

Quench Velocity-Based Approach in ANSYS APDL

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Abstract

This report presents the workflow of the quench velocity-based approach implemented in Python and ANSYS APDL. The method was developed to simulate the longitudinal and the turn-to-turn quench propagation in high-order corrector magnets. As illustrated in Fig. 1, there are four steps necessary for conducting the multi-strand analysis of a high-order corrector with the quench velocity-based approach. It is required to conduct a set of magnetic analyses, and a set of 1D quench simulations on simplified numerical models to predict both the quench velocity and the minimum propagation zone in the superconducting coil. When all three initial steps are completed, the quench simulation of the high-order corrector can be performed including the magnet discharge.

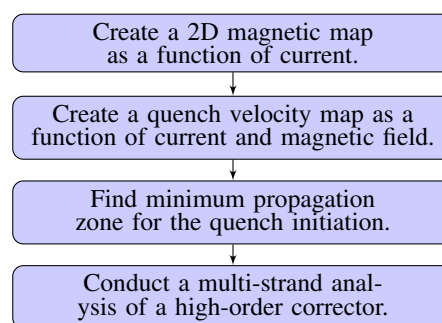


Figure 1: Analysis workflow for the quench analysis of a high-order corrector.

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Chapter 1

Magnetic 2D Analysis

The 2D magnetic field analysis serves for obtaining the map of the magnetic field strength in the coil for different values of operating current. Two tools are used within the studies: ANSYS Workbench and ANSYS APDL (version 2019 R1). The former serves for creating the 2D geometry, and the latter is used to perform the magnetic field simulations. For more information about conducting magnetic field analyses in ANSYS APDL for this particular case, please refer to [1, p. 77-81].

The files required to rerun the simulations are stored in `G:\Workspaces\A\ANSYS_Modelling\1_quench_velocity_modelling\documentation\Test_Simulation_Workflow\1_analysis_magnetic`

1.1 Creating the geometry in ANSYS Workbench

ANSYS Workbench is used because the iron yoke, being a part of the skew quadrupole geometry, was received as an external step file. It is not possible to open a step file in ANSYS APDL. Therefore, the geometry was created in Design Modeller of ANSYS Workbench and exported to ANSYS APDL. The geometry creation steps in ANSYS Workbench are as follows:

1. Import the step file with the iron yoke geometry to Design Modeller. The step file with the iron yoke can be found in `\input\skew_quad_iron_yoke.stp`.
2. Create the remaining part of the 2D high-order corrector geometry in Design Modeller. Figure 1.1 presents the final one-eighth of the skew quadrupole geometry. The geometry is reduced due to available three planes of symmetry in the geometry. It is recommended to mesh the geometry in ANSYS APDL after the exporting procedure. For more explanations why the meshing step is performed in ANSYS APDL rather than in ANSYS Workbench, please, read the private communication with ANSYS support presented in `\additional_help`.

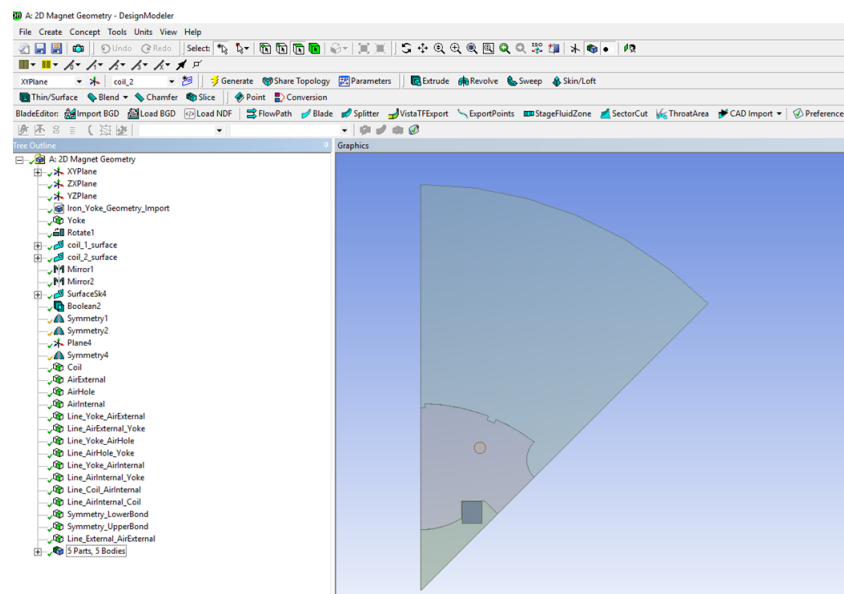


Figure 1.1: Final skew quadrupole geometry in Design Modeller of ANSYS Workbench.

