ATP simulation of switching transients in ASD systems including cable modeling and algorithm for damping overvoltage problems.

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ABSTRACT- This paper describes methods used to analyze and solve problems associated with Adjustable Speed Drives (ASD). Overvoltage mitigation techniques are evaluated. The complete system, including power cables and induction motor is simulated using the ATP version of the Electromagnetic Transient Program (EMTP). A new method to reduce overvoltages, due to switching of the IGBT and cable reflections, is proposed. Comparisons between the new method and other traditional methods, likes filtering, are included.

Keywords - ASD's, ATP-EMTP, IGBT, power cable, PWM drives, transients.

I. INTRODUCTION:

In ASD systems, particularly systems with long cables between drives and motors, overvoltage problems have been reported [6]. Due to the high switching speed of the Insulate Gate Bipolar Transistor (IGBT), fast transients are generated in drives. These switching pulses propagate along the cable and they are reflected at motor terminals. Pulse reflection produces overvoltages, typically 2pu or more.

To simulate the problem, EMTP program was preferred respect to other digital tools by two reasons. First, EMTP has lower CPU times because IGBT's are simulated as switches connected to current sources. They are included in the general solution of the system. Other programs use compensation methods, in combination with non linear solution methods. Representation of insulated gate bipolar transistor (IGBT's) for EMTP was developed in reference [1]. The second reason is the extensive modeling capability of lines and cables that EMTP includes, likes Ametani [2] , Marti [3], Semlyen[7] and Lee [4] models.

In order to reduce the transient generated by fast switches, a feedback control, made with a Delta Hysteresis Block is included in de PWM control. Thus, the pulse is modulated with two objectives, control the motor speed and reduce the transient overvoltage.

Three phase power cables, installed between inverters and motors of ASD systems, have been mostly ignored in computing transient performance of the system. They play an important role in the transient phenomena and must be included in studies of the system (see Fig. 2-5). These studies are necessary to accomplish with the new regulations of electromagnetic compatibility and to obtain reliable equipment. Unlike overhead power lines, cables are geometrically more compact. Distances among conductors are comparable with the dimensions of the conductors. Frequently, the conductors and cables have non-coaxial geometries, thereby close-form solutions are difficult or almost impossible. Proximity effect is no longer negligible in cables, as it is in overhead lines. Because of Proximity and Skin effects, cables have very important frequency dependent parameter characteristics. Mathematical models, which include these characteristics, are needed for cables in the transient analysis. This is an important reason to justify the analysis of ASD motors overvoltage using EMTP.

In the dynamics of ASD's applications, there are three frequency ranges involved in overvoltage problems [5-9-10] :

- The base operating frequency of the ac power being delivered to the motor: This frequency does not change during operation. It is selected in the range of 50 to 100 Hz, depending on applications.
- The frequency of the PWM carrier: It is selected between 800 – 3500 Hz in most ASD systems.
- The effective frequency derived from the switching time of the PWM voltage pulses: This frequency is approximately equal to the inverse of the pulse rise/fall time. For smaller IGBT's , it can reach a bandwidth of 100 KHz to 5 MHz.

Combining these three frequency ranges, the total frequency spectrum is between near dc to 5MHz. Accurate simulation of ASD transient behavior requires a model, capable to consider this frequency bandwidth.

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To simulate the behavior of the Drive - Cable - Motor system, the model of fig. 1 was developed.

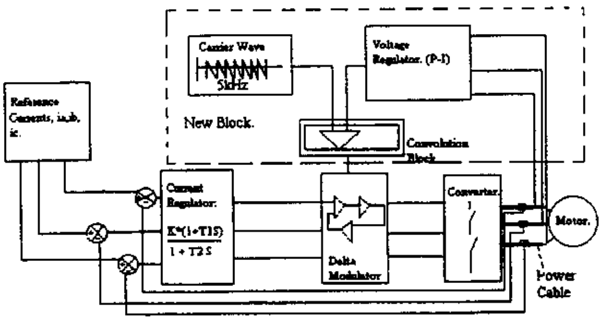

Figure 1: Block Diagram of the System.

II. CABLE MODELING:

The transient behavior of cables has been documented in detail in many textbooks and papers [2-3-4-8]. ATP includes routines to compute parameters and to simulate cable transients[13].

