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Powertrain Retrofit kit testing and thermal modeling

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Abstract

In the latest years automotive industry is experiencing continuous change, pursuing the so called “electrification” of vehicles; manufacturers are currently investing in research and development of electrical powered vehicles (EVs), since huge climate change recent impact on everyday life. Furthermore, the ban over the sale of the ICE vehicles imposed by the European Union, starting from 2035, is boosting this trend, too. In order to promote the adoption of EVs, worldwide governments are offering economic incentives, also providing an expansion of the charging infrastructure, to deal with the constantly increasing demand. Regardless of vehicle range anxiety, long charging time, low battery life and high initial costs, this electrification trend is set to increase in time as long as the technology will keep evolving and the request for sustainable means of transport will be maintained high. As a consequence, this conversion towards EVs and electrification is having a substantial influence on the automotive industry, modifying the concept of vehicles and urban transportation as we know it. This is the background of the objective of this thesis work: testing the performances of the powertrain an electric vehicle’s retrofit kit, developing a reliable way to confront the Virtual, Semi Real and Real Prototypes of the vehicle itself, applying the Extended V-Cycle methodology via MATLAB software.

The Extended V-Cycle is the core methodology adopted in the process in order to facilitate this shift toward electrification; this efficient and flexible method allows a reduction both in time and cost of software projects. The ultimate goal is to produce an optimized development process, considering the constantly changing and intricate aspects of software development.

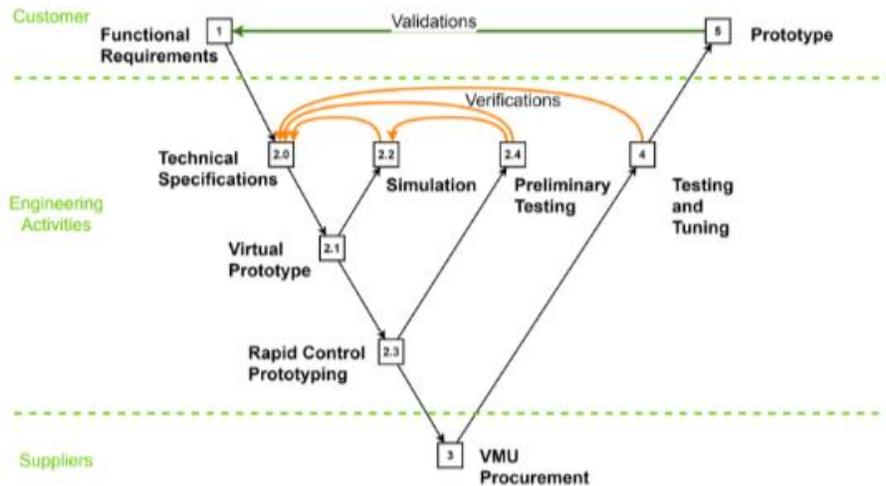


Figure 1: Extended V-Cycle

Five main steps and four additional sub-phases compose this method:

- Phase 1 has the purpose of defining the functional requirements, based on the customer's needs.
- In Phase 2, these requirements are transformed into technical specifications, in accordance with the automotive safety standard (ISO26262), following two different guidelines: the preliminary study and the user experience; the first one is applied to estimate the size and the characteristics of the retrofit components, while the second describes how the vehicle should work in terms of states and transitions.
- Sub-phases 2.1-2.2 involve the construction and validation of the Virtual Prototype, which is the complete module of the vehicle, including the control logic. The Virtual Prototype is created using the Modular Technical Model (MTM), which is a template tool built using MATLAB/Simulink; it has a modular architecture comprising different modules (Environment, Plant, Control, HMI, User), each of which is improved by an iterative MIL process.
- In sub-phases 2.3-2.4, the control logic is downloaded onto a powerful and real VMU (dSpace) and is tested on the testbench. This step constitutes the Semi-Real Prototype, where some parts of the Plant and Human Machine Interface are no longer models but real components. After the creation of the Virtual Prototype and the Semi-Real Prototype, the Extended V-Cycle proceeds to the next stages.
- In Phase 3, the control logic is downloaded onto a commercial VMU, and
- In Phase 4, the same validation tests, both of the model and of the VMU, are repeated on the testbench. Finally, when the tests are effectively concluded, the project shifts to
- Phase 5 which includes road testing of the Real Prototype. The traditional V model methodology has been optimized by including phases for iterative improvement and adaptation, highlighting testing and verification stages, ensuring a better alignment of the evolving requirements of the project. Thus, the quality and predictability of software development projects has been increased by the Extended V-Cycle methodology, leading to higher customer satisfaction and lower costs

Another mean of testing and evaluating the coherence of results coming from virtual, semi-real and real prototype is dealing with the thermal behavior of the powertrain. For this specific reason, a second-order thermal model was implemented to predict the average winding temperature of the involved electrical motor. The proposed model is briefly described. Experimental results providing the validation of the proposed thermal model are presented. Even if the model is very straightforward, it has general validity. For this reason it can be adopted for any electrical machine, regardless of windings type. Due to its simplicity and high accuracy in estimating the average winding temperature, this model results very useful in electric drives application.