3. As soon as the geometry is prepared in Design Modeller, the user should add the additional module in GUI of ANSYS Workbench, called Mechanical APDL as illustrated in Fig. 1.2. By clicking, “Edit in Mechanical APDL”, the geometry is easily exported to ANSYS APDL, and the ANSYS APDL window should open at this moment.

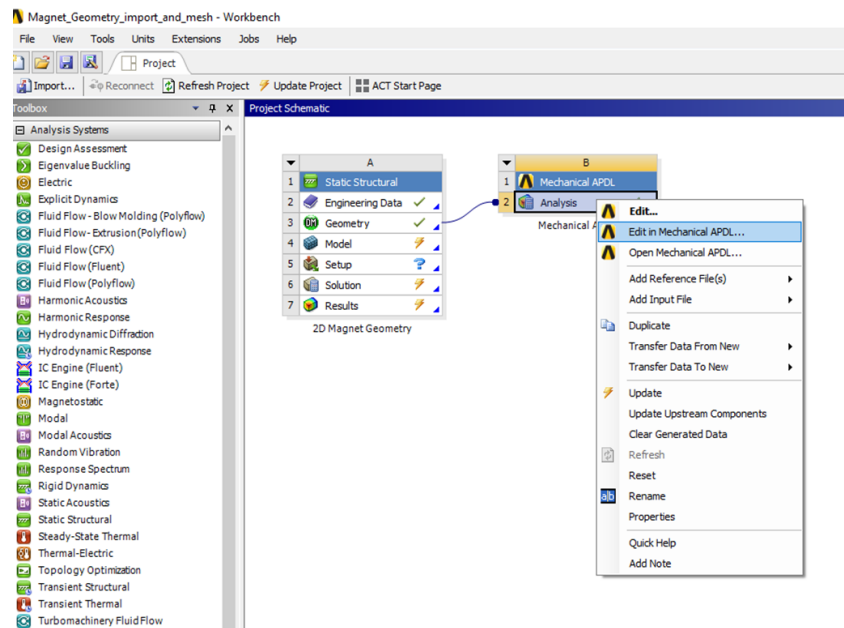


Figure 1.2: Exporting procedure of Workbench geometry to ANSYS APDL.

4. In order to verify whether the geometry is properly exported, the user should type “LPPLOT” command in the command window of ANSYS APDL as shown in Fig. 1.3. If the geometry contour lines appear, the geometry is exported to ANSYS APDL.

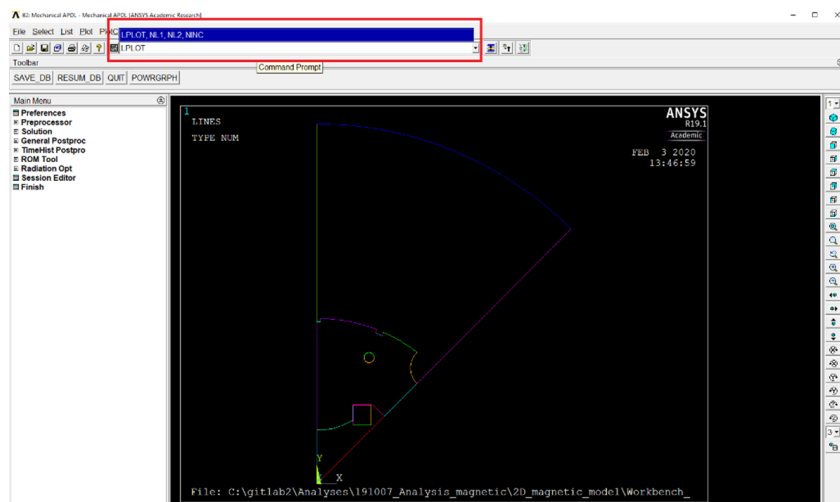


Figure 1.3: Illustration of APDL geometry and command to invoke its contour.

5. In the last step, the geometry should be saved in ANSYS APDL as a .db file, being a typical extension for the ANSYS APDL project.

