of encapsulated modules, separated in compartment with distinct functional role. The devices that satisfy a certain functional role are fitted inside a protective metal casing containing pressurized SF_6. The casing is sealed permanently (30 years) by using special surface treatment and assembly techniques. GIS solution is suitable in applications with space restrictions or very expensive premises (in large urban areas). Sealed pressure systems technology ensures negligible emissions of only 0.1% per year, given the large amount of gas, 100 kg, contained by a single bay [7] and [9].

Table 1 shows comparative investment costs, downtime costs paid to consumers and service costs for a 110 kV substation in a less polluted environment, for the following types of equipment: conventional with oil breakers (AIS) as reference version, with compact withdrawable modules (MAIS), hybrid modules (HIS) and type (GIS) prefabricated modules encapsulated in SF_6 .

Table 1.

Comparative costs for the construction of substations using different technologies (110 KV, pollution level I)

Chapter titles	AIS [%]	MAIS [%]	HIS [%]	GIS [%]
Total investment costs	69,2	50,9	71,9	193
Downtime costs (20 years)	18,9	1,2	4,1	0,5
Maintenance and service costs (20 years)	11,9	1,9	3,7	1
TOTAL COSTS	100,0	54,0	79,7	194,7

Major advantages in terms of costs can be attained using hybrid modules in polluted environments. GIS technology is much more expensive (investment + maintenance operations), justifiable for outdoor substations operating in highly polluted environments that require a high level of operability.

Substations in Romania and SE Europe (Republic of Moldova, Bulgaria) are characterized by high physical wear requiring operating expenses, high maintenance, high cost of servicing and equipment repair.

In Romania, out of more than 950 substations (AIS) of rated voltage between 35 ... 750 kV existing in the national energy system, about 90 % are of 35 ... 110 kV. Out of the 79 system substations (220 -750 kV) operated by National Company Transelectrica SA, more than 60 % were partially or completely modernized with AIS technology (SF_6) or GIS (one case in Breaza Refinery, Ploiesti) by means of national programs implemented after 2000.

Most 110 kV substations are equipped with first generation equipments (AIS oil, those which existed in the 1960s-1970s when they became operational). These substations need to be replaced or revamped urgently because only about 15% of them were modernized according to present energy efficiency and safe operation standards.

3. ENVIRONMENTAL IMPACT OF PRIMARY CIRCUITS OPERATION AND SERVICE

The potentially dangerous for the environment main risk factors of substations are:

• herbicides and pesticides, used to prevent uncontrolled growth of vegetation and rodent spread around the station area [10];

• small amounts of polychlorinated biphenyl's (PCBs) which can still be found in older equipments (liquid filled bushings and cables);

• Mineral oil leaks from electrical transformers and old circuit breakers;

• leakage of SF_6 from switchgear devices;

• heat emissions from equipments and mainly from the primary circuits.

Mineral oil is found in substations in very large amounts (one single transformer may contain 40 t of oil) and therefore even a minor incident can cause serious environmental problems. By preventive monthly measures that identify the smallest leaks and by continuous monitoring after detection, these problems are kept under control and do not represent a major risk of environmental pollution unless some extreme cases such as those caused by fire.

World production of SF_6 has increased continuously after 1970 due to the performances of the new switchgear technologies, the low cost of gas of only € 4.63 / kg (until 1990) and to the lack of restrictions on use; much later SF_6 was classified as HGHG by Kyoto Protocol (1997). The high price of 60 € / kg (2005) and the ever-rising demand of HV equipment in brought the efficiency of the self-assumed measures taken by large companies to responsibly use SF6 by limiting alleged losses during production to 3% (2005) and improving operational measures by transport and distribution companies (3% maintenance losses) [11].

Primary circuits are traveled by variable load current $I_s(t)$ that causes losses by the Joule-Lenz effect in the flexible connections, bus-bars, contact resistances, power transformers windings, choke coils and power transformers. Power transformers also present losses of active power in the magnetic circuit. All these losses are transferred to the environment as heat and contribute to its warming.

