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Mathematical Model of Residual Discharge of Capacitive Electrical Equipment through the Human Body in Regard with Safety

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Abstract: The paper inhere presents an approach for estimation the absorbed energy and the transient discharge current trough the human body in case of electrocution as a result of a sudden contact with switched off capacitive electrical equipment, having residual charge, such as power cables, capacitor banks etc. The derived here mathematical expressions could be used for safety analysis of low- and medium-voltage power cables in regard with the stored by them residual charge in dependence with their length, voltage rating and type.

Keywords: Electrical Safety, Residual Charge, Capacitive Electrical Equipment, Power Cables Capacitance, Discharge Current trough Human Body.

I. INTRODUCTION

Electrical power equipment, such as power cables and capacitor banks, due to their significant capacitance have the property to store proportionally electrical energy after they have been de-energized. Such stored charges and the associated with them residual voltage can lead to human electrocution as a result of a sudden contact. Most of the Bulgarian regulations [1], international standards [4-7] and scientific community publications [10, 11] define organizational and technical sets of measures to neutralize residual charges in de-energized capacitive electrical power equipment. Other regulations [7, 8] discusses the phenomenon of (Electrostatic Discharge) ESD of charged informational and power cables to sensitive electronic and electrical equipment, causing damage or EMC problems.

It is obvious that in case of electrocution due to discharge of a de-energized power cable through the human body, the flowing transient current and the time to decay will be indicative in regard with the rate of shock hazard. The derived mathematical expressions bellow clarifies the dependence of the transient current through the human body on the residual voltage of the cable, cable capacitances to ground and between the leads, cable series resistance and the body resistance.

II. EQUIVALEN SCHEME OF DE-ENERGIZED CABLE WITH RESIDUAL CHARGE AND A SUDAN CONTACT OF A HUMAN TO ONE OF THE PHASE LEADS

The following Fig. 1 shows a real situation of a human touching the phase lead of a de-energized three-phase power cable, which has residual line-to-line voltage U . The power cable could be considered as a capacitor, that has been powered off and between its leads has remained a residual voltage U . The residual voltage U will depend on the following factors:

- Magnitude of the power supply voltage;
- Type of power supply(AC or DC);
- Geometrical dimensions, construction and length of the cable.

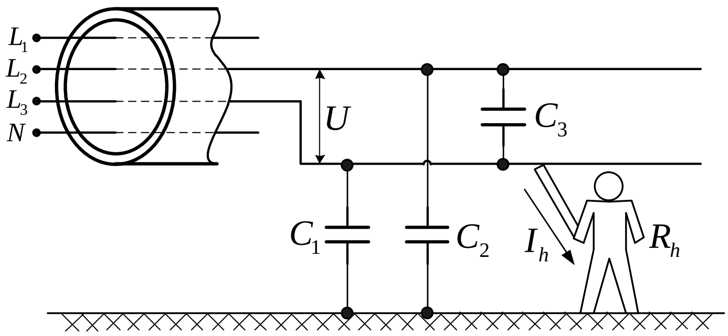

Fig. 1 Contact of human to the phase conductor of a de-energized cable with residual voltage between the leads U

The insulation resistances R_1 and R_2 have been disregarded in Fig. 1 since their values are much bigger than the resistance of the human body (it is assumed that human body has a standard resistance in the range 800 – 1000 Ω). In case of an insulation fault, both resistances R_1 and R_2 will have small values, the residual charge of the cable will be neutralized and the residual voltage will be 0 V.
The model from Fig. 1 could be transformed equivalently as shown in Fig. 2. This will make the analysis easier and will help for further simplifications.

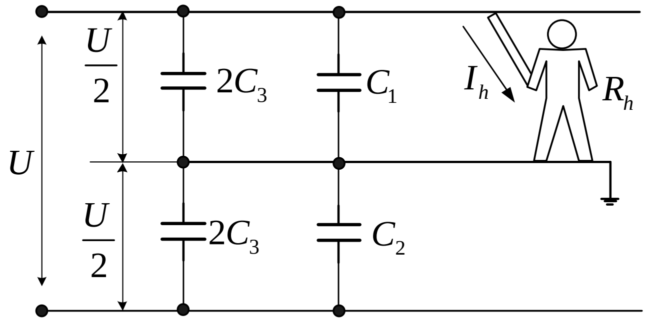

Fig. 2 Equivalent wiring diagram

Analysing Fig. 2, the following simplifications are made: The capacitor C_3 has been substituted by two capacitors in series with capacitances $2C_3$ each. In that way the equivalent capacitance of these two capacitors is C_3 .
In order to calculate the current flowing through the human body with resistance R_h (Fig. 2), it is obvious that we can take into consideration only the upper part of the equivalent circuit. Having in mind that capacitors C_1 and $2C_3$ are connected in parallel, the final equivalent scheme in Fig. 3 has been obtained.

