Scientific Bulletin of the Petru Maior University of Tirgu Mures
Vol. 6 (XXIII), 2009
ISSN 1841-9267

Power Capability in Low Voltage DC Distribution Systems

Ph.D. Student C.O. Gecan, Dr.Eng. M. Chindriş, Ph.D. Student R. Bindiu
Technical University of Cluj – Napoca
15 C. Daicoviciu St., RO 400020, Cluj – Napoca
Tel: +40264 401408
Calin.GECAN@eps.utcluj.ro
Mircea.CHINDRIS@eps.utcluj.ro
Radu.BINDIU@eps.utcluj.ro

Abstract

Recent developments in power electronics components enable the use of power electronics in Low Voltage (LV) networks. This development makes the model of a Low Voltage Direct Current (LVDC) distribution system possible. The technical and economical benefits of this technology make possible the alternative hypothesis of using DC instead of AC distribution systems. Some aspects, such as increasing the capability of the existing lines, interconnecting distributed generation units and even supplying in DC some loads are creating additional requirements of using a LVDC distribution system.

The paper presents some general considerations regarding cables used in a LVAC distribution system and different line reconfigurations witch enable the use of cobles in a LVDC distribution system. The reconfigurations are presented in respect of the DC network topologies: unipolar and bipolar.

The central aim of this paper is to investigate capability of power transmission and to calculate the transmission distance for cables used in Low Voltage AC and DC distribution systems.

Capability computation is considered in respect of two constrains imposed in the cables cross section selection: cable thermal limit and the maximum allowable voltage drop. Cable thermal limit is represented in calculations by the maximum rated current.

The equations used to calculate the power capability are presented for single-phase and three-phase AC networks and unipolar and bipolar DC networks. Based on these equations, comparisons between power capability of cables with different cross sections used in Low Voltage DC and AC distribution systems are realized and presented.

Keywords: Cables, Line Reconfiguration, DC systems, Power Capability, Transmission Distance

1. Nomenclature

P_{maxac} – power capability in AC circuits [W];
P_{maxdc} – power capability in DC circuits [W];
I_{max} – thermal limit [A];
U_f – phase voltage [V], (230 V);
U_l – line voltage [V], (400 V);
U_{dc} – DC voltage [V];
$\Delta U_{max}[\%]$ – maximum allowable voltage drop [%];
$\Delta U_{max}[V]$ – maximum allowable voltage drop [V];
$cos\rho$ – power factor;
R – circuit resistance [Ω];
s – conductor cross section [mm^2];
ρ – electrical resistivity [Ω·mm^2/m];
l – feeder lenght [m].

2. Introduction

Nowadays DC systems can be found in specific applications: telecommunications and electric traction systems. The telecommunication system uses a LVDC power system, and it was developed when the centralized battery system was built. The system is powered by the public network through rectifiers. Batteries are used to feed the system in case of a fault in the AC network. The DC voltages used in telecommunications are either +24 V or -48 V [1].

DC systems are also used in electric propulsion based vehicles and ships. Besides the combustion engine, hybrid electrical vehicles use an electric system witch supply power to the wheels when the car accelerates and stores the power produced in deceleration periods in batteries. The electric power is

Keywords: *cables, line reconfiguration, DC systems, power capability, transmission distance*

also used to supply the other loads in the car. A 300 V DC voltage level is suitable for full hybrid vehicles [2].

Quick development of semiconductors made electronic equipments to become dominant as a share in applications for residential buildings and offices. Because they use a different voltage level from the network, both in frequency and amplitude, the arising issue is the change of the voltage level, respecting the quality requirements. These efforts involve costs and energy losses. Since most electronic equipment used DC voltage, the questions arise regarding the use of DC distribution systems instead of AC distribution systems.

3. DC distribution systems

The DC systems are classified by means of voltage level in High Voltage DC systems (30 kV < U ≤ 1500 kV), Medium Voltage DC systems (1500 V < U ≤ 30 kV) and Low Voltage DC systems (U ≤ 1500 V). In the following a brief descriptions is presented for the LVDC system.

3.1. Low Voltage DC systems

The new worldwide energy policy seeks to take measures to produce electricity using renewable energy sources. In this context, a Low Voltage DC network can interconnect distributed generation units. DC voltage can be obtained directly by using some renewable energy sources.