3.1. CALCULUS METHOD

From the risk factors in assessing the impact of primary circuits in substations on the environment, this study used those related to the leakage of SF_6 from the switchgear equipments and heat losses resulted from operation of installations. The reference calculations considered the elements corresponding to a line cell, respectively, a transformer cell of 110 kV, Figure 1, given the high share of these IT stations in the national energy system and that they are representative of a potential sector that must be urgently modernized.

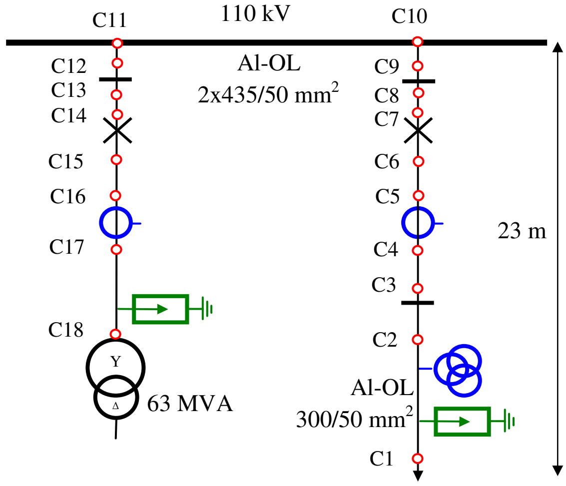

Fig. 1 Typical wiring diagram for substations made in AIS technology (oil or SF6 circuit breakers)

The method of calculating the harmful effects on the environment caused by the operation of the primary circuits of an existing substation observes the IEC, CIGRE, IPCC, CAPIEL-HV regulations [3] and [8]. Equivalent resistance R_e of a cell from a station is determined by the resistance of the paths of current and the amount of contact resistances R_{cj} that meet along the conductive path (at contact separators, circuit breaker, terminal connections):

$$R_e = \sum_{i=1}^{n} \rho_i \frac{l_i}{A_i} + \sum_{j=1}^{m} R_{cj} \tag{1}$$

where: n is the number of conductive paths; ρ_i - is resistivity of conductive material i; l_i is length of conductive path; A_i - area of conductive section; m – number of electrical contacts; R_{cj} - contact resistance measured at point j according to national standards.

Electricity converted into heat by Joule-Lenz effect during life-cycle of bay equipment, $t_s = 20...30$ years, for a known annual operating span t_f, determined by equipment reliability, results from the relation:

$$\Delta W_{J-L} = 3R_e t_s \int_0^{t_f} I_s^2(t)dt = 3R_e I_{max}^2 \tau \tag{2}$$

where: I_{max} is the maximum current recorded during bay operation; $\tau = 8760\left(1240 + t_{I_{max}}\right)^2 \cdot 10^{-8}$ is equivalent calculation duration of maximum annual energy losses (equation valid for a bay functioning duration of more than 1000 h / year) [12].

Span of maximum continuous load $t_{S_{max}}$ of operating installations can be determined using the counters indications (integrator appliances) for active W and reactive W_r power corresponding to the calendar period considered, in the hypothesis of some voltage variations that fall within the normal range and power factor variations between $cos\ \varphi = 0,5…0,95$:

$$t_{I_{max}} \cong t_{S_{max}} = \frac{1{,}03\sqrt{W^2 + W_r^2}}{S_{max}} \qquad (3)$$

where: S_{max} is the maximum continuous load absorbed by the bay (the highest of medium loads measured during an interval of 15 ... 60 minutes).

The losses of active power in the power transformer ΔW_T depend on the maximum load S_{max}, rated output S_{nT}, core losses ΔP_0, losses in the windings at rated load ΔP_{sc}, annual no-load operating time of transformer t_{fT} respectively, at maximum load τ:

$$\Delta W_T = \Delta P_0 t_{fT} t_s + \Delta P_{sc} \frac{S_{max}^2}{S_{nT}^2} \tau t_s \qquad (4)$$

The equivalent CO_2 emitted by power plant during the fuel combustion to generate the electric energy ΔW lost in the cell circuits and transformer depends on the type of the power plant and fuel used. Specific common values of CO_2 eq. emitted per kWh generated are in domain $k = 0{,}51...0{,}64$.

$$m_{CO_2 - \Delta W} = k \cdot (\ \Delta W_{J-L} + \Delta W_T\ ) \qquad (5)$$

The equivalent CO_2 corresponding to cumulated emission of SF_6 depends on the mass of gas m_{SF6} stored in the equipments, the annual gas loss Δm_{SF6} and the potential value to global warming $GPW = 23900$ of SF_6:

$$m_{CO_2 - \Delta m_{SF6}} = \Delta m_{SF6} \cdot GPW \cdot t_s \qquad (6)$$

Annual gas losses depend on the generation of SF_6 switchgear equipments, on the responsibility of maintenance operations and implementation degree of used gas recovery procedures.