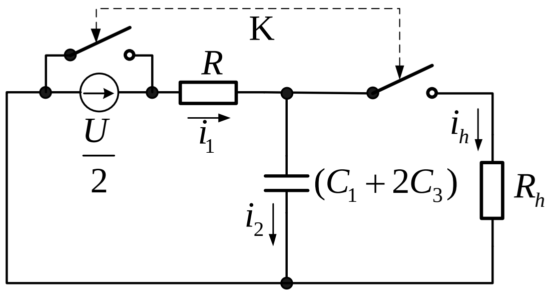

Fig. 3 Obtained equivalent circuit, where R is the series resistance of the cable conductor

III. ANALYTHICAL EXPRESSION FOR CALCULATING THE TRANSIENT CURRENT TROUGH THE HUMAN BODY IN CASE OF CONTACT WITH DE-ENERGIZED CABLE WITH RESIDUAL CHARGE

For the need of the analyses it is assumed that the cable has been charged to the amplitude of the AC rated voltage (the worst case) or the rated voltage of the system (in case of a DC supply). In that case the initial independent condition for the voltage of the capacitor (C_1+2C_3) before the discharge through the human body will be:

$$u_C(0)=\frac{U}{2} \tag{1}$$

The current trough the human body will have only a transient component (the steady-state current is 0). The system of equations governing the discharge process will be:

$$\left|\begin{array}{l} -i_1+i_2+i_h=0 \\ R\cdot i_1+\dfrac{1}{(C_1+2C_3)}\displaystyle\int_0^t i_2dt+u_C(0)=\dfrac{U}{2} \\ \dfrac{1}{(C_1+2C_3)}\displaystyle\int_0^t i_2dt+u_C(0)-i_h\cdot R_h=0 \end{array}\right. \tag{2}$$

By solving the system (2) an expression have been found in regard with the discharge current flowing through the human body:

$$i_h(t) = \frac{U}{2R_h} \cdot e^{-\frac{(R_h+R)}{R \cdot R_h (C_1+2C_3)} \cdot t} \qquad (3)$$

The residual charge of the cable will be discharged through the human body for a time $\Delta t = (3 \div 4) \cdot \tau$, where τ is the time constant of the circuit. The time constant is:

$$\tau = \frac{R \cdot R_h (C_1 + 2C_3)}{(R_h + R)}, \text{ s} \qquad (4)$$

The decent of the discharge current trough the human body against time has been presented graphically in fig. 4 for a cable with residual voltage of 400 V, cable capacitances $C_1 = 20\ \mu$F; $C_2 = 10\ \mu$F, phase conductor series resistance $R = 0,5\ \Omega$ and resistance of the human body model $R_h = 1000\ \Omega$.

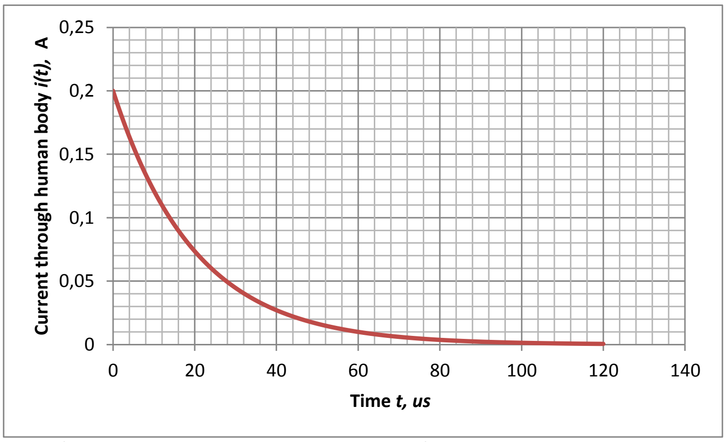

Fig. 4 Transient current flowing through the human body in case of contact with de-energized cable with residual charge

IV. CONCLUSION

The following conclusions could be made in regard with the expressions (3) and (4):

- The maximum value of the discharge current trough the human body i_h depends on the residual voltage of the cable U and the resistance of the human body R_h;
- The duration of the transient process depends on the time constant of the equivalent circuit and respectively on the values of the cable capacitances C_1, C_2 and the resistances R_h and R;
- Expression (3) is intended to be used in future investigations to determine the maximum allowable length of residually charged cables of different kinds and with different voltage ratings in regard with electrical safety;
- Cable parameters C_1, C_2 and R can be calculated for the generally used types of medium- and low-voltage power cables using the data-sheets of the respective cable manufacturers.

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