1.2 Magnetic Analysis in ANSYS APDL

Depending on the step, from which the user is willing to rerun the magnetic analysis, there are four input files given in the folder \input:

1. skew_quad_iron_yoke.stp, being the imported step file to Design Modeller;
2. Workbench_geometry_skew_quad.wbpz, representing the entire skew quadrupole geometry prepared in ANSYS Workbench;

1. magnetic_field_current_\\%iteration\\%.txt
2. peak_field_coil_current_\\%iteration\\%.png
3. peak_field_coil_vector_current_\\%iteration\\%.png
4. peak_field_yoke_coil_current_\\%iteration\\%.png
5. peak_field_yoke_coil_vector_current_\\%iteration\\%.png
6. peak_field_yoke_current_\\%iteration\\%.png
7. peak_field_yoke_vector_current_\\%iteration\\%.png

The output files 2-7 only aim to visualise the simulation. The files of type 1 are important for the quench velocity-based approach, because they contain the data required to create the magnetic map as a function of current and magnetic field strength. Figure 1.6 presents the exemplary magnetic_field_current_\\%iteration\\%.txt file for the given value of current. In Fig. 1.6, the top red rectangle represents the data about the mesh density in the area_coil from Fig. 1.5 as well as the value of current in the analysis. The red rectangle on the right side corresponds to the magnetic field strength in the Cartesian (x,y,z) -coordinate system presented in the blue rectangle.

```

magnetic_field_current_1.txt - Notepad
File Edit Format View Help
Coil number of elements, x-direction = 80.
Coil number of elements, y-direction = 40.
Current, [A] = 1.
1 X [MM]
2 Y [MM]
3 Z [MM]
4 BX [TESLA]
5 BY [TESLA]
6 B [TESLA]
-6.9388939E-18 2.7300000E-02 0.0000000E+00 2.9725280E-04 -7.7515328E-04 8.3019385E-04
2.4460000E-02 2.7300000E-02 0.0000000E+00 9.1531786E-05 5.3775984E-03 5.3783773E-03
6.1150000E-04 2.7300000E-02 0.0000000E+00 8.2173522E-05 -8.6432278E-04 8.6822022E-04
1.2230000E-03 2.7300000E-02 0.0000000E+00 3.3097816E-05 -9.2592648E-04 9.2651784E-04
1.8345000E-03 2.7300000E-02 0.0000000E+00 1.2008511E-05 -9.6490051E-04 9.6497523E-04
2.4460000E-02 2.7300000E-02 0.0000000E+00 -4.9338231E-06 -9.8053839E-04 9.8055080E-04
3.0575000E-03 2.7300000E-02 0.0000000E+00 -1.6842474E-04 -9.8613424E-04 9.8627806E-04
3.6690000E-03 2.7300000E-02 0.0000000E+00 -2.5684484E-05 -9.7896667E-04 9.7930355E-04
4.2805000E-03 2.7300000E-02 0.0000000E+00 -3.5586139E-05 -9.6128160E-04 9.6194007E-04
4.8920000E-03 2.7300000E-02 0.0000000E+00 -4.6432184E-05 -9.3318446E-04 9.3433890E-04
5.5035000E-03 2.7300000E-02 0.0000000E+00 -5.5840084E-05 -8.9390056E-04 8.9564297E-04
6.1150000E-03 2.7300000E-02 0.0000000E+00 -6.3299669E-05 -8.4257412E-04 8.4494852E-04
7.7265000E-03 2.7300000E-02 0.0000000E+00 -7.6956655E-05 -7.8847766E-04 7.9222431E-04
7.3380000E-03 2.7300000E-02 0.0000000E+00 -8.6785564E-05 -7.1034589E-04 7.1562771E-04
7.9495000E-03 2.7300000E-02 0.0000000E+00 -9.7445121E-05 -6.2754490E-04 6.3506547E-04
8.5610000E-03 2.7300000E-02 0.0000000E+00 -1.1247076E-04 -5.3118556E-04 5.4296203E-04
9.1725000E-03 2.7300000E-02 0.0000000E+00 -1.1888564E-04 -4.2191241E-04 4.3834219E-04
9.7840000E-03 2.7300000E-02 0.0000000E+00 -1.3272720E-04 -3.0161737E-04 3.2952929E-04
1.0395500E-02 2.7300000E-02 0.0000000E+00 -1.4682133E-04 -1.6827338E-04 2.2332137E-04
1.1007000E-02 2.7300000E-02 0.0000000E+00 -1.5665156E-04 -1.7372971E-05 1.5761196E-04
1.1618500E-02 2.7300000E-02 0.0000000E+00 -1.6847292E-04 1.3826737E-04 2.1794722E-04
1.2230000E-02 2.7300000E-02 0.0000000E+00 -1.8492881E-04 3.1223430E-04 3.6288969E-04
1.2841500E-02 2.7300000E-02 0.0000000E+00 -1.9059906E-04 4.9702614E-04 5.3231850E-04
1.3453000E-02 2.7300000E-02 0.0000000E+00 -2.0403690E-04 6.9444339E-04 7.2379740E-04
1.4064500E-02 2.7300000E-02 0.0000000E+00 -2.1841999E-04 9.0227106E-04 9.2833203E-04
1.4676000E-02 2.7300000E-02 0.0000000E+00 -2.2758223E-04 1.1305794E-03 1.1532578E-03
1.5287500E-02 2.7300000E-02 0.0000000E+00 -2.3687187E-04 1.3575083E-03 1.3780193E-03
1.5899000E-02 2.7300000E-02 0.0000000E+00 -2.5532489E-04 1.6042330E-03 1.6244243E-03
1.6510500E-02 2.7300000E-02 0.0000000E+00 -2.5625166E-04 1.8651021E-03 1.8826234E-03
1.7122000E-02 2.7300000E-02 0.0000000E+00 -2.6858940E-04 2.1269288E-03 2.1438205E-03

