Course Project:
Electromagnetic and thermal modelling of an underground power cable line.
General Description

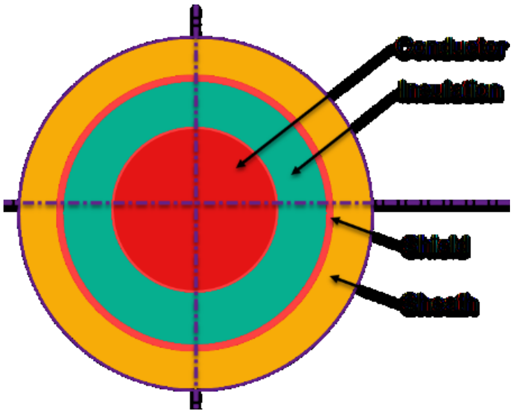
The goal of proposed work is calculating the ampacity of an underground cable power line. The ***ampacity*** (ampere capacity) is the maximum amount of current that a power line can continuously carry while the cable temperature not exceeded the allowed maximal value.

The object of study is a 3-phase power cable line, consisting of three single-core cables. The line is described by the rated voltage, the type of cable, cable formation and the bonding scheme.

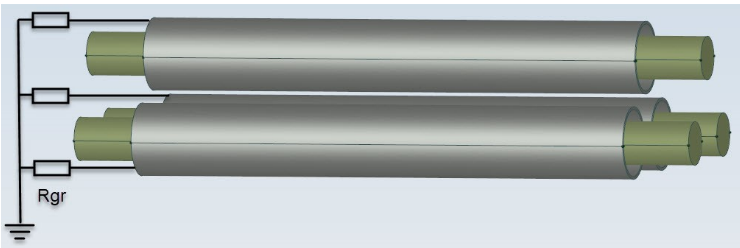
The calculation method is a two-dimensional finite-element simulation of coupled electromagnetic and thermal fields. The solved model gives the temperature of the cable conductor for a given current. It is a direct problem, whereas the project goal is to solve an inverse problem: to find the current that heats the cables to allowable temperature. It is proposed to solve the inverse problem using a small series of the direct problem.s

The given data included:

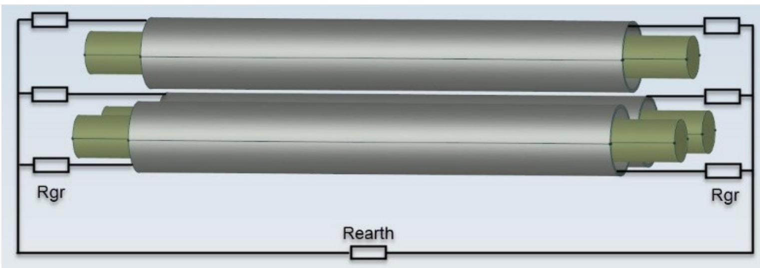
1. The cable design data including:
   - rated voltage
   - rated cross-section area of conductor and shield
   - Cable sizing: outer diameters of the conductor, insulation, electric shield and outer sheath:



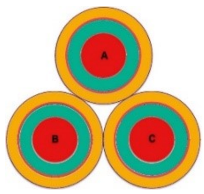
2. Cable shield grounding:
   - One-point grounding, or



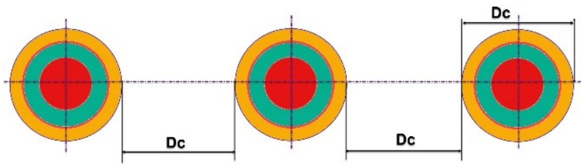
   - Both-ends grounding



3. Cable formation:
   - Touched trefoil formation, or



- Flat formation spaced by outside cable diameter



Project goal

1. For each combination of given data to find the RMS current value I_{rated} at which the most heated cable conductor reaches the temperature of 90 °C. The 3-phase current system is assumed to be symmetric.
2. To estimate the maximum magnetic flux density $\mathbf{B}$ (in μT) above the earth surface at an altitude of 0.5, 1.0 and 1.7 m. Compare the calculated magnetic flux density with maximum allowable value for electric personnel (100 μT) and for civilians (10 or 20 μT).