1.Extended V-Cycle

The Extended V-Cycle adopts an experimental approach that closely integrates numerical simulations (Virtual Prototype), experiments conducted with partial or complete powertrain on the test bench (Semi-Real Prototype), and road tests conducted with the Real Prototype on actual roads. A deeper analysis on this topic can be found at the document: [20221020 Extended V-Cycle for Model Based Design of Vehicle Management Units.pdf \(dropbox.com\)](#)

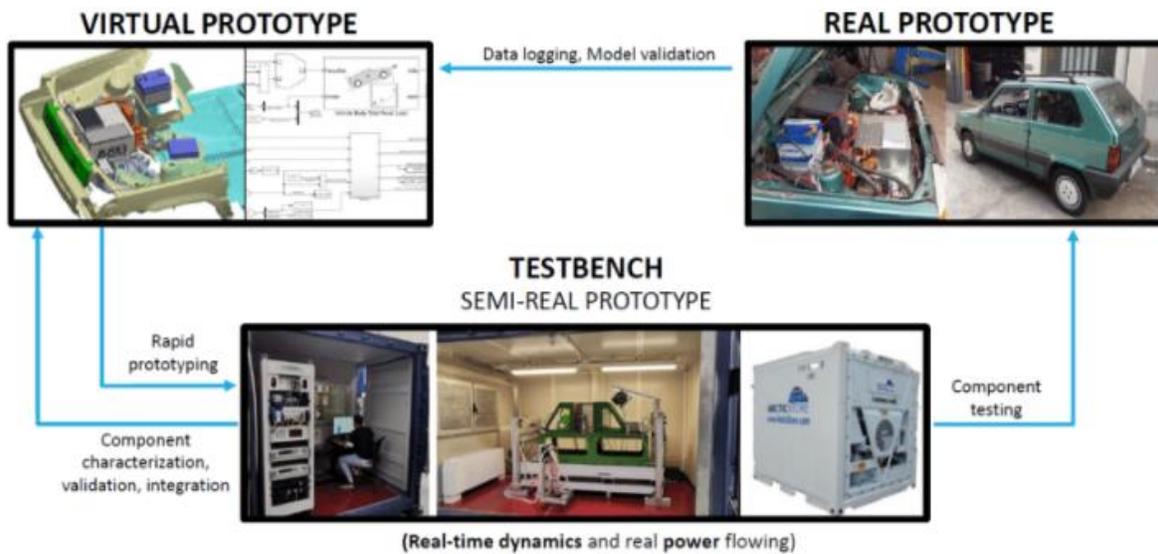


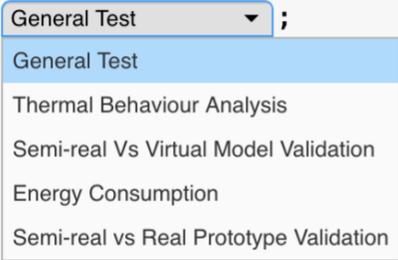
Figure 2: Virtual, Semi-real, Real prototype

2.Semi real prototype Testing

The testing end post-processing activity had the purpose to elaborate data coming from test bench/semi-real prototype, in order to have an interface on which to compare these signals with ones came from real and virtual prototype. The data processing has been carried out through a MATLAB script.

[Post_Processing_DATA_Preview.mlx](#)

```
%Test choice and data management

Test_Type =  ;

srcFolder = pwd;
dstFolder = fullfile(srcFolder, 'Reports');
if ~exist(dstFolder, 'dir')
    mkdir(dstFolder);
end

[file, folderPath] = uigetfile('*.csv', 'Seleziona un file CSV');
if isequal(file, 0) || isequal(folderPath, 0)
    error('Nessun file selezionato.');
```

Figure 3: Selection of test type via drop down menu

This software receives as input test bench data as .csv files, giving as output both a live view of different signals depending on testing category (General test, Thermal behavior Analysis, Semi-real Vs Virtual Model Validation, Energy Consumption, Semi-real vs Real Prototype Validation), and a report of the test processed. For example, in the following links it is possible to find the these documents for the general analysis performed on Test-2022-12-07-001

[GeneralInformationsTest_2022_12_07_001.pdf](#)

2.Processing and report

Live view allows, during post processing, for a quick check on all relevant signals. Automatic report generation allows for the instant tracking of signals belonging to a specific test category.