There also exists Ultra Low Voltage Direct Current (ULVDC) networks witch are characterized by a voltage level up to 120 V. In practice, this system is used only in case of electronic equipment for offices and residential buildings.

Equipments such as computers, fluorescent lamps with electronic ballast, or TVs use DC voltage. They have in their configurations a rectifier, which converts the AC voltage into DC voltage as presented in Figure 1.

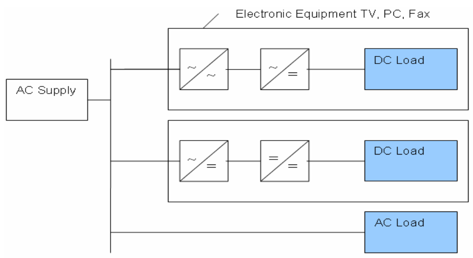

Figure 1. AC voltage supply [3]

The conversion process introduces harmonics in the AC network, which have different negative effects (currents in the null conductor, inadequate protection operation). Such equipment can be supplied directly by DC voltage. Problems arise for the electrical machine with rotating magnetic field, AC motors or other equipment, witch, for normal operation need to be supplied in AC voltage. The supply of the AC loads will be achieved in this case through an inverter witch can provide AC voltage to the bus where more AC loads are connected as presented in Figure 2.

Increasingly fewer equipment used in offices and residential applications are subject in operation to AC voltage and a proposed solution for DC and AC voltage distribution is shown in Figure 2.

The number of converters is reduced compared with the classical solution and the power losses of the electronic equipment are reduced accordingly by waiving the process of conversion and use a scheme such as that proposed in Figure 2.

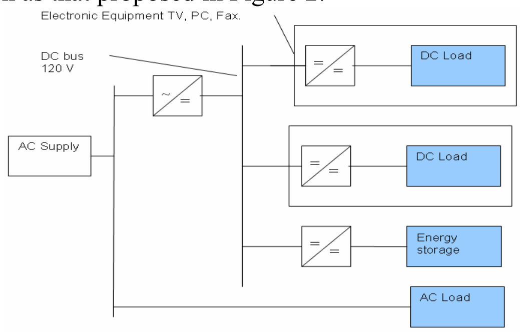

Figure 2. AC and DC voltage supply [3]

Besides the aspects regarding the power capability witch will be further investigated, LVDC networks used at the customer end present several others advantages:

- safety: the DC voltage is not as dangerous for human body as the AC voltage, because it does not lead to involuntary muscle contractions. The DC voltage must be less than 120 V to avoid this danger to the human body.
- magnetic fields are reduced;
- application of the DC system reduces voltage fluctuations at the customer's end and the operating voltage can be kept nearly constant;
- since for the whole system just one rectifier is needed, we can chose a better quality one in witch case with a proper control, the impact of electronic equipment in the AC network can be reduced by lowering the harmonic content;
- a converter that allows a bidirectional flow can introduce energy into the AC network when there is an extra energy produced in the DC network due to increased potential of renewable energy sources.

3.2. AC cable reconfiguration

In the following, some considerations are presented regarding the supply of existing cables (used in AC systems) at DC voltage.

All AC cables can be used in DC systems if the restrictive conditions imposed by the DC system are fulfilled (mechanical resistance, thermal stability in continuous operation, thermal stability in short time duty, voltage drop). Usually a three phase cable supplied at AC voltage is made of 3, 4 or 5 conductors as shown in Figure 3.

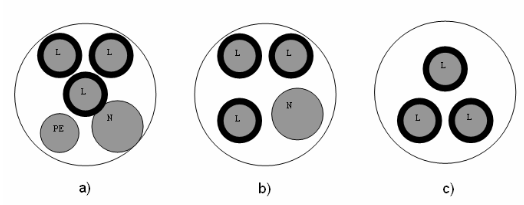

Figure 3. Cables used in AC systems a) 5 wires; b) 4 wires; c) 3 wires

As the AC system has two topologies (single-phase and three-phase) the DC system may also be realized in two topologies: unipolar and bipolar. The difference between the two topologies is represented by the numbers of conductors and the supply voltage level. Unipolar and bipolar DC systems are presented in Figure 4.