Series impedance and shunt susceptance matrices are computed from cable parameter routines, using multi-port theory. Boundary conditions like cables transposition or earth setting can be included. Finally, two options for transient simulation are possible lumped-parameter models (cascade π circuits) or distributed parameters models.

Cascade π-sections computed at a given frequency [4] are computationally fast. Although this model does not include frequency dependent parameters, a frequency dependent behavior is achieved by the cascade connections.

However, lumped circuits are not a good representation of distributed parameter effects. If the particular problem includes high frequencies, a great number of π circuits must be used. Numerical error can appear due to big differences of the π parameters respect to the network.

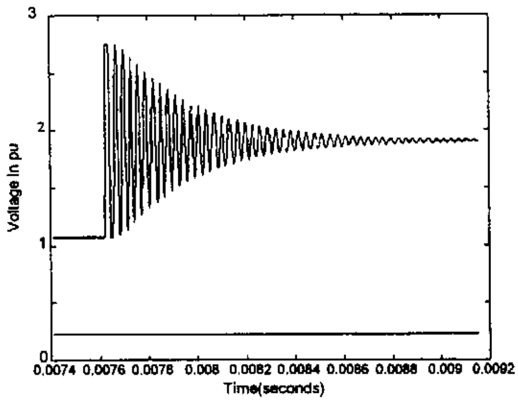

Figure 2. *Natural oscillation for a power cable of 200 meter length.*

In distributed parameter models, the frequency dependence and the distributed effects of the cable parameters are taken into account [3,4]. However, the validity of these models is restricted because modal transformation matrices are assumed to be real and constant.

In this work, J.Marti's routine was selected to carry out the simulations. The transformation matrices were computed at the critical frequency of the transient. It yields more critical transient that Semlyen's model. Similar results using cascade π sections were obtained.

III. EVALUATION OF MITIGATION METHODS:

There are many mitigation techniques which might be employed to solve the overvoltage problem. In this work l, effectiveness of three solutions methods were explored[14]:

- A capacitor in parallel with the motor, at motor terminals. It works as a passive low pass filter.
- A line RLC filter at the cable connection. It works as low pass filter in the output of PWM drive.
- A new control block, called Overvoltage Control Block (OCB). It is included in the delta modulators (the proposed PWM strategy).

The major disadvantages of passive filtering are: they are expensive, they require extra mounting space, and they introduce extra losses in the system. Additionally, filters need to be tuned with the system.

In fig. 3 voltage at motor terminals is shown. The simulation does not include a power cable. The effect of PWM action without switching transient can be seen. Voltages, including cables of 500 and 1000 meters are shown in fig. 4 and 5. Sharp peaks from cable and motor interaction are very important.

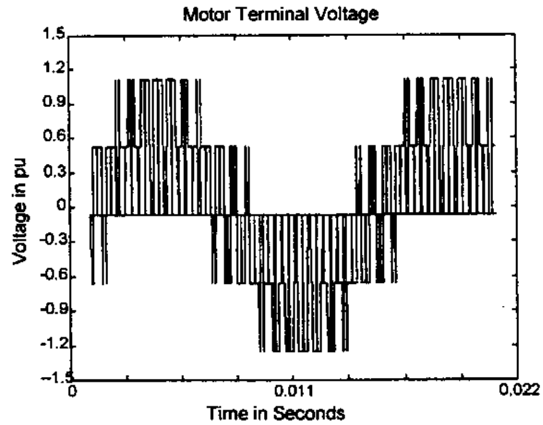

Figure 3. *ASD System without consider power cable model*

III A. OUTPUT LINE CAPACITORS:

Output line capacitor is a low-cost method of conditioning the inverter output voltage. It reduces the harmonics injected to the motor, and there after it will reduce the dv/dt seen at motor terminals. Lumped capacitor joined to motor inductance introduces oscillations and a voltage overshooting. They are of lower frequencies than pulses. They increase first peak voltage and distort pulse top form. Fig. 6 shows voltage at motor terminals using this mitigation method.