Simulation

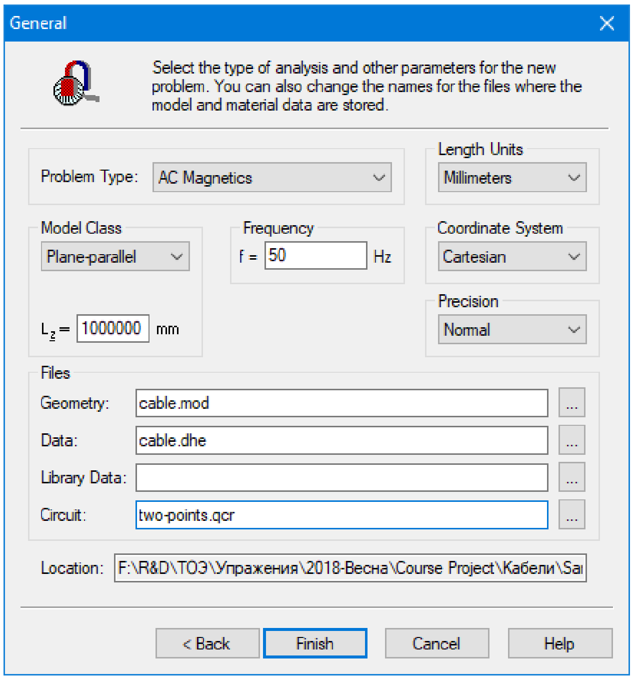
Part 1: Electromagnetic model

For coupled electromagnetic and thermal field simulation one must create the following QuickField files:

- The problem of AC-magnetics;
- The two-dimensional geometric model with a finite-element mesh including the cross-section of 3-phase power line as well as significant amount of surrounding space in both the soil below the cables and the air above it. The same geometry model is using for both electromagnetics and thermal analysis.
- The electric circuit connected to the electromagnetic problem. The circuit contains current sources for cable conductors and the elements connecting cable shields to the ground.
- Physical data files with material properties and boundary conditions.

1. Let's start with creating the electromagnetic problem ***cable_EM.pbm***.

- The problem formulation is **AC magnetic field**.
- The model class: **Plane-parallel** symmetry.
- The length of the model in Z-direction: **1 km**.
- Length units: **millimeters**.
- The connected electric circuit: ***two-ends.qcr*** or ***one-point.qcr*** depending on the cable shield grounding option.

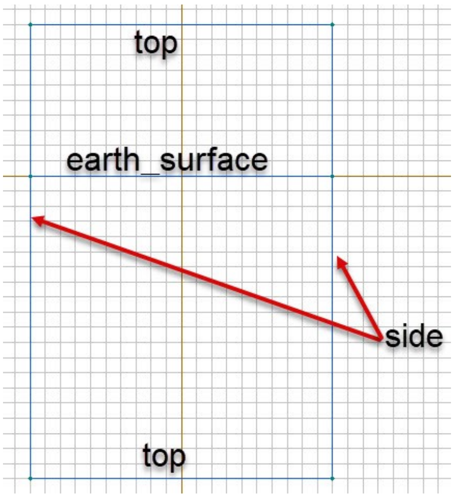


2. Next step is creating the geometry model. Start creating with two rectangles representing the soil and the air surrounding the cables. The width and height of the rectangles should enough so that electromagnetic field and the perturbation of the thermal field at the boundaries were small enough.

Reasonable sizes: the total width of 20 m, the height 10 m, the depth 20 m.

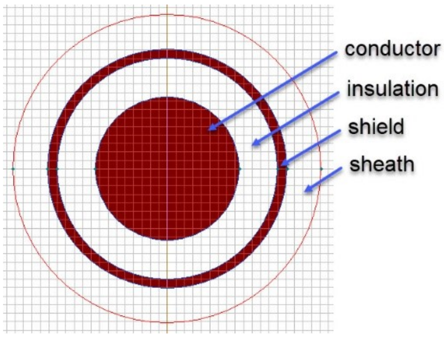
The grid size on the sketch is 1 m.

We must label the **top**, the **bottom** and the **side** edges for assigning boundary condition. Also, the **earth_surface** should be labeled for thermal model.



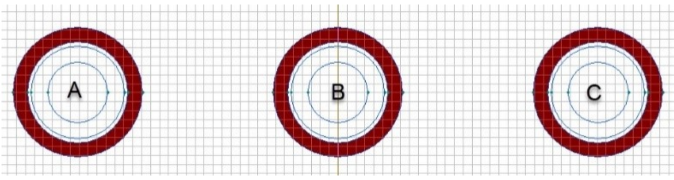
3. Now add to the model the cross-section of one cable, for example the phase A.