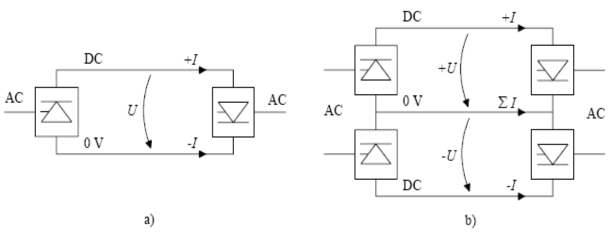

Figure 4. DC system [4] a) unipolar; b) 4 bipolar

A unipolar or bipolar DC circuit can be achieved using insulated conductors or thru the reconfiguration of the existing AC cables. Different reconfiguration possibilities for a 4 wire AC cable witch enable its use in a DC circuit are presented in Figure 5.

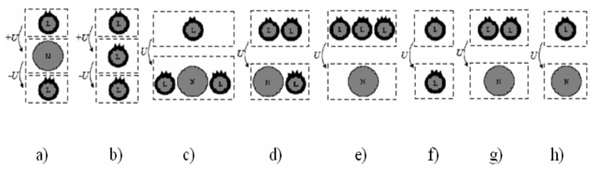

Figure 5. 4 wire cable reconfiguration [4] a)-b) bipolar system; c)-h) unipolar system

4. Power Capability in LV DC and AC systems

In the following section are presented some considerations (investigated cross section, computation equations, voltage drop, maximum rated current, computation hypothesis, results and graphical representations) regarding the power capability of conductors and cables supplied by AC and DC voltage. Conductors and cables power capability is represented by the maximum power that can be transmitted or transported for a certain distance and in certain imposed conditions.

The computation for a conductor or cable power capability is realized taking into account the cable thermal limit (maximum rated current) and maximum allowable voltage drop. Some aspects referring to this constrains are presented below.

4.1. Thermal limit

An important parameter in power capability computation is represented by the conductor or cable thermal limit or maximum rated current (I_{max}). This value is fixed for different standardized conductor cross sections depending on the conductor material, insulation type, emplacement, room temperature.

Maximum rated current values were adopted so that in permanent operating conditions the thermal effect will not cause the conductors melting or any insulation deterioration. The maximum rated current values for copper conductors with PVC insulation, installed in tubes, three conductors in tube are presented in Table 1. The thermal limits of 3 and 4 wire copper cables with PVC insulation, installed in open air are presented in Table 2.

Table 1. Copper conductors thermal limit [5]

Conductor cross section [mm^2]	Maximum rated current (I_{max}) [A]	Conductor cross section [mm^2]	Maximum rated current (I_{max}) [A]
1	12	25	84
1,5	14	35	108
2,5	20	50	135
4	26	70	171
6	34	95	218
10	49	120	250
16	64	150	280

Table 2. Copper cables thermal limit [5]

Conductor cross section [mm^2]	Maximum rated current (I_{max}) [A]	Conductor cross section [mm^2]	Maximum rated current (I_{max}) [A]
1,5	18.5	70	202
2,5	25	95	244
4	34	120	282
6	43	150	324
10	60	185	371
16	80	240	436
25	106	300	481
35	131	400	560
50	159	500	-

4.2. Maximum allowable voltage drop

The conductor maximum transmitted power is limited also by the voltage drop ΔU[%]. The maximum allowable voltage drop is established as presented in Table 3 according to the nature of the circuit and supply type.

Table 3 – Maximum allowable voltage drop [5]

Supply type	ΔU[%]	
	Lighting circuits	Other circuits
Electrical installations supplied through an electrical connection from the low voltage public network	3	5
Electrical installations supplied through a transformer	8	10

4.3. Computation equations

The equations used to determine the power capability of conductors or cables used in different circuit types (single-phase AC, three-phase AC, unipolar DC and bipolar DC) are presented below. The power capability was determined according to two constraints: thermal limit and maximum allowable voltage drop.

a) Single-phase AC circuit

a1. Thermal limit

$$P_{\max ac} = I_{\max} U_f \cos\rho, \text{ [W]} \tag{1}$$

a2. Maximum allowable voltage drop

$$\Delta U_{\max}[\%] = \frac{\Delta U_{\max}[V]}{U_f} = \frac{R I_{\max}}{U_f}, [\%] \tag{2}$$

From equation (2):

$$I_{\max} = \frac{\Delta U_{\max}[\%] \cdot U_f}{R} = \frac{\Delta U_{\max}[\%] \cdot U_f}{\frac{\rho \cdot (2l)}{s}} =$$

$$= \frac{\Delta U_{\max}[\%] \cdot s \cdot U_f}{\rho \cdot (2l)} \text{ [A]} \tag{3}$$