4. ENVIRONMENTAL IMPACT ASSESSMENT IN TERMS OF PRIMARY CIRCUITS TECHNOLOGY

To identify a modernizing technology for the existing 110 kV substations with minimal impact on the environment, we have conducted a case study for AIS technology (oil), MAIS and HIS for which we considered a series of experimental measurements made in substations or on some equipments in the Power Apparatus Laboratory of Suceava University.

Measurements of the ohmic resistance of primary current paths were performed for parts of circuit corresponding to fixed contact areas respectively, for switchgear contacts of separators and extinguishing chambers of circuit breakers. The method used was that of measuring the contact resistance during continuous current (100 A) and the voltage drop was measured with a digital instrument Metrix 3281 with an error of 0.1 %. The resistance of flexible and rigid conductive paths was determined by calculation based on lengths and sections shown in the construction projects or spot measurements. Resulting values for the equivalent resistances of primary circuits in the variants analyzed are presented in Table 2.

Table 2

Equivalent electrical resistance of primary circuits for a line bay and for a transformer bay at 110 kV

Technology	Equivalent resisitance [mΩ]	[%]
AIS (oil)	6,192	100
MAIS (Combined SF_6)	1,948	31,46
HIS	2,224	35,91

Transformers are the most expensive equipments from an electrical station, they have a lifetime of 40...50 years and represent about 60 % of the total investment costs, therefore choosing them wisely is extremely important for a long and proper operation adequate to the consumption demand in the area served and premature replacement with new transformers is an expensive and difficult operation. The choice between a new low-cost transformer, loss-optimized transformer or maintaining operable a transformer designed 40 years ago must take into account the average load time in optimal load depending on the energy losses (environmental impact), increasing energy costs and operating expenses. Low-loss transformers use better materials for their construction and thus initially cost more (+15…25 %). In case of distribution and power transformers, which operate continuously at partial load (30…60 %) the added cost can be recovered via savings in energy use (and emission of equivalent CO_2) in less than 3…5 years [13].

Our case study considered two kinds of bay transformer equipment: for AIS technology (oil) we considered a TTUNL 110/10 kV transformer (made in 1970) with apparent power S = 63 MVA, no-load losses ΔP_0 = 60 kW, load losses ΔP_{sc} = 260 kW and for MAIS (Combined) technology and HIS we considered a low-loss transformer Siemens 110/10 kV with apparent power S = 63 MVA, no-load losses ΔP_0 = 37 kW, load losses ΔP_{sc} = 196 kW.

We considered that the average annual time use of maximum load S_{max} is 3400 h and the calculation of energy losses in this situation for the entire service duration of the station for t_s = 30 years was done at different load values. Final results for each type of transformer loss, after transformation of energy losses into CO_2 eq. are presented in Figure 2.

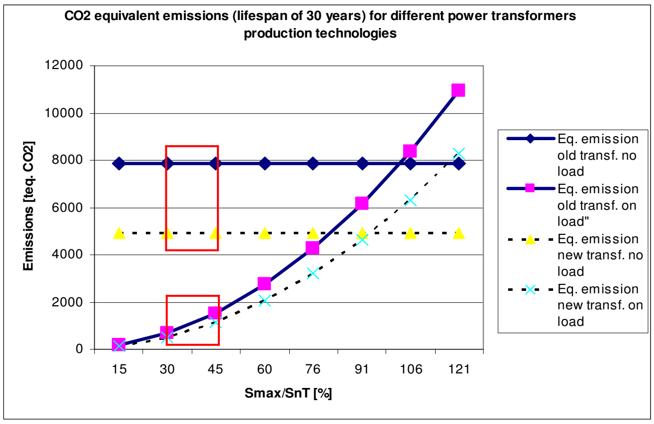

Fig. 2 CO_2 equivalent emissions (lifespan of 30 years) for different power transformers production technologies