The cable line is buried at the depth of $1\ m$.
(the coordinates of the center of the cable A are $(0; -1000)\ mm$

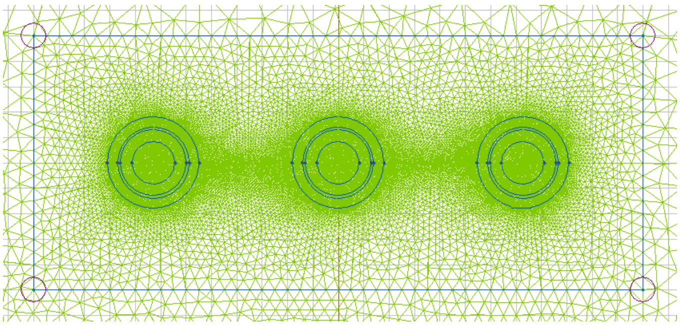


4. We build the two other cables B and C by duplicating the cable A.
   Please note that the conducting blocks of different cables shod be labeled with different labels, for example A, B, C for the conductors, and Ashield, Bshield, Cshield for the shields.

Non-conductive blocks of different cables may be labeled with the same label since they are not included to the electric circuit.



5. Make sure that all the blocks in the model are correctly labeled. Then it's time to build the finite element mesh and take care of its optimal density.
   A good estimate of the optimum mesh density is 1 mm inside the cables and 200…400 mm on the far boundaries.
   You may consider encircling the cable zone with a circle or rectangle only to better control the mesh density.



6. Define the material property of all blocks in the model. For non-conductive materials they are: the relative permeability $\mu=1$, electric conductivity $\sigma=0$.

The electrical and thermal conductivity of the conductor and the shield is not equal to the conductivity of material from which they are made it (copper or aluminum). This is since we used a simplified geometry model in which the area of the conductor and the shield is larger than the rated cross-section area.

The electric conductivity should be recalculated in inverse proportion to the ratio of the model and real cross-sectional area:

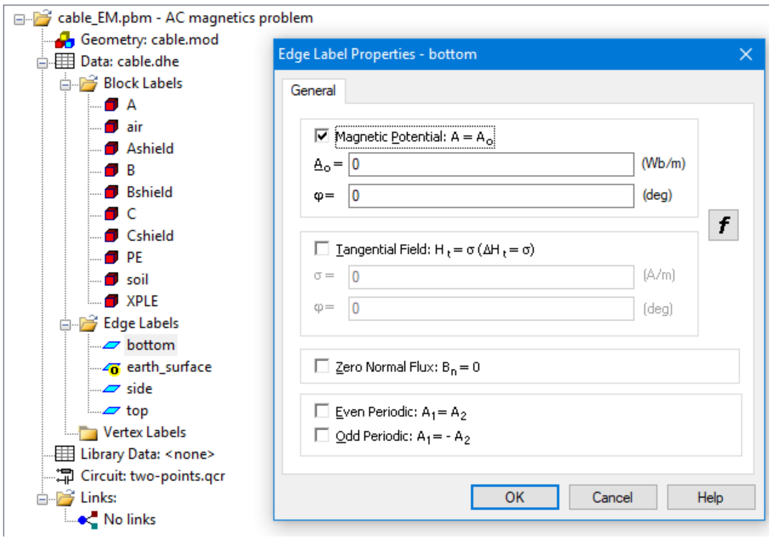
$$\sigma' = \sigma \frac{S_{\text{rated}}}{S_{\text{mod}}},$$

where σ' is electric conductivity in the model, σ – is electric conductivity of the material, S_{mod} – the block's area in the model, S_{rated} – the rated cross-sectional area given by cable manufacturer.

7. The physical sense of the boundary condition on outer boundaries (labels: top, bottom, side) is vanishing magnetic field.

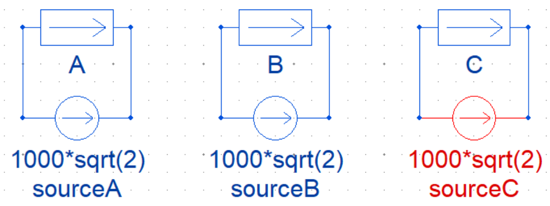
The appropriate boundary condition is zero Dirichlet condition $A=0$. It works well when the boundaries are located far enough from the zone of interest and the currents are balanced.