From equations (1) and (3) will result the power capability in respect of maximum allowable voltage drop:

$$P_{\max ac} = \frac{\Delta U_{\max}[\%] \cdot s \cdot U_f^2 \cos\rho}{\rho \cdot (2l)} \text{ [W]} \tag{4}$$

b) Three-phase AC circuit

b1. Thermal limit

$$P_{\max ac} = \sqrt{3} \cdot I_{\max} U_l \cos\rho \text{ [W]} \tag{5}$$

b2. Maximum allowable voltage drop

$$\Delta U_{\max}[\%] = \frac{\Delta U_{\max}[V]}{U_l} = \frac{R I_{\max}}{U_l} \text{ [\%]} \tag{6}$$

From equation (6):

$$I_{\max} = \frac{\Delta U_{\max}[\%] \cdot U_l}{R} = \frac{\Delta U_{\max}[\%] \cdot U_l}{\frac{\rho \cdot l}{s}} =$$

$$= \frac{\Delta U_{\max}[\%] \cdot s \cdot U_l}{\rho \cdot l} \text{ [A]} \tag{7}$$

From equations (5) and (7) will result the power capability in respect of maximum allowable voltage drop:

$$P_{\max ac} = \frac{\sqrt{3} \cdot \Delta U_{\max}[\%] \cdot s \cdot U_l^2 \cos\rho}{\rho \cdot l} \text{ [W]} \tag{8}$$

c) Unipolar DC circuit

c1. Thermal limit

$$P_{\max dc} = I_{\max} U_{dc} \text{ [W]} \tag{9}$$

c2. Maximum allowable voltage drop

$$\Delta U_{\max}[\%] = \frac{\Delta U_{\max}[V]}{U_{dc}} = \frac{R I_{\max}}{U_{dc}} \text{ [\%]} \tag{10}$$

From equation (10):

$$I_{\max} = \frac{\Delta U_{\max}[\%] \cdot U_{dc}}{R} = \frac{\Delta U_{\max}[\%] \cdot U_{dc}}{\frac{\rho \cdot (2l)}{s}} =$$

$$= \frac{\Delta U_{\max}[\%] \cdot s \cdot U_{dc}}{\rho \cdot (2l)} \text{ [A]} \tag{11}$$

From equations (9) and (11) will result the power capability in respect of maximum allowable voltage drop:

$$P_{\max dc} = \frac{\Delta U_{\max}[\%] \cdot s \cdot U_{dc}^2}{\rho \cdot (2l)} \text{ [W]} \tag{12}$$

d) Bipolar DC circuit

d1. Thermal limit

$$P_{\max dc} = 2 \cdot I_{\max} U_{dc} \text{ [W]} \quad (13)$$

d2. Maximum allowable voltage drop

$$\Delta U_{\max}[\%] = \frac{\Delta U_{\max}[V]}{U_{dc}} = \frac{RI_{\max}}{U_{dc}} \text{ [\%]} \quad (14)$$

From equation (10):

$$I_{\max} = \frac{\Delta U_{\max}[\%] \cdot U_{dc}}{R} = \frac{\Delta U_{\max}[\%] \cdot U_{dc}}{\frac{\rho \cdot l}{s}} =$$

$$= \frac{\Delta U_{\max}[\%] \cdot s \cdot U_{dc}}{\rho \cdot l} \text{ [A]} \quad (15)$$

From equations (13) and (15) will result the power capability in respect of maximum allowable voltage drop:

$$P_{\max} = \frac{2 \cdot \Delta U_{\max}[\%] \cdot s \cdot U_{dc}^2}{\rho \cdot l} \text{ [W]} \quad (16)$$

5. Results and graphical representations

The power capability of different conductors and cables was determined and represented as a function of transmission distance. In this purpose, certain computation premises were established: conductor material is copper for witch ρ_{Cu}= 0.0178 Ω·mm^2/m; the maximum rated current for the considered cross section are from Table 1 and Table 2; the maximum allowable voltage drop is 5%, $\Delta U_{max}[\%]$ = 5%; U_f = 230 V and U_l = 400 V; $cos\rho$ = 0.9.