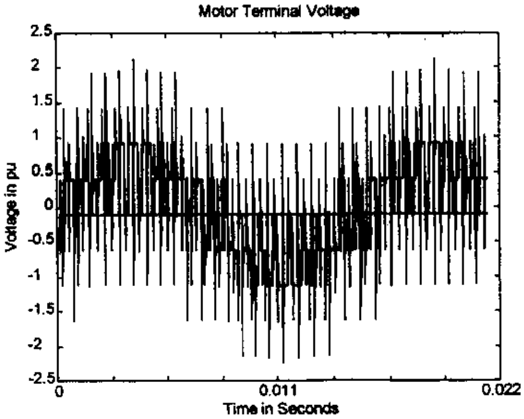

Figure 4. *Simulation with 500 meters of power cable.*

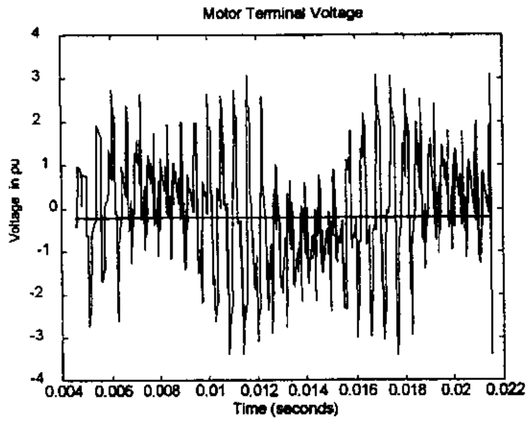

Figure 5. *Simulation with 1000 meters of power cable.*

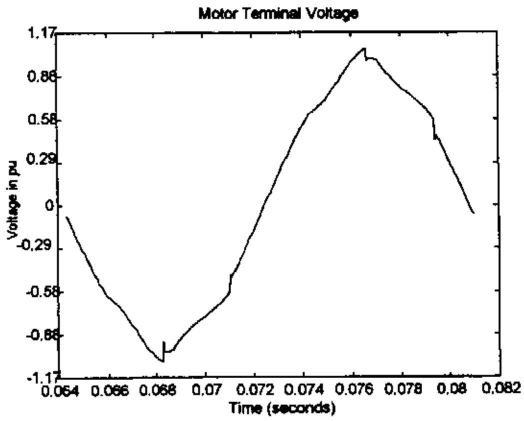

Figure 6. *Mitigation of transient overvoltage Capacitor bank at motor terminals.*

III B. RLC FILTER:

This filter uses output inductors, shunt capacitors and damping resistors (when necessary) to form a conventional low-pass filter. High-frequency harmonic currents are short-circuit. Lower-frequency fundamental current pass to the motor.

The result is a near sinusoidal wave being applied to the motor in terms of both, voltage and current. It can be seen in Fig. 7.

It is important to remark that:

- No transient overvoltage appear at the terminal of the motor.
- There is lower thermal stress in the dielectric winding.
- There are more losses in the system.

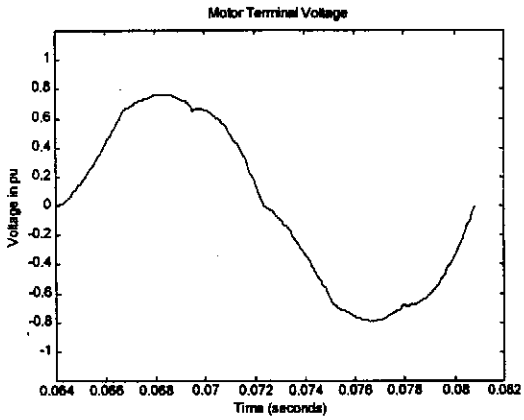

Figure 7. *Mitigation of transient overvoltage. RLC at inverter AC output..*

III C. OVERVOLTAGE CONTROL BLOCK IN DELTA MODULATORS:

Damping of switching pulses can be obtained by control actions as it is shown in fig. 8. A Double Pulse Effect is used to damp the overvoltage at ASD terminals. Consequently further reflections of the sharp peaks are damped. A first pulse is injected following the speed control. It is reflected from the motor terminals to the ASD terminals. The second pulse is injected, following the OBC control at the same time that the reflected first pulse arrive at the ASD. A cancellation effect between both pulses damps the transient.