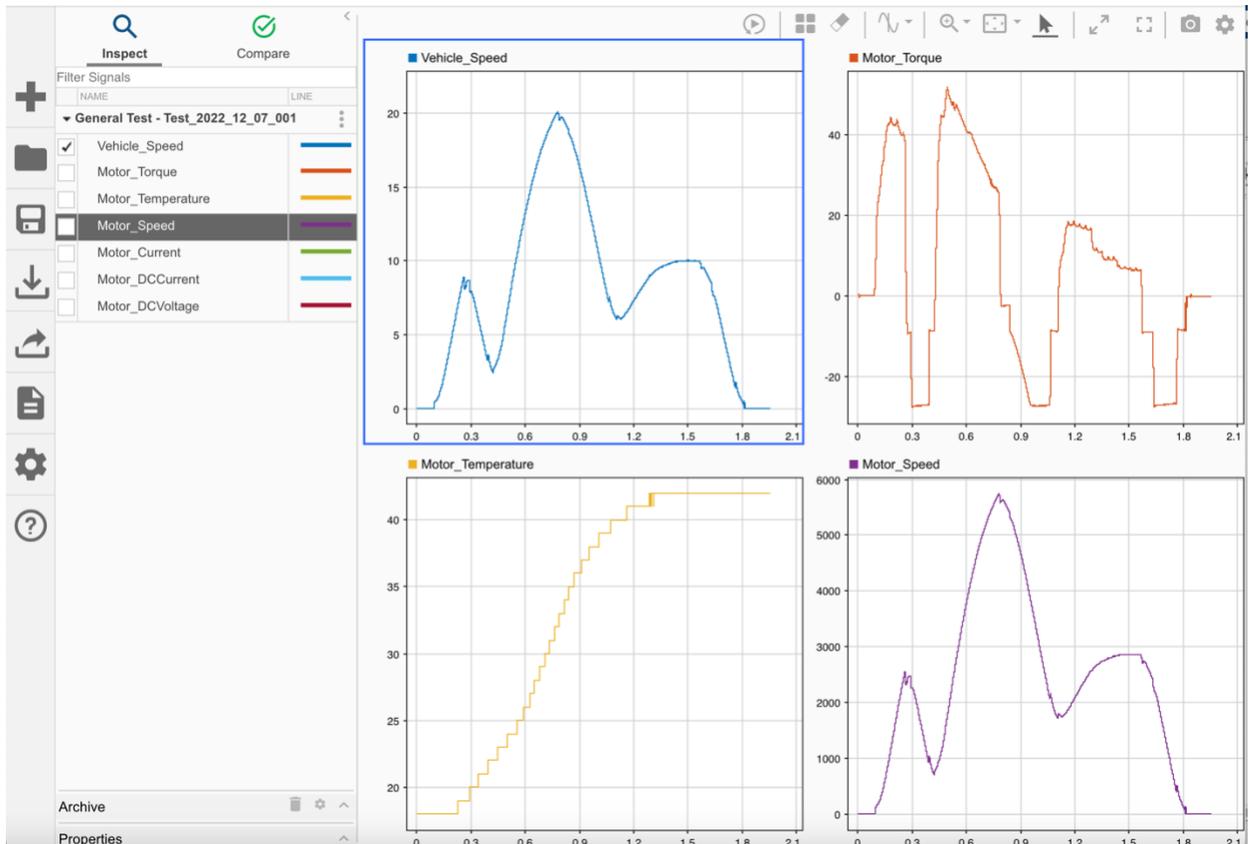


Figure 4: Example of test results automatically displayed in MATLAB data inspector

General Test - Test 2022 12 07 001

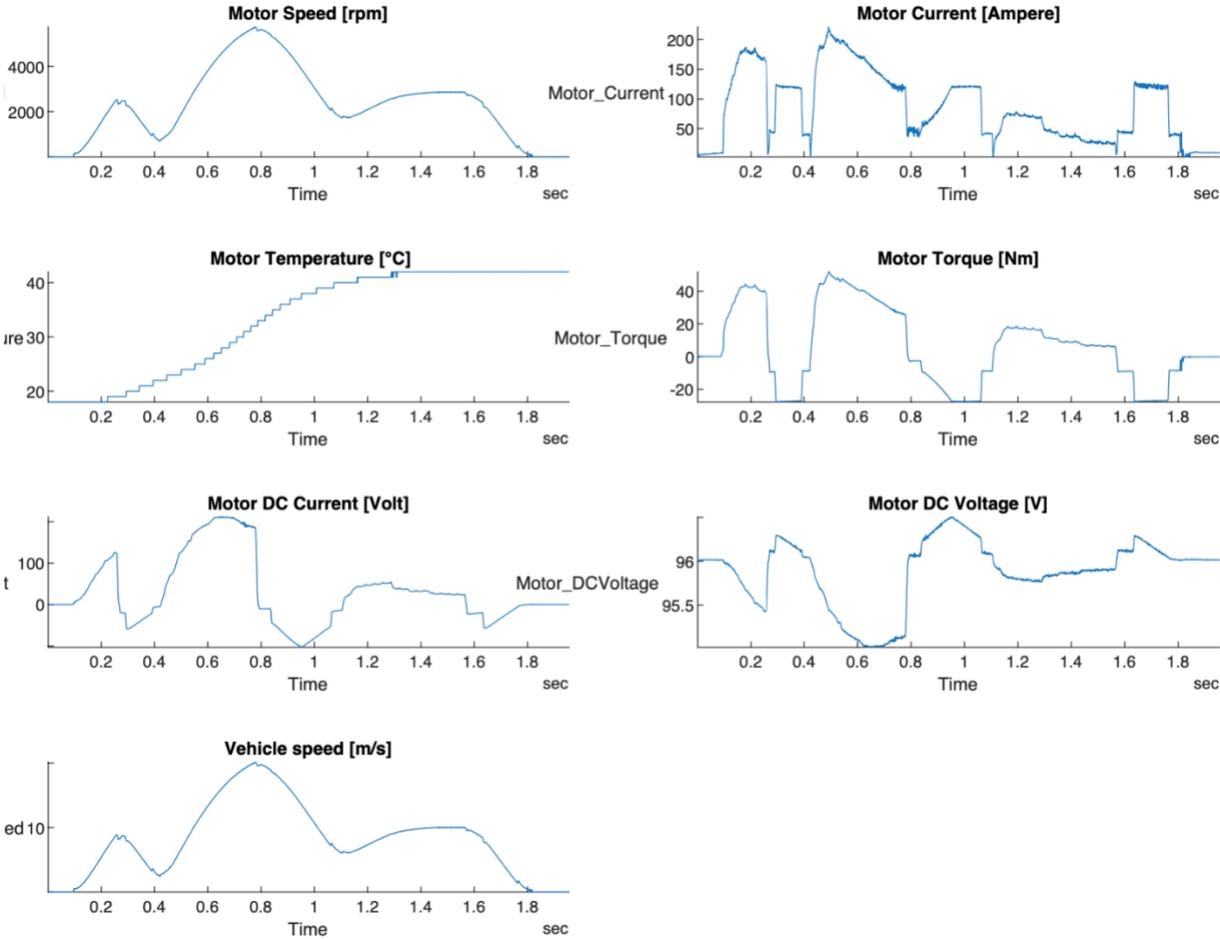


Figure 5: Example of .pdf report automatically generated via MATLAB script

General Information

Energy [kWh] = 0.0039
Energy without regen [kWh] = 0.0039
Distance [km] = 0.0159
Consumption [Whkm] = 247.1165
Consumption without regen [Whkm] = 247.1165
Consumption reduction [percentual] = 0.0000

Figure 6: General information collected for every test generated report

The following link contains a manual for the correct use of the MATLAB script mentioned above.