Comparisons between power capability for conductors and cables with different cross sections used in Low Voltage DC and AC distribution systems were realized and are further presented.

5.1. Conductors

Even if in this case the results were predictable, several conductor cross section (1.5 mm^2, 2.5 mm^2, 4 mm^2, 6 mm^2, 10 mm^2, mm^2, 16 mm^2, 25 mm^2, 35 mm^2, 50 mm^2, 70 mm^2, 95 mm^2, 120 mm^2 and 150 mm^2) were investigated and the power capability of the conductor used in a single-phase AC was compared with the one obtained for the same conductor used in a unipolar DC circuit. The results obtained for the 2.5 mm^2 cross section used in a unipolar DC circuits and single-phase AC circuits (variable power factor) are presented in Figure 6.

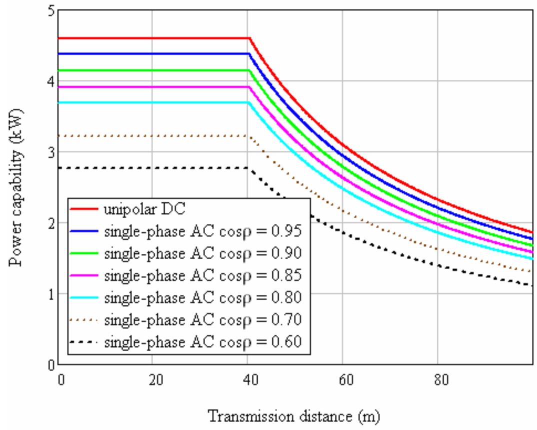

Figure 6. Power capability for a 2.5 mm^2 copper conductor

5.2. Cables

Different copper cables were investigated in respect of power capability: 3x35 mm^2, 3x35+16 mm^2, 4x35 mm^2. For all this cables, used in three-phase AC circuit and unipolar and bipolar DC circuit, the power capability was calculated at different voltage levels. The European Union directive 2006/95/EC enables the use of DC voltage distribution systems up to 1500 V DC [6]. In these circumstances, the voltage levels used in computations were 400 V and 1000 V AC and 400 V, 750 V, 900 V, 1500 V DC Voltage.

The investigation could be carried out in the hypothesis that the cables can be supplied to AC voltage up to 1000 V and DC voltage up to 1500 V.

The results obtained are similar for all cable investigated. In the following figures are presented the results obtained for the 4x35 mm^2 copper cable used in: a three-phase AC circuit (Figure 3b); a unipolar DC circuit (Figure 5d); a bipolar DC circuit (Figure 5b). After cable reconfiguration, in case of a DC bipolar circuit, one conductor remains unused.

