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Investigation of the necessity of methodical support of the developer to combine the advantages of two hybrid electric topologies in order to increase the number of realizable functions

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Summary

Within this paper, the necessity of methodical support of the developer to combine the advantages of two hybrid electric topologies in order to increase the number of functions will be investigated. This investigation bases on results of an automated topology synthesis, simulation and evaluation approach, combined with a clinic with development engineers. In this clinic, the participants have the task to apply the method on a given use case and to rate the tool regarding input parameters and the output results. Furthermore, the test persons are to examine whether the topologies proposed as similar are also similar for them.

Keywords: emissions, energy consumption, HEV (hybrid electric vehicle), optimization, powertrain

1 Introduction

As the regulations on CO_2-emissions are defined with 95g/km for the registration of new vehicles from the year 2020 in the European Union [1], the car manufacturers aim to develop more efficient drivetrains. Thereby the electrification of the drivetrain gets into focus. Purely electric vehicles are still quite expensive and customers have the so-called 'Range Anxiety', which means that they are afraid of the short driving range, because of the restrained battery capacity and long charging times, compared to the fuelling process of conventional vehicles [2]. Hybrid electric vehicle drivetrains combine the advantages of conventional and electrical drivetrains and are therefore in the focus in the current drivetrain development. Beside the development of the electric machines and the optimization of the combustion engine, the topology of these drivetrains has a high impact on the efficiency of the drivetrain, as LI and WILLIAMSON [3] have shown.

The developer aims to find a topology which is most suitable and globally optimized for his system of objectives and the driving cycle, which has to be driven for the vehicle certification. This leads to competing development goals, since global optimisation over an entire driving cycle covering different speed ranges can also lead to different topologies that are differently well suited for different speed ranges. As shown in Figure *1*, a topology with an electric machine (EM) that is close to the differential unit (D) can be more efficient in areas where the vehicle is driving at low speed, for example in urban areas. In inter-urban areas, where a combined usage of the internal Combustion engine (ICE) with the EM is more likely, a topology with a gearbox between ICE; EM and D might be more efficient, as the operation points of the propulsion machines can be influenced by different gear ratios. In addition, the EM can shift the load point on the ICE in partial load ranges without gear losses. For high speed driving on highways, where more power is needed, a combination of the two formerly described topologies might be the best solution. Of course these estimations are highly dependent on the characteristics of the propulsion machines and on the topology and can not be regarded without their interactions.

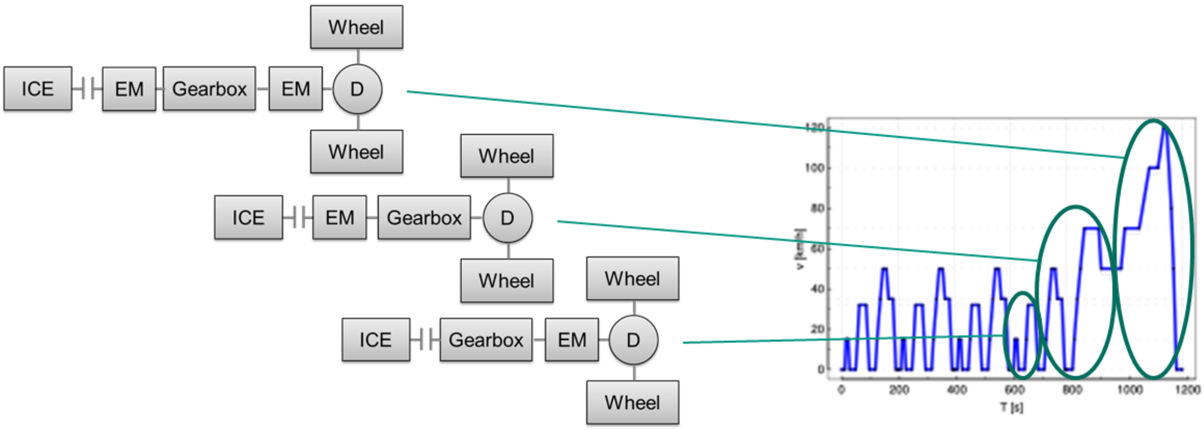

Figure 1: Exemplary topologies that are estimated to be differently efficient in different speed ranges.