[+Semi-Real Prototype Test Post-Processing Procedure](#) .

3.Second order thermal motor model

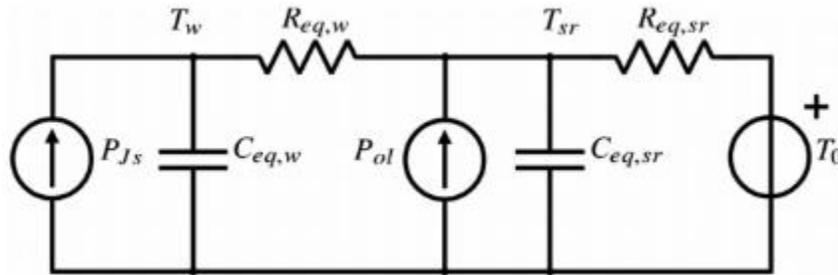
The purpose of this activity was the implementation of a second order thermal model for an electrical engine. The chosen motor is an IPM Synchronous Reluctance one. The goal was to obtain a model that, receiving data from tests bench, could accurately simulate the evolution of the stator temperature of the mentioned engine. The model implementation arose from the electrical equivalent circuit , mentioned in the “Definition and Experimental Validation of a Second-Order Thermal Model for Electrical Machines”, which was produced by: professor Eric Armando (Senior Member, IEEE), Aldo Boglietti (Fellow, IEEE), Fabio Mandrile (Member, IEEE), Enrico Carpaneto (Member, IEEE), Sandro Rubino (Member, IEEE), and Devi Geetha Nair.

The publication can be found here: [Definition and Experimental Validation of a Second-Order Thermal Model for Electrical Machines - Armando et al 2021.pdf \(dropbox.com\)](#)

The need to predict the stator temperature evolution comes from the fact that stator windings are the most sensitive part of every electrical machine. An excessively high temperature of the

winding causes a deterioration of the insulating material, thus reducing the machine's life span. Therefore, when developing a machine's thermal model, designers should prioritize monitoring the average temperature of the stator winding.

It would be possible to introduce a first order model in order to take into account the thermal behavior, but its time validity would be limited, and, thus, the model responses could not be used to evaluate thermal transients that last more than the thermal time constant of the winding. A comparison among the accuracy of second order thermal model vs first order one, will be shown in this document nonetheless. For this specific reason, to predict the winding temperature for a longer time while preserving the accuracy, a second order model seems a more suitable solution:



The proposed thermal model is shown above presents:

- $R_{eq,w}$ is the equivalent thermal resistance between the winding copper and the stator lamination.
- $C_{eq,w}$ is the equivalent thermal capacitance of the winding by including copper and insulation system.
- $R_{eq,sr}$ is the equivalent thermal resistance between the stator lamination and the ambient. This resistor represents the motor capability to transfer the heat produced by the stator winding to the ambient.
- $C_{eq,sr}$ is the thermal capacitance of the stator and rotor but without including the stator winding capacitance $C_{eq,w}$.
- T_w and T_0 are the temperatures of the stator winding and ambient, respectively, while T_{sr} is the temperature associated with the thermal capacitance $C_{eq,sr}$.
- P_{Js} and P_{ol} are the Joule losses of the stator winding and other machine losses (e.g., iron, PM, and rotor Joule ones), respectively.

4.1. Second order Simulink motor thermal model

The implementation of the Simulink second order thermal model mentioned above, was carried out in this section with the purpose of experimentally reproducing the stator temperature evolution. Once the Simulink was built, it was possible to make a comparison with temperatures measured from test bench, so to obtain an high accuracy rate of the experimental model. Therefore, it was necessary to know the four circuit parameters ($R_{eq,w}$ - $C_{eq,w}$ - $R_{eq,sr}$ - $C_{eq,sr}$), related

to the data coming from testbench. For the purpose of parameter calculation, a software was used.

This tool, implemented by prof. Enrico Carpaneto, provided with the numerical value of the parameters for the tests mentioned above, upon reception of all data processed from the signals from the test bench. The worksheet used to provide all of the necessary data, and computed parameters value is shown below. It displays all of the variables needed for Carpaneto's software to suitably run. These were computed from signals received by the Test_2022_04_13_001. Circuit parameter values coming from the calculator are highlighted in yellow on the top right side of the worksheet.