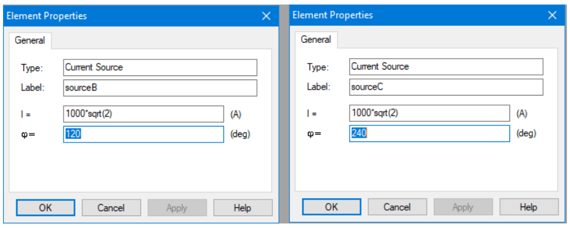
The boundary condition on the edge labeled as *earth_surface* is only needed for thermal analysis. Here we leave it undefined. For doing so one have to open the edge label's property window and press the OK button keeping data fields untouched.



8. The last thing needed is constructing the connected electric circuit. Use the ***Edit Circuit*** in the ***Problem*** menu. At first time QuickField asks whether you want to create a new circuit. Answer *yes* and add to the circuit the labels of all conductive blocks from the model: cable conductors and shields.

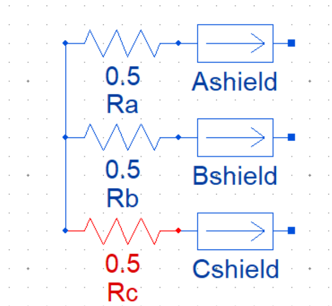
Each conductor is powered by its individual current source. The current magnitudes are equal whereas its phases differ by 120°. At this stage the current magnitude is unknown. We will look it by brute force approach. It is desirable to choose a realistic value as an initial approximation.





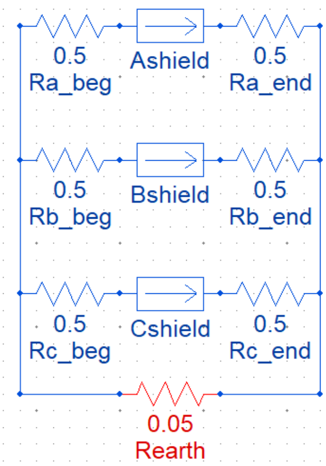
9. The shield grounding circuit depends on the grounding mode.

With one-point grounding the shields are connected to the zero-potential conductor via resistors with small resistance. Second end of each shield is left open.

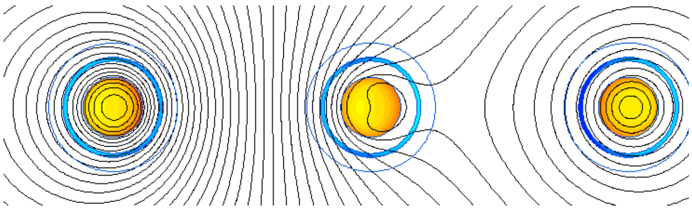


10. With both-sides grounding shield are connected to the earth via resistors by the both ends on the cable. Those resistor are connected to each other via the small valued resistor R_{earth} that model the earth resistance.

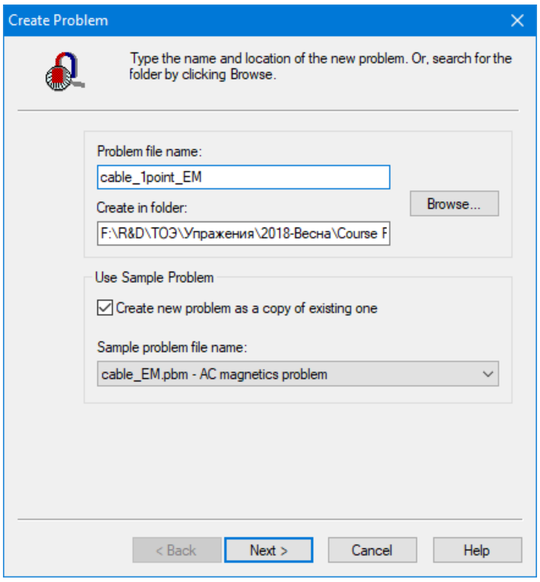
The exact values or grounding resistor are defined by cable line design. In the course project is reasonable to accept $R_{x\_beg} = R_{x\_end} = 0.25\ Ohm$ and $R_{earth} = 0.05\ Ohm$, where x stands for $a,\ b,\ c$.