Analysis of energy losses shows that in the case of present transformers (oversized and technologically outdated) working at medium loads of 30 ... 45 % of rated power of the transformer, the winding losses do not decrease significantly when using a low-loss transformer but significant energy savings can be obtained by lowering core loss. According to Figure 2, only this measure can decrease the environmental impact of primary circuits with 30 ... 35 %.

If we consider all losses that appear the primary circuits level, Figure 3, we notice that in terms of energy losses and implicitly CO_2 equivalent emissions, the recommended modernization solution is that of equipments using HIS technology.

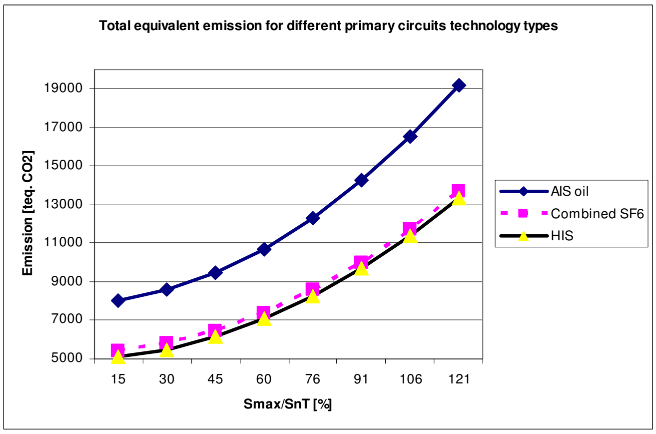

Fig. 3 Total CO_2 equivalent emissions (30 years lifespan) for different primary circuits production technologies

In the long-term, this solution can be better than MAIS, if estimated price paid by companies for CO_2 emissions will rise.

In terms of investment costs, Table 1, but also in terms of environmental impact, MAIS solution is competitive because energy losses of primary circuits are slightly inferior compared to those corresponding to HIS technology, Table 3.

Table 3

Emissions (lifespan of 30 years) due to electric circuit losses (Joule-Lenz)

S_{max}/S_{nT} [%]	30	45	60	76	91	121
AIS [teq. CO_2]	24,3	54,7	97,3	152,1	218,9	389,3
HIS [teq. CO_2]	8,9	20,0	35,6	55,7	80,1	142,5
Combined [teq. CO_2]	7,8	17,5	31,1	48,6	70,0	124,4

The share of emissions equivalent to such losses (compared to total emissions), even at recommended transformer loads, remains relatively small, 0.5 ... 0.6 % therefore the economic criteria of investment costs of switching equipments will be decisive.

The share CO_2 equivalent emissions due to SF_6 leaks, compared to the total level of emissions and an average load of 70 ... 80 % in HIS technology is 0.3 % and for MAIS technology (Combined) is 4.3 %. In absolute values the entire service duration for the switching equipment, the above percentages are 25.8 t eq. CO_2 respectively 367.8 t CO_2. The worst case scenario this level of pollutant emissions is equivalent to the emissions resulting from operating 100 auto vehicles for one year at a medium run of 15,000 km / year.

5. CONCLUSIONS

Primary circuits of substations produce a limited impact on the environment but which cannot be neglected.

During modernization of 110 kV substations the most economically effective solution with a minimum equivalent impact on the environment is to replace the existing transformers with low-loss transformers designed for an average load of 70 ... 80 % and to equip line and transformer bays with MAIS Combined technology equipments in case of slightly polluted ambient.

The equivalent CO_2 equipments emissions are small, therefore the economic criteria of investment costs in switching equipments will be decisive.