A	B	C	D	E	F	G	H	I	J	K	L	M
DATI PER LA STIMA DEI PARAMETRI TERMICI												
										Parametri stimati per il circuito di Fig. 2		
										Ceq, w:	666,75	J/K
										Ceq, sr:	15060,1	J/K
										Req, w:	0,14485	K/W
										Req, sr:	0,11625	K/W
Modello I ordine												
t	Tw	Tw mod	Req DC	P	Ieq DC	VeQ DC	Is	Rs	Pjs	Poi	Ieq DC	VeQ DC
[s]	[°C]	[°C]	[ohm]	[W]	[A]	[V]	[A]	[ohm]	[W]	[W]		
0	22	19,35772099	0,99747631	521,843	22,87276332	22,81503956	74,18334424	0,006065194	100,1333566	421,7096434	10,01931642	9,994030771
0,100000143	22	22	1,007858546	517,107	22,65115839	22,82916357	74,18334424	0,006128324	101,175595	415,931405	10,01931642	10,09805368
0,200000048	22	22	1,007858546	528,574	22,90092935	23,08089737	74,18334424	0,006128324	101,175595	427,398405	10,01931642	10,09805368
0,300000191	22	22	1,007858546	521,031	22,73693867	22,91561795	74,18334424	0,006128324	101,175595	419,855405	10,01931642	10,09805368
0,400000095	22	22	1,007858546	520,892	22,7339056	22,91256105	74,19072127	0,006128324	101,1957184	419,6962816	10,02031277	10,09905786
0,5	22	22	1,007858546	522,25	22,76352071	22,94240889	74,19072127	0,006128324	101,1957184	421,0542816	10,02031277	10,09905786
0,600000143	22	22	1,007858546	527,283	22,87294541	23,0526935	74,19072127	0,006128324	101,1957184	426,0872816	10,02031277	10,09905786
0,700000048	22	22	1,007858546	520,715	22,73004276	22,90866785	74,19072127	0,006128324	101,1957184	419,5192816	10,02031277	10,09905786
0,800000191	22	22	1,007858546	523,477	22,7902459	22,9693441	74,19072127	0,006128324	101,1957184	422,2812816	10,02031277	10,09905786
0,900000095	22	22	1,007858546	525,509	22,83443592	23,01388139	74,19072127	0,006128324	101,1957184	424,3132816	10,02031277	10,09905786
1	22	22	1,007858546	521,905	22,75600064	22,93482973	74,19072127	0,006128324	101,1957184	420,7092816	10,02031277	10,09905786
1,100000143	22	22	1,007858546	521,755	22,75273027	22,93153365	74,19072127	0,006128324	101,1957184	420,5592816	10,02031277	10,09905786
1,200000048	22	22	1,007858546	517,744	22,66510555	22,84322033	74,19072127	0,006128324	101,1957184	416,5482816	10,02031277	10,09905786
1,300000191	22	22	1,007858546	526,931	22,86530945	23,04499754	74,19879527	0,006128324	101,2177454	425,7132546	10,02140326	10,10015692
1,400000095	22	22	1,007858546	517,727	22,66473345	22,8428453	74,19879527	0,006128324	101,2177454	416,5092546	10,02140326	10,10015692
1,5	22	22	1,007858546	517,479	22,6593044	22,83737359	74,19879527	0,006128324	101,2177454	416,2612546	10,02140326	10,10015692
1,600000143	22	22	1,007858546	520,237	22,71960764	22,89815072	74,19879527	0,006128324	101,2177454	419,0192546	10,02140326	10,10015692
1,700000048	22	22	1,007858546	522,559	22,77025397	22,94919506	74,19879527	0,006128324	101,2177454	421,34412546	10,02140326	10,10015692
1,800000191	22	22	1,007858546	519,662	22,70704857	22,88549296	74,19879527	0,006128324	101,2177454	418,4442546	10,02140326	10,10015692
1,900000095	22	22	1,007858546	531,197	22,95768092	23,13809491	74,19879527	0,006128324	101,2177454	429,9792546	10,02140326	10,10015692
2	22	22	1,007858546	512,519	22,55044901	22,72766275	74,19879527	0,006128324	101,2177454	411,3012546	10,02140326	10,10015692
2,100000143	22	22	1,007858546	533,518	23,00778163	23,18858935	74,19879527	0,006128324	101,2177454	432,3002546	10,02140326	10,10015692

Figure 7: Data worksheet for circuit parameters calculation

4.2. Model Characterization

The estimated parameters ($C_{eq,w}$ - $C_{eq,sr}$ - Req_{w} - Req_{sr}) allow for the implementation of the second order thermal model simulation dynamics, which is then run via Simulink. Here is the recollection of the values:

$$C_{eq,w}=666.75 \quad [J/K]$$

$$C_{eq,sr}=15060.1 \quad [J/K]$$

$$Req_{w}=0.14485 \quad [K/W]$$

$$Req_{sr}=0.11625 \quad [K/W]$$

The Simulink model allows for the computation of the winding temperature and the stator iron temperature. It was basically built by the integration of the following differential equation:

$$\frac{dT}{dt} = \left[P_{tot} - \frac{T_a - T_b}{R_{th}} \right] \frac{1}{C_{th}}, \quad \text{with}$$

P_{tot} = total power losses

R_{th} = thermal resistance

C_{th} = thermal capacitance

The equation was applied twice, first between winding and stator iron, then between iron and environment.

- In the first case: T_a = winding temperature; T_b = stator iron temperature.
- In the second case: T_a = stator iron temperature; T_b = environmental temperature.