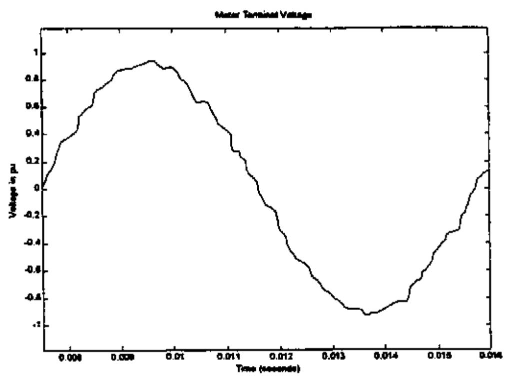

Figure 8. *Mitigation of transient overvoltage. Overvoltage Control Block.*

The configurations of the system, the length of the cable and the load of the motor, introduce modifications of the peak transient. The control adapts automatically the system to different cable configurations or motor loads by controlling peaks voltages. Cable connections between motor and inverter are automatically adapted.

The control used in the simulations is based in two main theories. Spiral Vector Control is used in the speed loop control. Instantaneous Power Analysis is used in the Overvoltage Control Block.

Fig. 9 and 10 show details of the Converter and Inverter. The basic diagram of the overvoltage control block (OCB) is included. Delta modulation is used in both, converter and inverter.

Spiral Vector Control:

In the last two decades, Spiral Vector Control has been successfully used to control ASD. It has shown to be a robust and efficient technique. This method is applied in both, synchronous and induction machines. It works using the well-known d-q transformation (Park or Blondel transformation). Variables are changed to a coordinate reference frame, rotating at rotor speed. Now all the variables are transformed to dc equivalent magnitudes.

Commonly, in control device, the main component of air gap flux is used. Additionally, magnetic saturation is considered constant. Reference [5] shows that these assumptions do not introduce important errors in the control loop.

Under the constant saturation hypothesis, d and q axes are uncoupled. That's mean, there is not mutual inductance between both axes. No Cross Magnetizing Effects are included. Due to the flux can not change abruptly (Constant Flux Principle), the projections of main flux over each axis are considered constant in the control loop. Thus main flux and mutual inductance change slowly. From the control point of view it is more important to use a fast solution. It permits compute variables faster than more accurate models.

Instantaneous Power Theory (IPT):

Due to the topological similitude between the ASD systems and active filter devices, IPT is employed. The instantaneous power is transformed to a plain whose axes are rotating at the network nominal frequency [15]. With this transformation instantaneous power in phase components $p(a,b,c)$ is transformed to real power $p(\alpha,\beta,0)$ and imaginary power $q(\alpha,\beta,0)$ in pq theory. α, β and 0 are coordinates over real, imaginary and zero sequence axes.

Under steady state condition p and q include constant terms only in p-q components. If a transients appear, the p-q components include oscillatory terms. The control action try to minimize the oscillatory components.

$$p=\overline{p}+\widetilde{p}; \qquad q=\overline{q}+\widetilde{q} \qquad (1)$$

Where:

p = Instantaneous real power.

$\overline{p}$ = Instantaneous average real power.

$\widetilde{p}$ = Instantaneous oscillatory real power.

q = Instantaneous imaginary power.

$\overline{q}$ = Instantaneous average imaginary power.

$\widetilde{q}$ = Instantaneous oscillatory imaginary power

Converter Step:

Fig. 9 shows one part of the converter. It is adapted to work as a Series Active Filter (SAF). It is composed by a single-phase voltage source inverter (PWM-VSI-1ϕ). A high-pass filter connected to the DC terminals is used to measure the voltage ripple. SAF control produce a voltage equal to the measured ripple, but with inverted sign [11-14]. This signal is fed to the delta modulator in order to cancel high frequency harmonics. A small passive filter, not shown in Fig. 9, could be included at the AC side to damp switching harmonics.