The challenge in the product engineering process is to identify in a first step topologies, that are suitable for the defined system of objectives. As the number of possible drivetrains rises with increasing number of topology components, the developer needs support to identify the most suitable drivetrain for his application. When this step is done and there are various topologies, that are globally seen suitable for the application, the question is, whether the advantages of these topologies might be combined in order to identify a even better topology.

In this paper, a methodical support for the identification and evaluation of hybrid electric vehicle drivetrains for a definable system of objectives is introduced and its applicability investigated in a study with development engineers.

2 Current procedure in the development of hybrid electric vehicle drivetrains and new method in order to identify new drivetrain topologies

2.1 Current procedure in the development of hybrid electric vehicle drivetrains

The current development of hybrid electric drivetrain topologies is focussed on the conventional drivetrain. To profit from scale effects, the hybrid drivetrain derivate of a vehicle series has many similar subsystems of the conventional drivetrain of this vehicle series. The hybrid functionalities are integrated in the conventional drivetrain, as construction kits are established [4] and the cost as wells as the development risk can be reduced in this way. As described in the introduction, the topology of the hybrid electric vehicle drivetrain has a high impact on the overall efficiency of the drivetrain. This is in contrast to the current procedure in the development of hybrid electric vehicle drivetrains, where the topology of the conventional drivetrain is reused. Therefore, the authors developed a new method which is introduced in the following sections of this chapter.

2.2 New Method to identify new hybrid electric vehicle drivetrain topologies

Based on the integrated Product engineering Model –iPeM- [5], RUOFF presented a new method to identify new hybrid electric vehicle drivetrain topologies for a defined system of objectives, which supports the developer with an automated topology synthesis, simulation and rating process [6]. The evaluation of the topologies, based on the analytic hierarchy process, makes it possible to reduce the complexity for the developer and to suggest him the most suitable drivetrain topologies for the defined system of objectives [7].

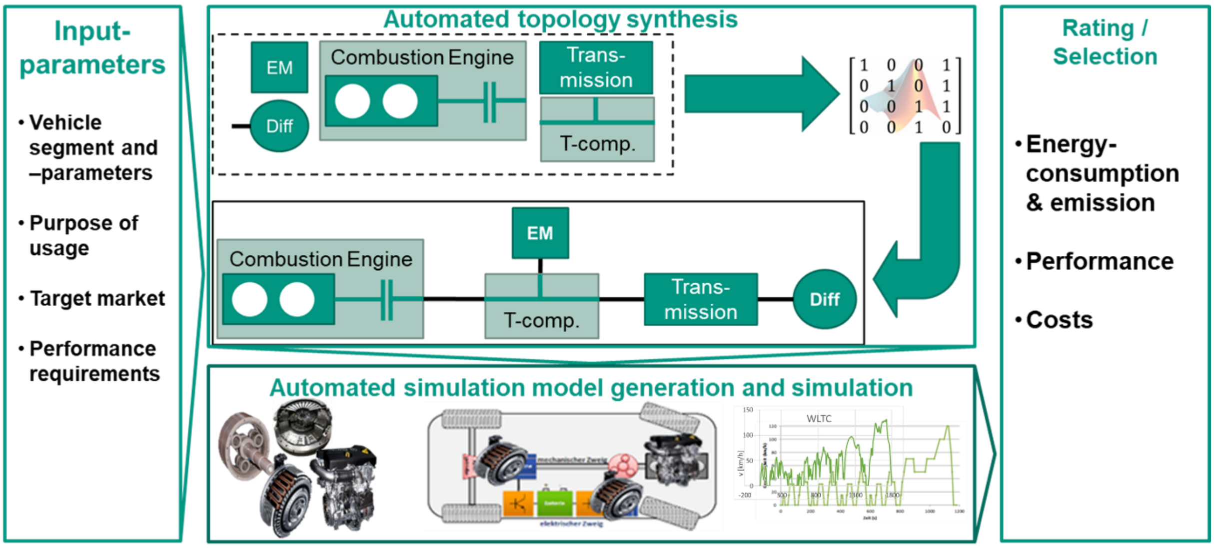

Figure 2: Method for the automated topology synthesis, simulation and rating based on [6]