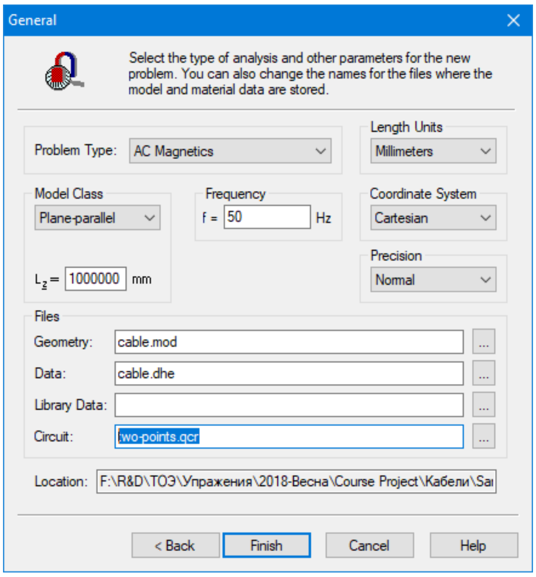
11. Now everything is ready for solving the electromagnetic problem.
    The calculation result gives us the magnetic field picture, current density distribution, and integral values of ohmic losses power (in W per km) in each conductor and shield.



12. Each project must include two variants of calculation: with different cable formation or with different grounding mode. Preparing the model for second calculation is much easier than the first one. One have to create a new QuickFied problem as a copy of existing one and replace the electric circuit, if the grounding mode changed, or the geometry model, if the cable formation varies.



Create a problem as a copy of existing one. Try to choose a self-descriptive name for a new problem.



Keep the same names of all referenced files for the new mode except of one: the electric circuit.

Then press OK, modify the grounding circuit, and solve the second version of electromagneic problem for ohmic lossses.

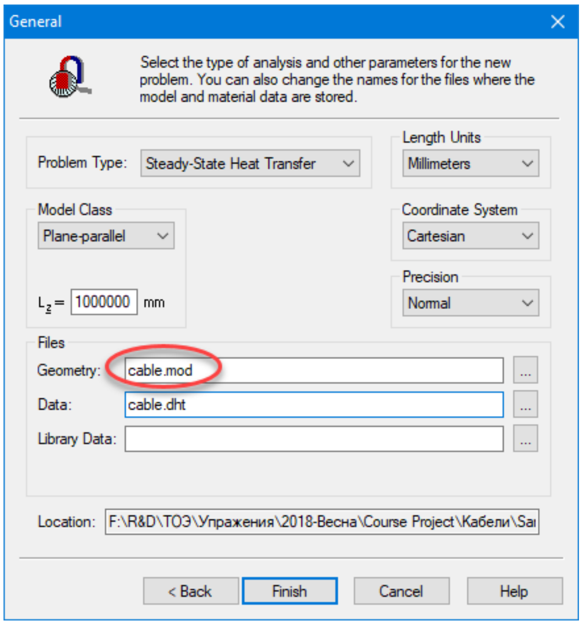
13. Remember the local magnetic field B values in desired ponts:
    $P_1=(500, 0)$; $P_2=(1000, 0)$; $P_3=(1700, 0)$;

$B_1=22\ \mu T$
$B_2=12\ \mu T$
$B_3=6.5\ \mu T$

Part 2: Thermal analysis

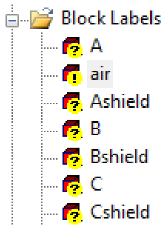
14. Create a new QuickField problem of steady-state heat transfer formulation. The new problem has to refer to the same geometry model as the coupled electromagnetic problem.

It is reasonable to construct a name for the thermal problem by replacing the suffix _EM with _HT (HT stands for heat transfer).



15. Exclude the block ***air*** from the model because the primary heat transfer mechanism in the air is convection, not conduction. To do that one has to open the block property window for the label ***air*** and press OK button keeping everything unchanged.