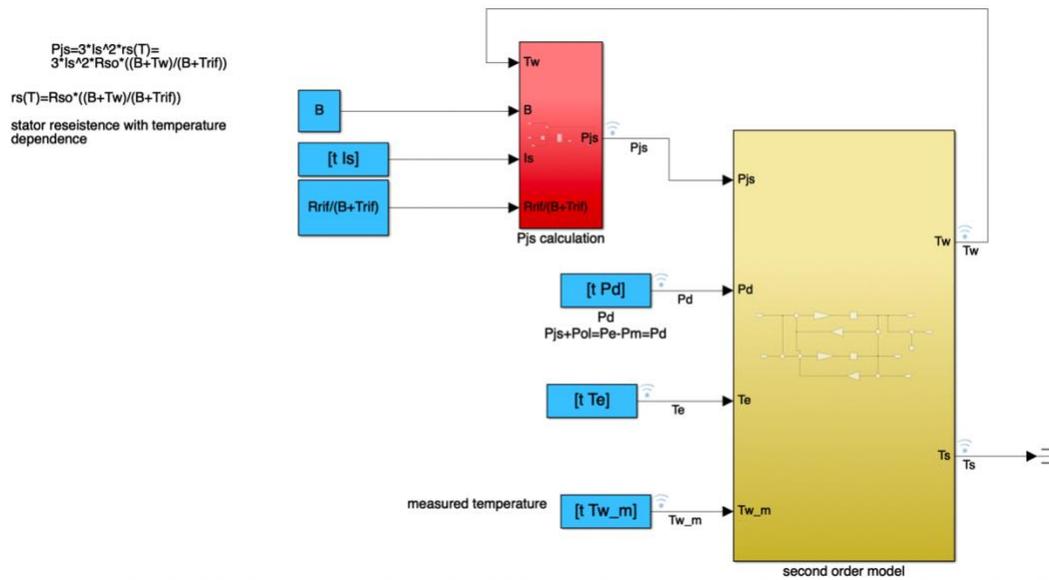


Figure 8: Simulink model overview

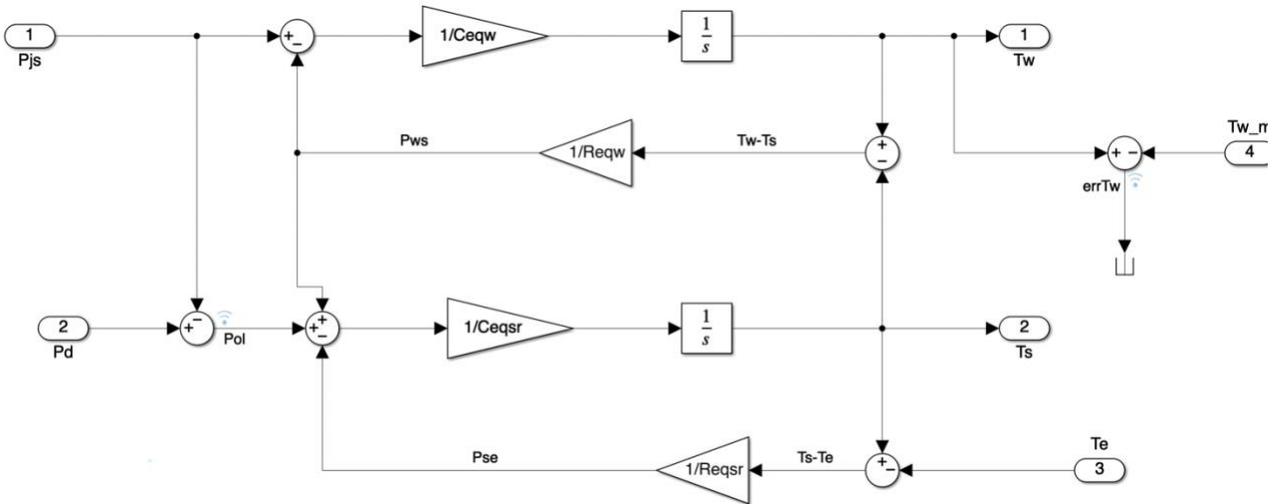


Figure 9: Second order Simulink thermal model

The complete model is available at the link:

[Second_Order_Thermal_Motor_Model.slx](#)

From figures 4 and 5, it is possible to see how, providing proper input data coming from testbench result (P_{js} , P_d , T_e , T_{wm} ,), the model is able to calculate winding temperature (T_w) and iron stator temperature (T_s). All these parameters are defined in the following section.

4.3. Parameters definition

- I_s = stator current;
- P_d = power losses (electrical power-mechanical power)
- T_{w_m} = winding measured temperature
- t = simulation time
- T_e = Test bench environment temperature
- T_{s0} = stator iron initial temperature
- T_{w0} = winding initial temperature

Moreover, Joule losses power (P_{js}) were computed taking into account the dependance of the stator resistance from temperature ($R_s(T)$).

- B = initial copper temperature
- R_{SO} = stator phase resistance at the temperature T_{RIF}
- T_{RIF} = temperature at which stator resistance was calculated
- $R_{RIF} = 3 * R_{SO}$

P_{js} = Joule losses, computed with reference to the resistance dependance from the temperature

$$P_{js} = 3 \cdot I_s^2 \cdot R_s(T), \quad R_s(T) = R_{so} \frac{B+T_w}{B+T_{RIF}}$$

with: $R_{so} = 0.0062\Omega$, $T_{RIF} = 25^\circ C$ $B = 234.5^\circ C$ (*Copper*)

All others variables inside the model are:

- P_{ws} = power dissipation between winding and stator iron;
- P_{se} = power dissipation between stator iron and environment
- t = simulation time
- T_s = stator iron temperature

4.4 Model running

Once all circuit parameters are known, it is possible to use the model to get a winding temperature forecast, and then compare it with the measured one. In this case, a static test “Test_2023_06_23_14_16_08” (constant torque and constant speed) was processed.

[Test_2023_06_23_14_16_08.csv](#)

It was necessary to provide the model with all of the parameters for its proper operations. For this purpose, a .mlx script has been implemented (Test_data_loading.mlx); it collects in a .mat file (prova.mat) all of the signals required by the simulink model, as shown in figure 10.

[Test_data_loading.mlx](#)

Import	Name ▲	Size	Bytes	Class
<input checked="" type="checkbox"/>	 B	1x1	8	double
<input checked="" type="checkbox"/>	 Ceqsr	1x1	8	double
<input checked="" type="checkbox"/>	 Ceqw	1x1	8	double
<input checked="" type="checkbox"/>	 Is	45846x1	366768	double
<input checked="" type="checkbox"/>	 Pd	45846x1	366768	double
<input checked="" type="checkbox"/>	 Reqsr	1x1	8	double
<input checked="" type="checkbox"/>	 Reqw	1x1	8	double
<input checked="" type="checkbox"/>	 Rrif	1x1	8	double
<input checked="" type="checkbox"/>	 Te	45846x1	366768	double
<input checked="" type="checkbox"/>	 Trif	1x1	8	double
<input checked="" type="checkbox"/>	 Tso	1x1	8	double
<input checked="" type="checkbox"/>	 Tw_m	45846x1	366768	double
<input checked="" type="checkbox"/>	 Two	1x1	8	double
<input checked="" type="checkbox"/>	 t	45846x1	366768	double

Figure 10: prova.mat file

Downloading in the same folder

“Second_Order_Thermal_Motor_Model.slx” and “prova.mat” (these signals are related to the Test_2023_06_23_14_16_08), it is possible to run the Simulink model, in order to have a comparison between experimental winding temperature and measured one. In case it is necessary to use the model with the data from another test, it is sufficient to update the new values on the Test_data_loading.mlx script. It will create automatically the “prova.mat” file with actual parameters. Anyway, the following link contains a manual for Test_data_loading.mlx script.