2.2.1 Input parameters of the tool that is based on the described method

In a first step, the developer has to specify the system of objectives. Therefore, he has to define the vehicle segment, for which he wants to identify a suitable drivetrain. Beside this information, the target market and the purpose of usage have to be defined, as well as the preferred fuel of the combustion engine and a decision has to be made, whether the vehicle should be external chargeable or not. Based on this information, a suggestion of the performance requirements is given by the tool, which can be adapted by the user. In the next step, a suggestion of the number of used components for the topology syntheses is provided to the user that can be adapted as well. The user has the possibility to vary the number of used electric machines and transmissions and can specify whether all topology classes are to be investigated or only selected ones.

2.2.2 Synthesis and calculation of the tool

Based on the input parameters regarding the number of components for the topology synthesis, the topology synthesis process starts and generates all mechanical realizable topologies. These topologies are described mathematically within matrices, by applying the graph theory.

These topology matrices are afterwards used to build up simulation models for each topology automatically. The simulation models are operated with a general operation strategy that fits to all topologies. Each topology can be tested in the defined driving cycle, which correlates with the input parameter “target market”. As the regulatory for the calculation of the fuel consumption prescribe how to initial conditions of the tested vehicle have to be, the simulation performs according to the regulatory. For example, the simulation starts once with a full battery and once with a flat battery and the regulatory conform fuel consumption is calculated afterwards.

The automatic evaluation process, at the end of the tool chain, is taking the simulation results into account and rates the topologies according to their fulfilment of different criteria in the three categories: “Performance”, “energy consumption”, “emission and costs”. The result of the evaluation is a utility value for each topology. The utility value is calculated by using the analytic hierarchy process in combination with a weighting procedure, that considers the system of objectives, according to the description by RUOFF et al. [7].

2.2.3 Output of the tool

The user gets a ranking of all topologies regarding the defined use case, which is based on the utility value.

Besides this ranking, there is detailed information provided for each topology. The structure of the topology is displayed and the category classified, e.g. as parallel hybrid. The state of charge at the beginning and end of the driving cycle, as well as the fuel consumption are given as values and as graphs. Despite the energy consumption there are also graphs for the vehicle speed and the chosen operation modes during the driving cycle. For the used propulsion machines, there are also the efficiency and fuel consumption maps given, with the used operation points in the driving cycle. There is further information given about the vehicle data, as e.g. the vehicle mass, and of course the utility value is displayed. As the simulation is performed twice for each topology, once with a flat battery at the beginning of the simulation and once with a full battery at the beginning of the simulation, the user gets the output files for each simulation run, for each topology. The calculation of the fuel consumption and the electrical driving range according to regulatory is provided as well.

These output files are provided for each topology. An additional output of the tool is a list of similar topologies, which might be combinable. The idea behind the combination of two hybrid topologies and the relevant criteria are described in the next chapter.

3 Combination of the advantages of two hybrid topologies

3.1 Modelling of the hybrid topologies in the synthesis

To be able to understand the idea of the combination of two hybrid topologies, the modelling of the hybrid topologies in the synthesis process is described in this section. The propulsion machines, internal combustion engine (ICE) and electric machine (EM), are modelled as components with one mechanical interface, as they are mechanical power sources. A transmission is modelled with two mechanical interfaces, an input and an output. The differential is modelled with one mechanical interface, as it is the end power of the mechanical power flow in the synthesis process and represents in the vehicle the differential including the side shafts, chassis and the driven wheels. To be able to connect an ICE and an EM to a transmission input shaft, an additional component is needed, that allows to connect three interfaces. This is the so called T-component, which has three mechanical interfaces. In its standard configuration it stands for a loss-free torque addition with a ratio of 1. Despite this configuration it can also stand for a planetary gear, which is used for example