BIBLIOGRAPHY

[1] **Smythe, Katie D.,** *Production and Distribution of SF_6 by End-Use Application*. Conference on SF_6 and the Environment, November 2-3, San Diego, California, 2000

[2] **van der Zel, L.,** *SF_6 and the Environment-Guidelines for Electric Utility Substations.* EPRI, Palo Alto, CA, 1002067, 2003

[3] **IPPC.,** *ClimateChange 2001: A Scienific Basis.* Cambridge University Press, Cambridge, UK, 2001

[4] **Ravishankara, A.R., Solomon, S., Turnipseed, A.A., Warrun, R.F.,** *Atmospheric lifetimes of long-lived halogenated species.* Science, No. 259, 1993, pp. 194-199

[5] www.epa.gov., EPA International Conference on SF_6 and the Environment: Emission Reduction Strategies, 2002

[6] **Muller, B.,** *Gas Management Service.* Airgas Inc., 2005

[7] **SP Transmission.,** *Business Plan Update-Environment Submission.* December 2011

[8] **CAPIEL.,** *Switchgear and SF_6 Gas.* CAPIEL HV-ESDD1-R1-1.02, 2002

[9] **Christophorou, L.G., Olthoff, J.K., von Brutt, R.J.,** *Sulfur Hexafluoride and the Electric Power Industry.* IEEE Electrical Insulation Magazine, 1997, pp. 20-24

[10] www.ucahelps.alberta.ca., *Environmental Aspects of Substation.* ENMAX

[11] **Maiss, M., Breninkmeijer, C.A.M.,** *A reversed trend in emissions of SF_6 into the atmosphere?.* Proceedings of the 2nd International Symposium on Non-CO_2 Greenhouse Gases, Kluwer, 2000

[12] **Preda, L., Heinrich, I., Buhuş, P., Ivas, D., Gheju, P.,** *Staţii şi posturi de transformare.* Editura Tehnică, Bucureşti, 1988

[13] **Siemens.,** *Transformers.* Siemens Power Engineering Guide – Transmission and Distribution, 4th Edition, 2008

About the authors

Assoc. Prof. Eng. **Cezar POPA**, PhD.
University „Stefan cel Mare" from Suceava, Faculty of Electrical Engineering and Computer Science, Department of Electrotechnics, 13 Universităţii Street, Suceava, zip code 720229, Romania.
email: cezarp@eed.usv.ro

Graduated from „Gh. Asachi" Technical University of Iasi, Faculty of Electrotechnics, study program – Use of Electricity. After graduation he worked at Machines Tools Company in Suceava, Department of Prototypes, as engineer. PhD. graduate from „Gh. Asachi" Technical University of Iasi, Faculty of Electrotechnics, study program – Electric Machines, Power Apparatus and Electric Drive. He has been working at the Faculty of Electrical Engineering and Computer Science since 1992, and in the area of Power Apparatus and Substations, as associate professor since 2003. His research topics are design of Power Apparatus and optimization of Electro thermal Converters.

Prof. Eng. **Radu PENTIUC**, PhD.
University „Stefan cel Mare" from Suceava, Faculty of Electrical Engineering and Computer Science, Department of Electrotechnics, 13 Universităţii Street, Suceava, zip code 720229, Romania.
email: radup@eed.usv.ro

Graduated from „Gh. Asachi" Technical University of Iasi, Faculty of Electrotechnics, study program – Use of Electricity. After graduation he worked at Machines Tools Company in Suceava. PhD. graduate from „Gh. Asachi" Technical University of Iasi, Faculty of Electrotechnics, study program – Use of electricity, Low Voltage Electrical and Electric Traction. He has been working at the Faculty of Electrical Engineering and Computer Sciences since 1992.

Eng. **Alexandru MIRON**, PhD.
CNTEE Transelectrica S.A., Bacau Power Transmission Branch
email: alexandrumiron49@yahoo.com

Born in Romania, on November 19, 1949. He received the M.SC. and PhD. degree in Power Engineering from Technical University "Gh. Asachi" of Iasi, Romania, in 1972 and 1999 respectively. Currently he is the head of High Voltage Department with CNTEE Transelectrica S.A., Bacau Power Transmission Branch. His research area is the microcomputer-based monitoring, protection, and control of power systems. He is author of a book on relaying and author or co-author more than 50 papers. He is member of the IEEE Power Engineering Society and CIGRE, Study Committee B5 - Protection and Automation.