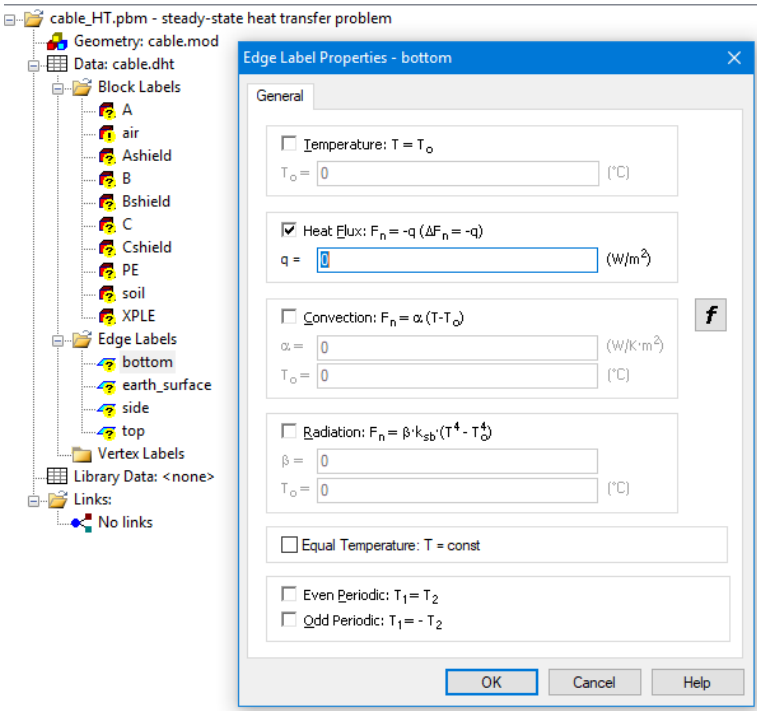
By the same way we exclude the edge labeled as ***top***.



16. Set the boundary condition of thermal insulation (zero Neumann's condition) on the edges ***side*** and ***bottom***.

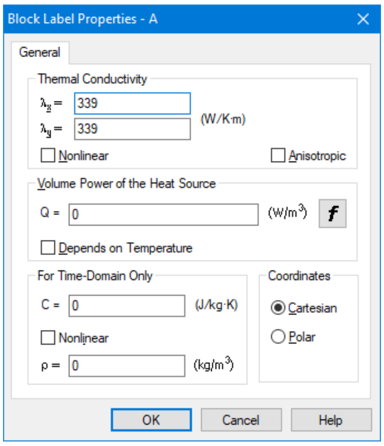
For the ***bottom*** edge, serving as a bottom of the modelling area, also another approach is acceptable: isothermal boundary condition (Dirichlet condition) with the year average soil temperature (usually in range 4 to 10 °C).

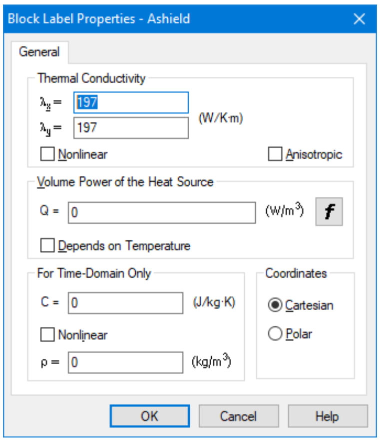
On the **earth_surface** edge we set the convection boundary condition, which is given by two numbers: convection coefficient α and the gas temperature T_0. In the course project is recommended to use the values α=*10 W/(K·m)* and T_0=*20 °C*.



17. Give the thermal conductivity value for each block in the model.

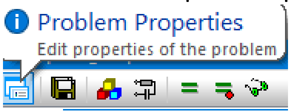
For non-metallic materials the thermal conductivity values are given among other project data. For cable conductors and shields thermal conductivity of copper should be recalculated inversely proportional to the ration of block's area in the model to the rated cross-sectional area given by the manufacturer. This is quite similar to recalculating of electrical conductivity we have done in the p. 6.