```

Figure 1.6: The output file from the magnetic simulation with specified data for the quench velocity-based approach.

The files magnetic_field_current_\\%iteration\\%.txt should be ordered from the lowest to the highest value of current, i.e. from magnetic_field_current_\\%current_init\\%.txt to magnetic_field_current_\\%current_max\\%.txt. This is carried out by default if integer values of the parameters related to operating current levels are specified (see Fig. 1.4). The files order is important for the right uploading procedure of the magnetic field strength in Python required in the following steps of the quench velocity-based approach.

Chapter 2

Quench Velocity Map Analysis

In the studies related to the quench velocity map, a set of 1D numerical analyses is conducted in ANSYS APDL with or without an additional insulation layer. The analysis is performed in ANSYS APDL with the external Python script. For more details about using the Python script in ANSYS APDL simulations, please, refer to [1, p. 51-69]. The files required to rerun the simulations are stored in: G:\Workspaces\a\ANSYS_Modelling\1_quench_velocity_modelling\documentation\Test_Simulation_Workflow\2_analysis_v_quench_map.

2.1 Input json File

First of all, the user should fill the input json file to run the ANSYS APDL simulation. The default json file is placed in the folder \input. As presented in Fig. 2.1, the user specifies the analysis_output_directory corresponding to the directory in which ANSYS APDL is running during the simulation. In this chapter, ANSYS executes standard simulations without the quench velocity-based approach. Therefore, the user specifies the analysis_type.type as "standard".

```
"analysis_output_directory": "G:\Workspaces\a\ANSYS_Modelling\1_quench_velocity_modelling\documentation\
Test Simulation Workflow\2_analysis_v_quench_map\output",

"analysis_settings": {
  "x_quench_init": 0.0,
  "L_quench_init": 0.1,
  "t_simulation": 0.5,
  "t_com": 0.01,
  "t_step_range_min": 0.01,
  "t_step_range_max": 0.1
},

"analysis_type": {
  "type": "standard",
  "input": {
    "png_quench_state_output": true,
    "png_resistive_voltage_output": true
  }
},
```

Figure 2.1: Input json file with specified analysis_output_directory and analysis_type.type marked in blue and red, respectively.

In the next step, the user specifies the data related to the current and the magnetic field strength as illustrated in Fig. 2.2. The parameters are outlined in Table 1. It is recommended to keep the value of B_initially_quenched_winding equal to B_constant.

```

"magnetic_field_settings": {
  "type": "constant",
  "input": {"B_constant": 0.0}
},

"circuit_settings": {
  "electric_ansys_elements": false,
  "electric_ansys_element_input": {"I_init": 26.0},
  "build_electric_circuit": false,
  "transient_electric_analysis": false,
  "transient_electric_analysis_input": {}
},

"temperature_settings": {
  "type": "gaussian",
  "input": {
    "T_bath": 4.3,
    "T_max": 20.0,
    "B_initially_quenched_winding": 0.0,
    "png_temperature_output": true
  }
},

```

Figure 2.2: Input json file with specified values related to the magnetic field strength and the current.

Table 2.1: Parameters related to the current and the magnetic field strength.