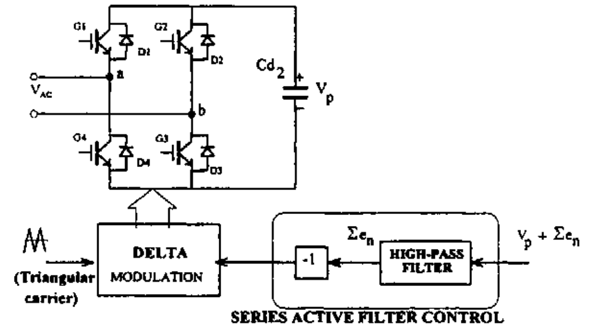

Figure 9. *Converter*

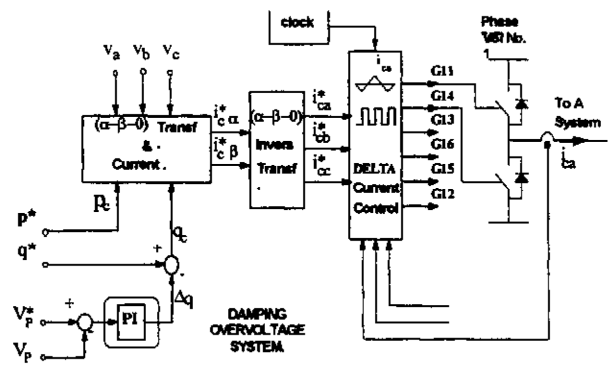

Figure 10: *Overvoltage Control Block and Delta Modulation of the inverter.*

The control algorithm:

The control algorithm of the proposed block is based on the concepts of the instantaneous p-q power theory [11,12]. Magnitudes of Fig. 10 are (asterisk indicates reference values):

V_p= DC voltage.

V_p^*= reference DC voltage.

p^* = Nominal active power reference of the motor.

q^* = Nominal reactive power reference of the motor.

V_a, V_b, V_c = feedback AC voltages.

P_c = Compensation active power.

q_c = Compensation reactive power.

$i_{c\alpha}, i_{c\beta}$ = compensation currents in α- β components.

$i^*_{ca}, i^*_{cb}, i^*_{cc}$ = compensation currents in phase components

Ideally, the proposed Series Damping system is designed to generate or absorb only reactive power.
Thus:

$$p_c = 0 \quad \text{and} \quad q_c = \tilde{q} \qquad (2)$$

If the VSI is controlled to compensate for a given real power p_c (W) and imaginary power q_c (Var) the reference compensation currents are given in (a-b-c) coordinates by:

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_c \\ q_c \end{bmatrix} \qquad (3)$$

In relation with Fig. 10, q^* is the reference imaginary power that has to be injected or absorbed by the compensator. The inverters output currents track their references (i^*_{ca}, i^*_{cb} and i^*_{cc}) with a very small amplitude error or phase delay. The instantaneous reactive power qc is used to keep the converter dc voltage (VP) at a given value. The dc voltage error is fed to a PI-controller which output (Δq) is added to the instantaneous reactive power reference signal (q*).

Fig. 11 summarizes the inverter switching action. Speed and OCB are shown. Each block introduces a pulse signal following its control strategy. Finally, the convolution of both signals yields pulses feed to the IGBT.

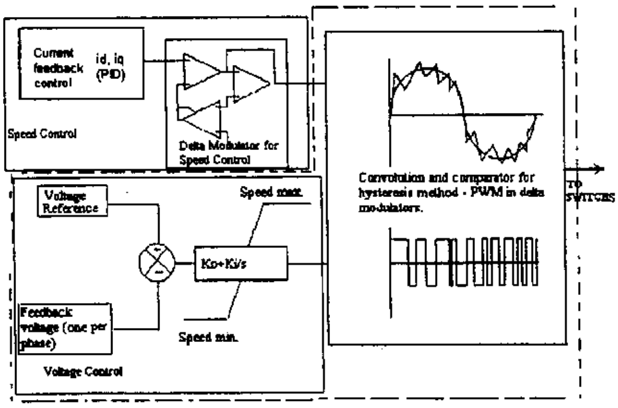

Figure 11. Switching signal block.

The inverter Switching Signal Block works with Delta Modulation principle. It encloses an additional Proportional Integral Control (PI) used to follow the voltage control.

Static Speed Limits are included in the PI of the OCB control. Their function is to avoid deterioration in the control of the speed. The Pulse Overvoltage Control does not work during the speed transients due to a delay in the transfer function.

Thus, for a zero speed error and considering independence between current and voltage regulation, the transfer function of the Overvoltage Control Block is:

$$C_{(s)} = k_p + \frac{K_i}{s} \qquad (4)$$

Fig. 12 and 13 show the speed transient during the motor start. Both conditions, with and without OCB are simulated. Although the speed regulation with OCB works properly, it takes influence in the velocity control.