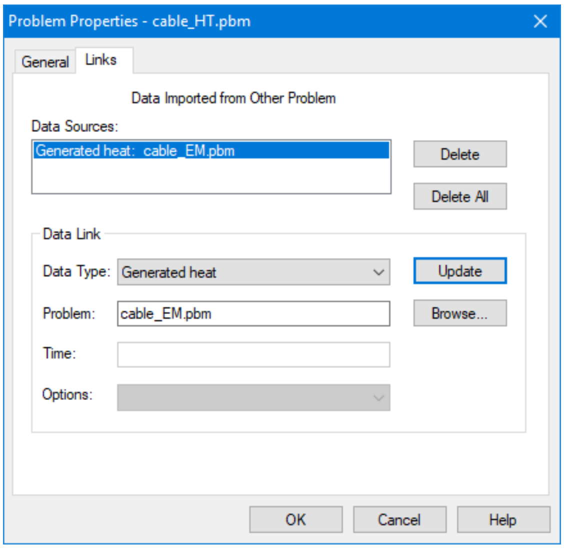


18. Establish the connection link from thermal problem to the electromagnetic one.

To do that one has to open the problem's property window



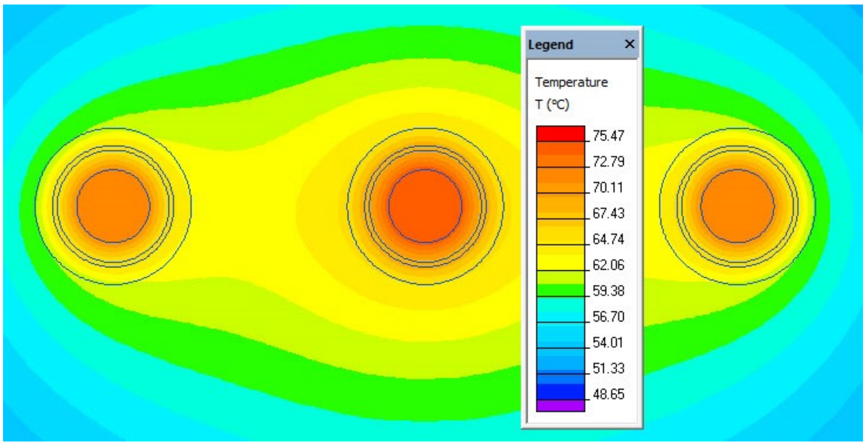
and the ***Links*** tab. Then choose the Data Type for the link (Generated heat), linked problem name (it is the name of electromagnetic problem ***cable_EM.pbm***) and click the **Add** button. QuickField checks the linked problems for compatibility and if everything is good the linked problem appears in the ***Data Source*** list in the upper part of the window.



19. Solving the thermal problem we get the overall picture of the temperature field, including the temperature of cable conductors.

As seen from the color legend, the maximum conductor's temperature is 75.5 °C, that is 14.5 °C less than possible. Further we have to find such amount of current that heats the most heated conductor to 90 °C.

The temperature tolerance for the course work is -1…+0.2 °C.



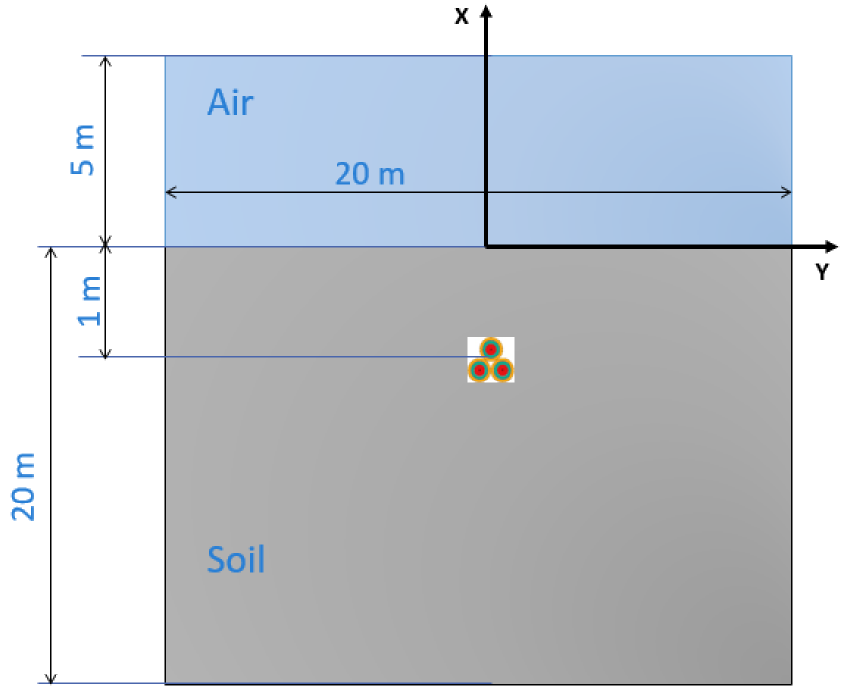
Common Data

Below you find the geometrical and physical data recommended for each project.