Parameter	Type	Description
B_constant	float	Constant magnetic field strength during the analysis
I_init	float	Constant current during the analysis
transient_electric_analysis	boolean	Specifies whether the current discharge is analysed
B_initially_quenched_winding	float	Magnetic field subjected to the initially quenched winding

2.2 Running ANSYS APDL in Python

The user should launch ANSYS APDL in the Product Launcher. In order to run ANSYS APDL with Python, the given steps must be followed:

1. The ANSYS directory must correspond to the folder \output, as illustrated in Fig. 2.3.

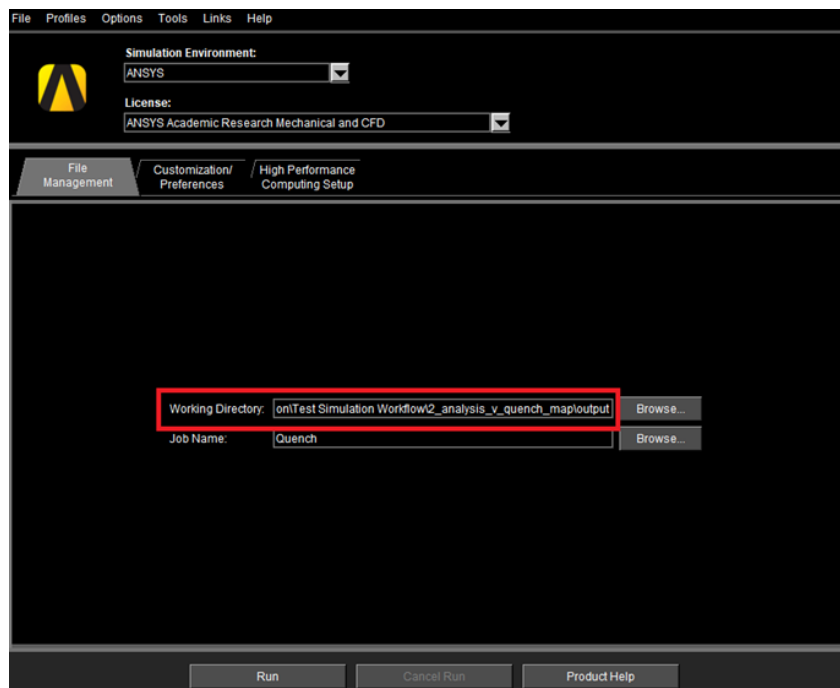


Figure 2.3: Specification of output file directory in APDL Product Launcher.

2. The additional parameter must be specified in the Product Launcher, called “-aas” as shown in Fig. 2.4. At this point, ANSYS APDL is launched by clicking the "Run" button in the Product Launcher window.

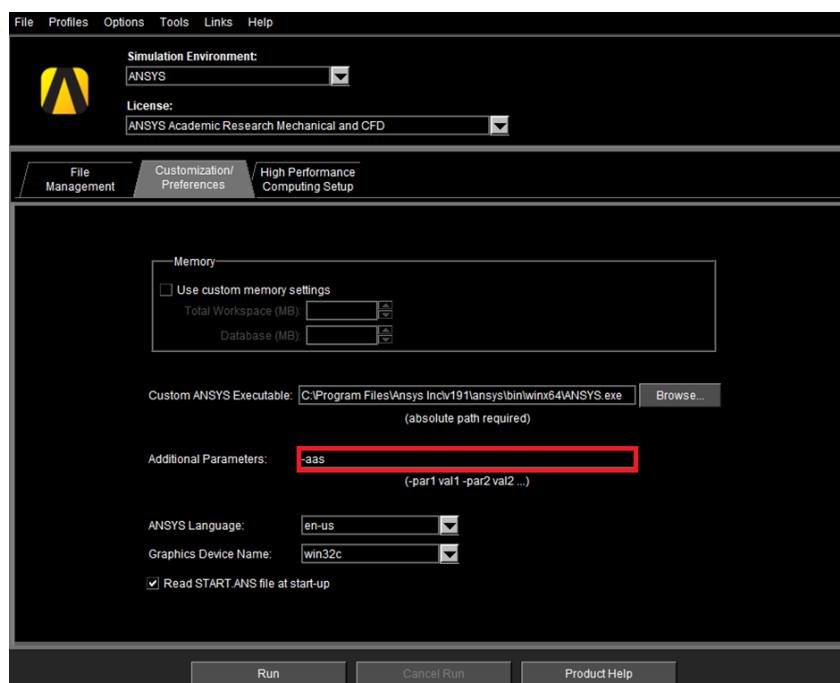


Figure 2.4: Specification of the `-aas` mode in APDL Product Launcher.