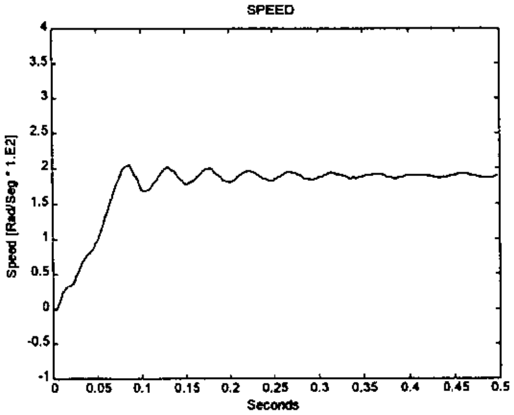

***Figure12**: Speed transient during motor start. Traditional control without voltage mitigation method.*

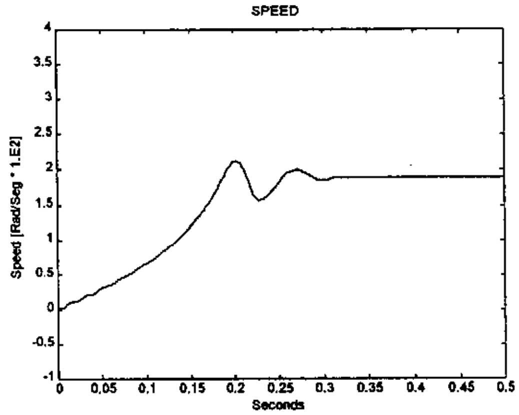

***Figure 13**: Speed transient during motor start. Overvoltage Control Block Present.*

IV. CONCLUSIONS:

In this paper, two important aspects of ASD systems were investigated:

• Inclusion of cable models in simulations was analyzed. Different cable models were tested. Good agreements were obtained between different cable models .

• Three mitigation techniques were evaluated, two traditional methods and a new method, proposed by the authors. The Overvoltage Control Block (the proposed method) shows good results in simulations. This method is cheaper than traditional ones and it is automatically adapted to different cable configurations and motor loads.

• The OCB requires time to control overvoltage. That means, the first transient peak after a change in the system can not be controlled. However, dielectric strength is reduced by damping subsequent peaks. Further research is necessary to study influence of the OCB and its parameters in speed control.

V. APPENDIX

The parameters used in the simulations are as follows:

Motor Data:

Rated output power	11 kW.
Rated voltage	340 V.
Rated frequency	50 Hz.
Poles	4.
Rated speed	1430 rpm.
Max. Speed	3000 rpm.
Rated power factor	0.87
Rated efficiency	85%
Inertia J	0.15 N. m/s^2
Stator resistance	0.371 Ω.
Rotor resistance	0.415 Ω
Stator leakage inductance	2.72 mH.
Rotor leakage inductance	2.72 mH.
Mutual inductance	84.23 mH.

Cable data:

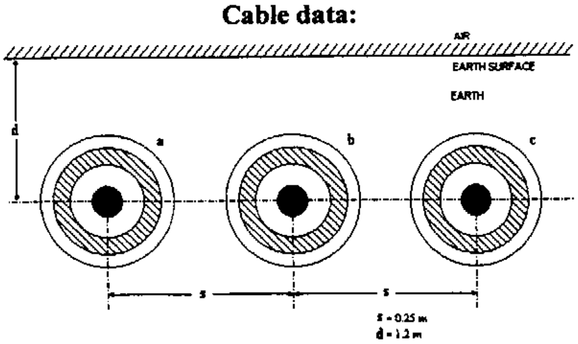

***Figure 14**. Cable configuration*

Conductor radius	2.34 cm.
Sheath inner radius	3.85 cm.
Sheath outer radius	4.13 cm.
Relative permittivity of main insulator	3.5
Relative permitivity of cable covering	8.0
Resistivity of copper conductor	$1.7*10^{-7}$ Ω/ m.
Resistivity of lead sheaths	$2.1*10^{-7}$ Ω/ m.
Resistivity of soil	50 Ω/ m.
Cable length	3* 211 m.
Average depth of laying	1.2 m.
Center spacing	0.25 m.

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