Size of the calculation area

The electromagnetic and thermal field around the cables are theoretically infinite. Since QuickField is not able to solve unbounded problem, one has to introduce artificial outer boundary located far enough from the zone of interest. Introducing such boundaries researcher have to prove that its location does not affect significantly on the result's accuracy.

For the course project the following size of the whole model's region is recommended:



Parameter	Value
Depth	*1 m*
Full Width	*20 m*
Full Depth	*20 m*
Air Height	*5 m*

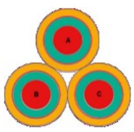
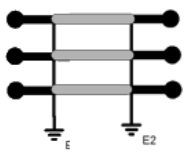
Material properties

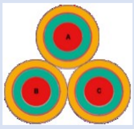
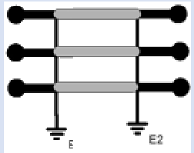
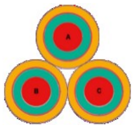
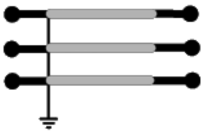
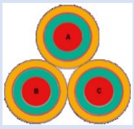
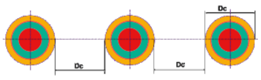
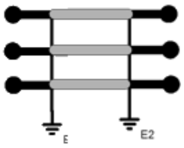
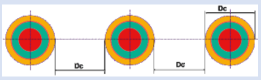
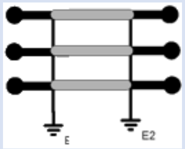
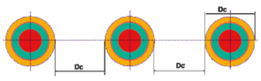
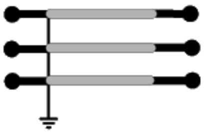
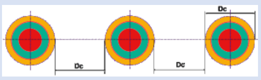
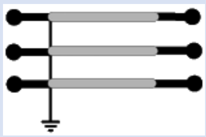
Material	**Relative magnetic permeability**	**Electric conductivity, S/m**	**Thermal conductivity**
Copper	**1**	$56 \cdot 10^6$	385
		(should be recalculated to take into account the real cross-sectional area)	
Cross-linked polyethylene	1	0	0.29
Polyethylene	1	0	0.29
Soil	1	0	0.9
Air	1	0	-

Samples folder

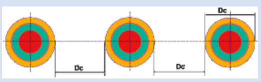
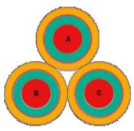
As sample is given the solution of the problem solved during the seminar. The cable data is:

- Voltage class of 35 kV, c
- Cross-sectional area 800/120 mm^2
  (the first number is the conductor's area, the second one is the shield's area).

File name	**File type**	**Geometry**	**Circuit**
	QuickField Problems		
trefoil_EM.pbm	Electromagnetic problem	 trefoil.mod	

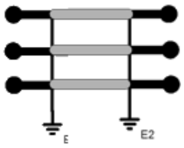
			two-points.qcr
trefoil_HT.pbm	Thermal problem	 trefoil.mod	 two-points.qcr
trefoil_1point_EM.pbm	Electromagnetic problem	 trefoil.mod	 one-point.qcr
trefoil_1point_HT.pbm	Thermal problem	 trefoil.mod	 one-point.qcr
flat_EM.pbm	Electromagnetic problem	 flat.mod	 two-points.qcr
flat_HT.pbm	Thermal problem	 flat.mod	 two-points.qcr
flat_1point_EM.pbm	Electromagnetic problem	 flat.mod	 one-point.qcr
flat_1point_HT.pbm	Thermal problem	 flat.mod	 one-point.qcr

QuickField geometry models

flat.mod			
trefoil.mod			

QuickField physical data and boundary conditions

cable.dhe	QuickField physical data and boundary conditions for AC magnetics analysis

cable.dht	QuickField physical data and boundary conditions for thermal analysis	
	QuickField electric circuit	
one-point.qcr	Circuit for one-point grounding	
two-points.qcr	Circuit for both-ends grounding	

Presenting the results

No formal report required. Simply fill in the table in the bottom of your project data sheet with a few numbers: the power line current and the magnetic field above the cable.

Each student is expected to send me all relevant QuickField files before the final exam.

In the exam you should be able to reproduce and explain the whole sequence of calculation. It is mandatory to demonstrate the ability and skills to build a QuickField model, extract engineering data and explain it.