[Test_data_loading.mlx manual](#)

4.5 First order vs second order

TEST 2023_06_23_14_16_08

As mentioned in the introduction, it would be possible to introduce a first order thermal model, but its time validity would be limited. In fact, this section shows a comparison of the accuracy in the description of the temperature evolution, of first order and second order model. A first order Simulink thermal model, related to the equivalent circuit in fig.11, can be found to the link: [1_order_thermal_model.slx \(dropbox.com\)](#)

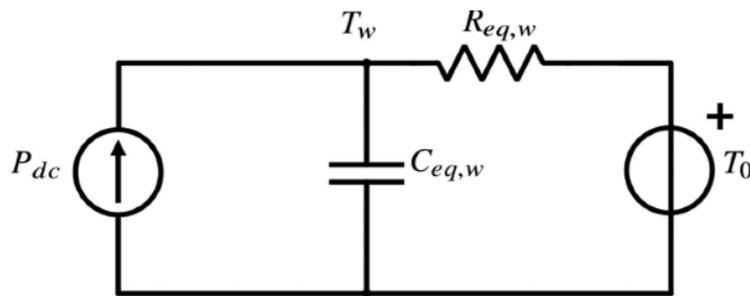


Figure 11: First order thermal model

Circuit parameters have been assumed to have the following values:

- $R_{eq,w} = 0.132$. [K/W]
- $C_{eq,w} = 12500$. [J/K]

As a first approximation it could be stated that, testing the engine over a time range of about 1h 30 min, the first-order model might result inaccurate during the second part of the test.

Thermal behaviour is shown in fig.12.

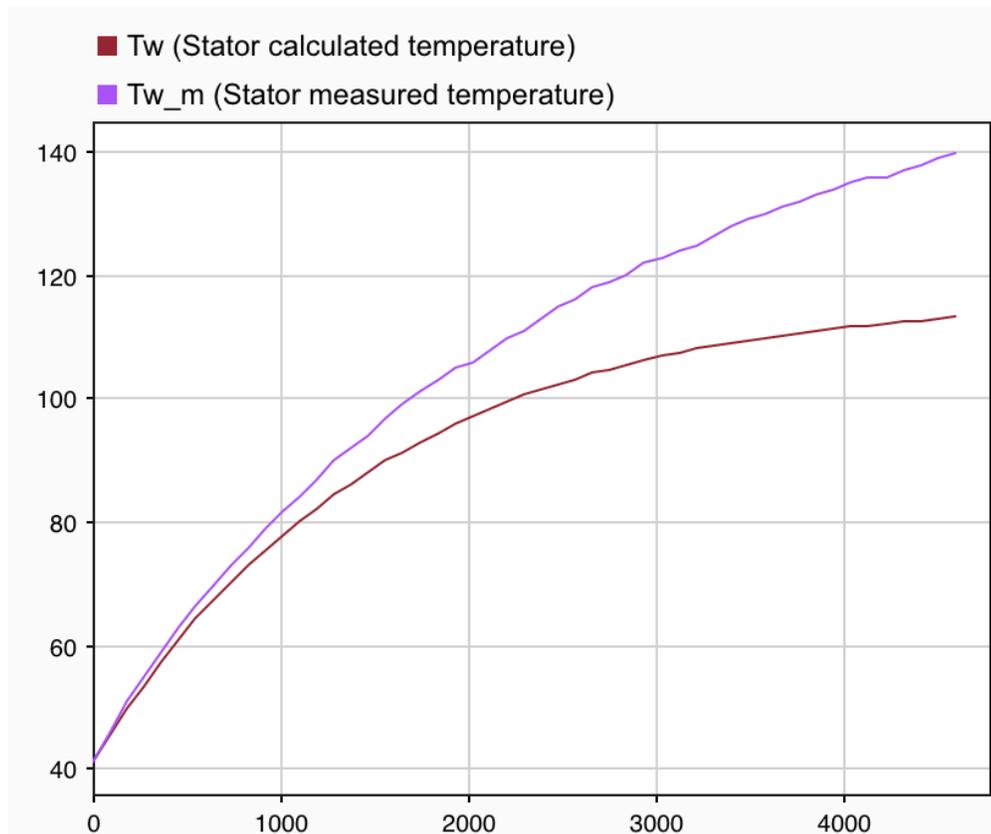


Figure 12: First order model behavior

From the picture above, it can be seen that the model is quite accurate in the first few minutes of simulation. On the other hand, the error between the computed temperature and the measured one increases as the test progresses in time.