3. In the `execution_script` module of the Python script, the `input_file_directory` with the json filename must be specified as illustrated in Fig. 2.5. After starting ANSYS APDL, and following the given step, the Python script can be initialised. From this point, the analysis is running until the total simulation time is computed.

```
# creation of analysis directories
input_files_directory = "G:\\Workspaces\\a\\ANSYS_Modelling\\1_quench_velocity_modelling\\documentation\\" \
                        "Test_Simulation_Workflow\\1_analysis_magnetic\\input"
json_filename = "input.json"
factory = AnalysisFactory(input_files_directory, json_filename)
```

Figure 2.5: Specification of input file directory in the `execution_script` module of the Python script.

2.3 Results from ANSYS APDL

The results output consists of a set of folders as shown in Fig. 2.6. The files in each of the folders are presented in Table 2.2.

geometry_output	26/12/2019 00:04	File folder
input_copy	26/12/2019 00:04	File folder
magnetic_field	24/12/2019 23:09	File folder
material_properties	26/12/2019 00:04	File folder
quench_state_output	26/12/2019 00:08	File folder
resistive_voltage_output	26/12/2019 00:04	File folder
temperature_profile_output	26/12/2019 00:04	File folder

Figure 2.6: Folders in output directory created during the analysis.

Table 2.2: Description of output files from the simulation.

Folder	File name	Description
geometry_output	im_coil_length.txt	imaginary nodes vs. coil length
input_copy	input.json	input json file (copy)
magnetic_field	-	-
material_properties	%item%_%property%.txt %item%_%property%.png	property vs. temperature property vs. temperature
quench_state_output	quench_velocity.txt quench_state%iteration%.txt quench_state%iteration%.png	quench length, quench velocity vs. time quench state vs. coil length quench state vs. coil length
resistive_voltage_output	resistance_voltage.txt v_res_ansys.png	resistance, resistive voltage vs. time resistive voltage vs. time
temperature_profile_output	initial_energy_deposition_in_strand.txt temperature_profile_%iteration%.txt temperature_profile_%iteration%.png	initial energy in the strand temperature vs. coil length temperature vs. coil length

The file im_coil_length.txt represents a set of nodal positions in the longitudinal direction of the analysed cable. In the material_properties folder the following data are given:

1. heat capacity, thermal conductivity, thermal diffusivity of copper, Nb-Ti, and G10 and composite strand;
2. resistivity of copper and composite strand;
3. Joule heating power density profile.

The quench velocity value is stored in the quench_velocity.txt file in the folder quench_state_output. This value is important for the the quench velocity-based approach in further steps of the analysis. Another type of the file obtained from the simulations is Coil-Nodal-Temp%iteration%.png in which the coil top view from ANSYS APDL is presented with the temperature distribution at the given iteration. The remaining files in the \output directory are not used for the post-processing.

Chapter 3

Minimum Propagation Zone Analysis

In the minimum propagation zone (MPZ) studies, a set of 1D numerical analyses is conducted to predict how much of initial energy is required to initialise the quench inside of a coil. For more information about the MPZ simulations, please, refer to [1, p. 85-87]. Similarly to the previous chapter, the analysis is performed in ANSYS APDL by means of the Python script. The files needed to rerun the simulations are stored in G:\Workspaces\A\ANSYS_Modelling\1_quench_velocity_modelling\documentation\Test_Simulation_Workflow\3_analysis_mpz.

3.1 Input json File

The input file for the analysis is stored in the folder \input. In analogy to the case discussed in the previous chapter, analysis_output_directory corresponds to the directory in which ANSYS APDL is running during the simulations. As shown in Fig. 3.1, the parameter L_quench_init imposes the initial quench length in the coil. If the simulation is conducted with a symmetry condition, the value of this parameter is halved.

```
"analysis_output_directory": "G:\\Workspaces\\A\\ANSYS_Modelling\\1_quench_velocity_modelling\\documentation\\Test_Simulation_Workflow\\3_analysis_mpz\\output",  
  
"analysis_settings": {  
  "x_quench_init": 0.0,  
  "L_quench_init": 0.1,  
  "t_simulation": 0.1,  
  "t_com": 0.01,  
  "t_step_range_min": 0.01,  
  "t_step_range_max": 0.1  
},
```

Figure 3.1: Input json file with specified analysis_output_directory and L_quench marked in blue and red, respectively.

Figure 3.2 presents the input parameters corresponding to the initial temperature profile. They are described in Table 3.1.

```
"temperature_settings": {  
  "type": "gaussian",  
  "input": {  
    "T_bath": 4.3,  
    "T_max": 20.0,  
    "B_initially_quenched_winding": 0.0,  
    "png_temperature_output": true  
  }  
},
```

Figure 3.2: Input json file with specified values related to the initial temperature profile.