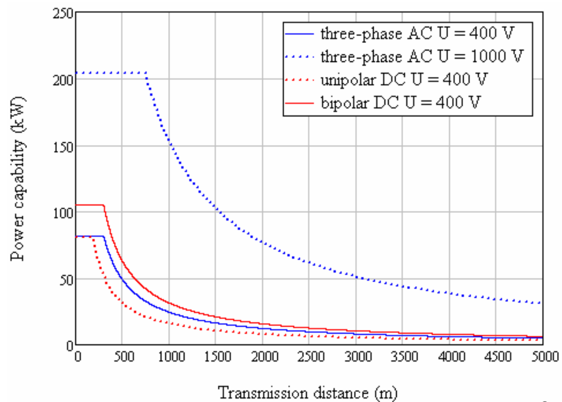

Figure 7. Power capability for a 4x35 mm^2 copper cable U_{dc} = 400 V

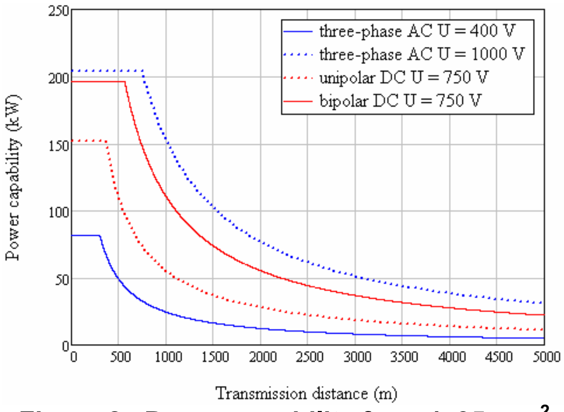

Figure 8. Power capability for a 4x35 mm^2 copper cable U_{dc} = 750 V

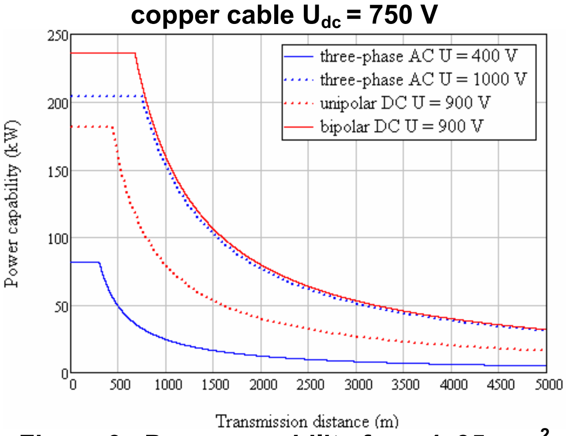

Figure 9. Power capability for a 4x35 mm^2 copper cable U_{dc} = 900 V

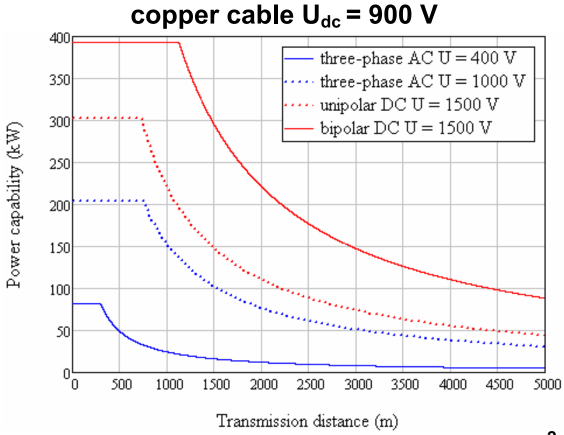

Figure 10. Power capability for a 4x35 mm^2 copper cable U_{dc} = 1500 V

6. Conclusions

Even if the LVDC distribution system is a new concept in energy distribution some consideration regarding the reconfiguration of cables used in AC systems witch enable their usage in DC systems are presented. Investigations were carried out in respect of power capability and transmission distance for cables used in AC and DC systems. The theoretical information regarding power capability computation is presented for single-phase and three-phase AC circuits and unipolar and bipolar DC circuits. Based on them the power capability could be presented in graphical representations as a function of transmission distance. For the investigated conductors the predictable results were presented: power capability of a cable used in a unipolar DC circuit is greater then of a single-phase AC circuit due to the power factor witch in DC does not interfere. Interesting results reveled for cables. As it can be seen in the graphical representations power capability of reconfigured cables used in DC bipolar circuits is greater then of three-phase AC circuits for the same voltage level (400 V). If the DC voltage level increases (750 V, 900 V and 1500 V) the power capability increases, and it is much greater then the three-phase AC circuits even for the unipolar DC circuit.

Through the reconfigured AC lines used in a DC system, a higher transmission power and transmission distance can be achieved.

7. References

[1] W.D. Reeve, *DC Power System Design for Telecommunications*, IEEE Press, Piscataway, NJ, 2007

[2] D. Nilsson, *DC Distribution Systems*, Thesis for Degree of Licentiate of Engineering, Chalmers University of Technology, Goteborg, Sweden, 2005

[3] C.O. Gecan, M. Chindriş, G.V. Pop, *Aspects regarding DC Distribution Systems*, in proceedings of Conference of Energy Engineering – Clean and Available Energy CIE 2009, 4-5 June 2009, Oradea, Romania, pp.226-231.

[4] T. Kaipia, P. Salonen, J. Lassila, and J. Partanen, *Possibilities of the Low Voltage DC Distribution Systems*, Stockholm, 2006,http://www.lut.fi/fi/technology/lutenergy/electrical_engineering/research/electricitymarkets/research/networkbusiness/Documents/DCdistribution_Kaipia.pdf.

[5] *NP I 7-02 - Normativ pentru proiectarea şi executarea instalaţiilor electrice cu tensiuni până la 1000 v c.a. şi 1500 v c.c.*, aprobat prin ordin M.L.P.T.L. nr. 1606/02.11.2001

[6] European Commission, *Low Voltage Directive, LVD 2006/95/EC*, European Union Directive, Brussels 2006.