As it is reasonable to point out, the second-order model can better describe the temperature evolution over the whole test time. The comparison is shown in fig.13

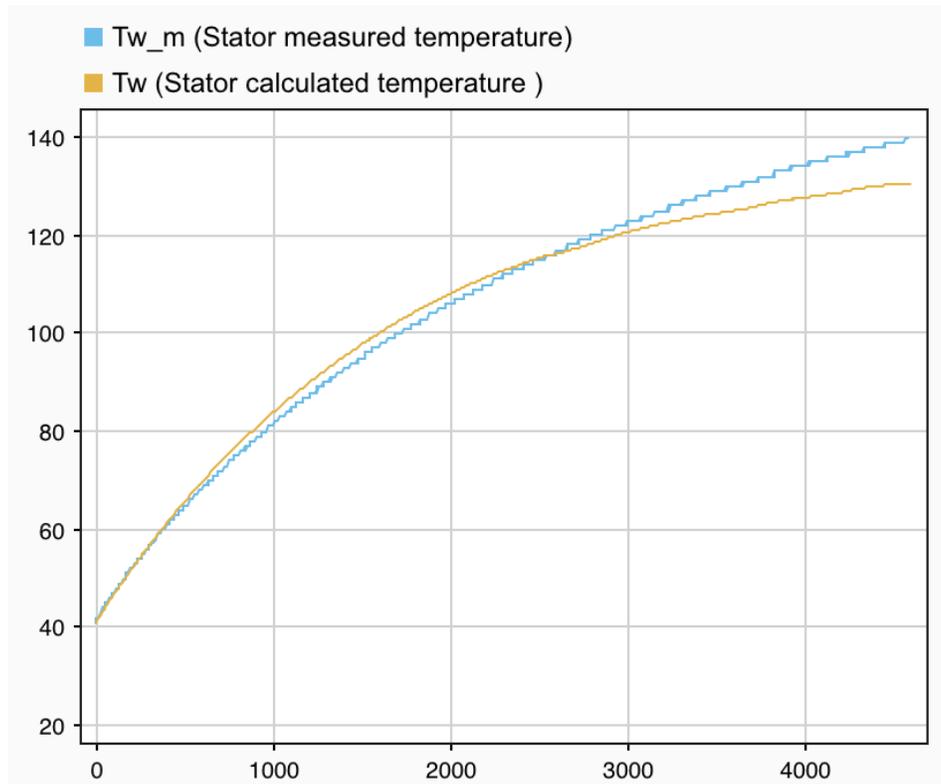


Figure 13: Second order model behavior

The previous picture clearly highlights how the error between the two temperatures is much lower due to the use of a second order thermal model.

4.6 Experimental Results and Validation

TEST 2023_06_23_14_16_08

Figure 10 shows the result of the comparison between the two temperatures;

- experimentally computed winding temperature vs measured winding temperature;
- iron stator temperature;

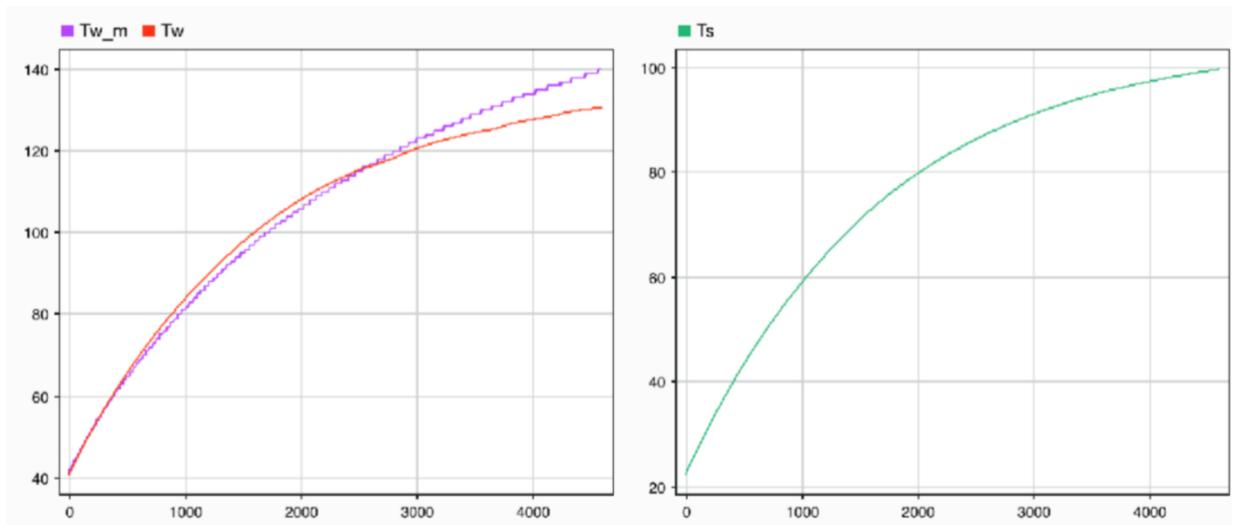


Figure 14: Thermal model signals

The comparison between measured winding temperature (T_{wm}) and estimated one (T_w), shows how good the precision of the second order model is. Moreover, it is possible to see how the accuracy is higher in the first part of the test, while it decreases in the end. This is due to the fact that the circuit parameters have been calibrated with a test of around 30 minutes, while the test processed is around 1h 30min. Last, but not least, as stated at the beginning of this document, the first order thermal model is not as precise as the second order one. Approaching the transient the second order model shows better results with respect to the first order one. Thus, the first order model response cannot be used to evaluate thermal transients that last more than the thermal time constant of the winding.

5 Conclusion

Looking at the accuracy of the second order thermal model of the IPM Synchronous Reluctance motor over the simulated time range, it can be said that it is validated. In fact, it predicts stator winding temperature evolution properly. It can be noted how the accuracy is higher in the first part of the test, while it decreases in the end. This is due to the fact that the circuit parameters have been calibrated with a test of around 30 minutes, while the processed test lasts for about 1h 30min.

In addition, it can be seen that the time simulation range is not sufficient for the steady state to be reached. In other words, calibrating the equivalent electrical circuit parameters over a test with longer duration than the motor time constant, the error between computed and measured temperatures can still decrease. Moreover, it should be possible to observe the evaluation until the motor steady state condition.