Table 3.1: Parameters related to the current and the magnetic field strength.

Parameter	Type	Description
T_bath	float	Initial bath temperature
T_max	float	Maximum temperature of the Gaussian profile
B_initially_quenched_winding	float	Magnetic field which serves for calculating the critical temperature to estimate the quench front position in the Gaussian profile
png_temperature_output	boolean	Specifies whether the output temperature profile is plotted as the simulation continues

3.2 Running ANSYS APDL in Python

The case corresponds to that, presented in Section 2.2.

3.3 Results from ANSYS APDL

The case corresponds to that, presented in Section 2.3.

Chapter 4

Quench Analysis of Skew Quadrupole

This chapter an exemplary analysis of the skew quadrupole with the quench velocity-based approach. The analysis can be used for the quench simulation of any high-order corrector geometry. For further information concerning the quench analysis of the skew quadrupole, please, refer to [1, p. 70-97]. The files required to rerun the exemplary simulation are stored in the following directory: G:\Workspaces\A\ANSYS_Modelling\1_quench_velocity_modelling\documentation\Test_Simulation_Workflow\4_analysis_high_order_corrector.

4.1 Input Files

As presented in Fig. 4.1, in order to run the simulation, the Python script requires a set of input files such as inductance.txt, quench_velocity_map.txt, and input.json. The file inductance.txt represents the evolution of the magnet inductance as a function of current. The file quench_velocity_map.txt is based on the simulations discussed in Chapter 2. The input.json file is a text file with a set of simulation parameters similarly to the analyses discussed in the previous chapters. The folder \magnetic_field_map stores a set of magnetic field maps for a varying value of the operating current. The files are obtained from the magnetic simulations discussed in Chapter 1.





 magnetic_field_map	07/02/2020 14:32	File folder
 inductance.txt	15/12/2019 16:10	Text Document
 input.json	07/02/2020 16:49	JSON File
 quench_velocity_map.txt	26/12/2019 00:12	Text Document

Figure 4.1: Input files required to run the simulation.

4.2 Input json File

Apart from the data discussed in the previous chapters, the quench velocity-based approach requires additional information concerning the quench velocity map as a function of current and magnetic field strength. The input.json file contains the data in the analysis_type part of the text file as illustrated in Fig. 4.2. The parameters are described in Table 4.1.

```
"analysis_type": {  
    "type": "v_quench_based_approach",  
    "input": {  
        "v_quench_model": "numerical",  
        "v_quench_map_filename": "quench_velocity_map.txt",  
        "png_quench_state_output": true,  
        "png_resistive_voltage_output": true}  
    },  
}
```

Figure 4.2: Input json file with specified values related to the quench velocity-based approach.

Table 4.1: Parameters related to the quench velocity-based approach.

Parameter	Type	Description
v_quench_model	string	Specifies what type of quench velocity map is chosen
v_quench_map_filename	string	Specifies filename with the quench velocity map
png_quench_state_output	boolean	Specifies whether the quench state profile is plotted as the simulation continues
png_resistive_voltage_output	boolean	Specifies whether the resistive voltage profile is plotted as the simulation continues

Figure 4.3 depicts the analysis settings corresponding to the magnetic field strength as well as the circuit. The parameters are described in Table 4.2. The parameters used for the discharge of the skew quadrupole are explained in [1, p.70-76 and 91].

```

"magnetic_field_settings": {
  "type": "2D_static",
  "input": {
    "B_map_foldername": "magnetic_field_map"
  }
},

"circuit_settings": {
  "electric_ansys_elements": true,
  "electric_ansys_element_input": {"I_init": 86.0},

  "build_electric_circuit": true,
  "transient_electric_analysis": true,
  "transient_electric_analysis_input": {
    "R_dump": 2.0,
    "L_diff_filename": "inductance.txt",
    "V_th": 0.05,
    "t_delay": 0.005,
    "I_discharge_criterion": 80.0}
},

```

Figure 4.3: Input json file with specified values related to the circuit settings and the magnetic field mapping procedure.

Table 4.2: Parameters related to the circuit settings and the magnetic field mapping procedure.