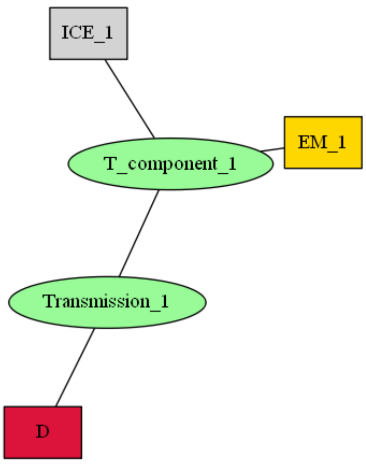

Figure 3: Exemplary topology synthesis result – representing a parallel hybrid

in power split hybrid transmissions. As a clutch might be positioned between each single component of a topology, the number of possible topologies would rise too high. That is why clutches are not modelled in the topology synthesis. An exemplary topology, which consists of an ICE, an EM, a transmission, a T-component and a differential, is displayed in Figure *3*. This topology corresponds to a parallel hybrid, which many German OEMs applicate in their drivetrain, by integrating an EM in the conventional drivetrain at the transmission input shaft.

3.2 Aim and criteria of the similarity analysis

The idea of the combination of two hybrid topologies results from the described modelling principle and has as one aim to detect possible positions of a clutch in the drivetrain, in order to enable various driving modes, where different propulsion machines are participating at the drive of the vehicle. Therefore, the two hybrid topologies have to have similarities, which allow their combination.

3.2.1 Mechanical similarity of topologies

In order to be able to combine two hybrid topologies, it must first be examined to what extent they are suitable for a synthesis. If they are suitable, they are called similar in this method. Although there is a clear mathematical definition of the term similarity from the field of statistics, it is very commonly used in everyday language. Also, a mathematical measure of similarity may vary according to the characteristics considered. Therefore, this chapter will show which possibilities exist to compare two graphs, so that a similarity measure or alternatively a distance measure can be assigned to them. The aim is not to capture the functional proximity of the topologies, but rather the constructive effort for a combination of the individual functions.

The clutch plays an elementary role in the combination of two drive topologies. It allows individual components in the vehicle to be separated from the power flow or integrated into it. Each possible combination can then be regarded as its own topology, whereby the effort for a change in this case is minimal. Two topologies, which can only be transferred into each other by using a few couplings, are therefore easy to synthesize and should also be recognized as such by the algorithm. It should be noted that functional similarity, i.e. comparable driving behaviour, does not guarantee this. Rather, a combination of such topologies, which show as different simulation results as possible, is of interest, because in the ideal case the advantages of both can be used.

Thus, a solution was searched for that leads to an identification of structural similarities, but either ignores functional similarities or even evaluates them as exclusion criteria. The consideration of the simulation results is therefore not absolutely necessary, but can lead to the fact that, in addition to the synthesizability of two structures, the meaningfulness of such an operation can also be made recognizable.

However, the analysis of possible combinations should not only identify topologies consisting of the same components that are connected differently. Up to a degree, the integration of additional components can also result in a positive cost-benefit ratio. One of the decisive factors is where they are located. If an additional component is to be inserted at the edge of a topology, this represents less design effort than if it were to be accommodated centrally, because the entire installation space must be adapted for this purpose.

In addition to the position of the individual components - i.e. integrated in the middle of the topology or exposed - it also plays a role by which components two structures differ. The easiest way to explain this is to give an example: Assuming that two topologies differ only by one transmission inserted at any point. Then a combination is quite simple, only one shiftable gear with a ratio of one has to be added to the transmission, and one can be transferred into the other. The exact opposite is the case when two drive trains are identical except for one planetary gear. This means that it appears at the same point in both cases, but the shafts are connected differently. In order to achieve identical behaviour, a considerable design effort is required, for example by inserting several couplings. Exposed components such as the motors can be easily integrated by using an additional coupling. This aspect must therefore also be taken into account in the evaluation. Ideally, the difference between two topologies is calculated according to type, position and connected components of each component.