Parameter	Type	Description
B_map_foldername	string	Foldername in which the magnetic field map is stored (see Fig. 4.1)
electric_ansys_elements	boolean	Specifies whether LINK68 elements are used to model the composite strand (default for quench velocity-based approach)
I_init	float	Initial current in the analysis
build_electric_circuit	boolean	Specifies whether the independent current source, dump resistor, and inductor are built in ANSYS APDL
transient_electric_analysis	boolean	Specifies whether the magnet discharge is simulated
R_dump	float	Dump resistor value added to the circuit
L_diff_filename	string	Filename of the differential inductance as a function of current (see Fig. 4.1)
V_th	float	Threshold voltage value at which the quench is detected
t_delay	float	Time after which the current source is disconnected from the circuit after reaching the threshold voltage
I_discharge_criterion	float	Current value at which the simulation ends during the discharge

The high-order corrector geometry parameters are specified in the input json file as well. They are shown in Fig. 4.4 and further described in Table 4.3. The geometrical meaning of the parameters is discussed in [1, p.81-83 and 87-88].

```

"geometry_settings": {
  "dimensionality": "multiple_1D",
  "type": "high_order_corrector",
  "type_input": {
    "d_strand": 0.7,
    "d_ins": 0.84,
    "a_strand": 0.941,
    "u_ins": 1.0,
    "u_resin": 0.5,
    "e_coil": 387.3,
    "d_coil": 82.9,
    "rad_coil": 9.15,
    "n_windings": 9,
    "n_layers": 3,
    "n_turns_in_layer": 3,
    "which_layer_first_in_analysis": 1,
    "which_turn_first_in_analysis": 1,
    "type_insulation_settings": {
      "insulation_analysis": true,
      "insulation_analysis_input": {"n_divisions_ins": 2}
    },
    "type_mesh_settings": {
      "n_divisions_e_coil": 26,
      "n_divisions_d_coil": 6,
      "n_divisions_rad": 2
    }
  }
}

```

Figure 4.4: Input json file with specified values related to the geometry of the high-order corrector.

Table 4.3: Parameters related to the geometry of the high-order corrector.

Parameter	Type	Description
d_strand	float	Diameter of the composite strand
d_ins	float	Diameter of the composite strand with insulation
a_strand	float	Side of the square resin area assigned to one composite strand
u_ins	float	Coefficient of the insulation element area
u_resin	float	Resin packing coefficient
e_coil	float	Length of the coil long side
d_coil	float	Length of the coil short side
rad_coil	float	Initial radius of the coil between its long and short side
n_windings	int	Total number of analysed windings
n_layers	int	Total number of analysed layers
n_turns_in_layer	float	Total number of turns in a single layer
which_layer_first_in_analysis	int	Layer number from which the geometry is created
insulation_analysis	boolean	Specifies whether the insulation layer with turn-to-turn propagation is analysed
n_divisions_ins	int	Number of mesh divisions across the insulation elements
n_divisions_e_coil	int	Number of mesh divisions along the long side of the coil
n_divisions_d_coil	int	Number of mesh divisions along the short side of the coil
n_divisions_rad	int	Number of mesh divisions along the each of curvatures of the coil

4.3 Running ANSYS APDL in Python

The case corresponds to that, presented in Section 2.2.

4.4 Results from ANSYS APDL

The files obtained from the analysis with the quench velocity-based approach are similar to that presented in Section 2.3. The difference is based on two file types described in Table 4.4. The files marked in red represent those that are not included in the output folders with respect to the case described in Section 2.3. First of all, the file `magnetic_map.png` is obtained from the simulation that is a graphical representation of the magnetic field strength assigned to each winding of the simulated coil. Second of all, the file `quench_velocity.txt` is not included in the results due to the fact that the quench velocity is an input parameter in the quench velocity-based approach.

Table 4.4: Description of additional output files from the simulation.

Folder	File name	Description
magnetic_field	magnetic_map.png	magnetic field strength vs. winding position across the coil
quench_state_output	quench_velocity.txt	quench length, quench velocity vs. time

In addition, there are the following output files in the directory `output`:

1. `Coil-Nodal-Temp%iteration%.png` with the the coil top view from ANSYS APDL showing the temperature distribution at the given iteration;
2. `Coil-Nodal-Volt%iteration%.png` with the the coil top view from ANSYS APDL showing the voltage distribution at the given iteration;
3. `sol_dump_resistor.inp` with the values of current, voltage and power in the resistor at the given time step;
4. `sol_inductor.inp` the values of current, voltage and power in the inductor at the given time step.

Bibliography

- [1] M. Wilczek, “Finite element analysis of magneto-thermal transient effects in superconducting accelerator magnets,” Master’s thesis, Lodz University of Technology, January 2020.