3.2.2 Criteria for the suggestion of the combination of two topologies

After a similarity value has been assigned to all drive trains to be tested, these still have to be evaluated. At the end, the user should receive concrete suggestions as to which topologies further investigation or synthesis would make sense. The easiest way to solve this problem is to define a limit value for the distance. If this limit is exceeded, the topologies are too different for a combination, if their distance is less, they should be examined more closely. This value could first be determined using a few examples and then tested experimentally. Unfortunately, this method ignores one important aspect: not only the constructive effort is decisive, but also the potential added value of a synthesis. If two structures achieve identical simulation results, it makes little sense to be able to transfer them into each other, for example by means of couplings, because the resulting vehicle would not be superior to its predecessors at any point. On the other hand, a high synthesis effort can be justified if a significant increase in performance can be achieved. In addition to the distance value, another parameter must be introduced between two topologies to evaluate how promising a combination is. This must then represent how differently well these different test cycles run, and whether one of the two is not already the better choice in all areas.

After the simulation, a lot of data is available, which must first be filtered for an evaluation: The fuel consumption, the state of charge of the battery, the speed driven and many more. For a simple distinction as to whether a synthesis can be useful or not, however, the basic statement as to whether both topologies offer advantages over the other is sufficient. This can be determined on the basis of a number of previously defined properties: The state of charge of the battery at the end of the driving cycle, the average fuel consumption achieved and the difference between target and actual speed, which are queried after different cycles. The bigger the difference between the two topologies in these areas, the more likely it is that a combination will bring benefits.

Two criteria are decisive for the decision as to whether or not a synthesis of two topologies is recommended: their feasibility within a reasonable effort and their added value in relation to the driving characteristics of the vehicle depicted. The calculated distance values make it easy to determine the former by means of a limit distance. All graph pairs lying within the permitted distance values are then considered to be constructively transferable into each other.

The meaningfulness of a combination of two topologies is more difficult to assess. A number of characteristics can lead to the fact that a synthesis brings an added value. Several measurable simulation results can be considered. If there is a difference between the topologies across all the results considered or if there are clear advantages of a topology in individual areas, the proposal for a synthesis can be made. The considered properties are: Average fuel consumption, state of charge (SOC) at the end of a drive cycle and the difference between vehicle speed and target speed within a simulation.

Each of these properties is determined and stored in several driving cycles. These values can be scaled: Relative to the other topologies, each individual result is mapped to a number between zero and one. A one would mean that it is the best of all values within all simulations, a zero the worst. If all properties for each driving cycle are scaled accordingly, a property vector containing these values can be defined for each topology. The Euclidean distance between two of these vectors can then be used to estimate the extent of the functional differences.

If the Euclidean distance of the property vectors lies above a fixed threshold value, and none of the topologies considered dominates the other one, the synthesis is evaluated as meaningful. Dominance means that one topology performs better than its counterpart in all considered areas of the simulation. Once the meaningfulness has been decided, this information is stored similarly to the distance values.

The effort for a combination of two topologies increases proportionally with the distance in between, so the inclusion of pairings with a higher distance value than necessary should be avoided.

3.3 Exemplary investigation of similar topologies

In the following section three topology pairings are introduced, which are classified as similar after the evaluation of the mechanical similarity and the simulation results.

The first pairing, displayed in Figure *4*, differs in one component, as a transmission is integrated in the second topology. If the transmission is a multi-stage transmission and one gear step is implemented with a ratio of one, the mechanical functionality is the same, when the gear with the ratio of one is engaged. From this point of view, the similarity can be understood, by assuming, that the transmission exists within one topology. The effort of integrating a transmission in the other topology is of course not to be neglected.

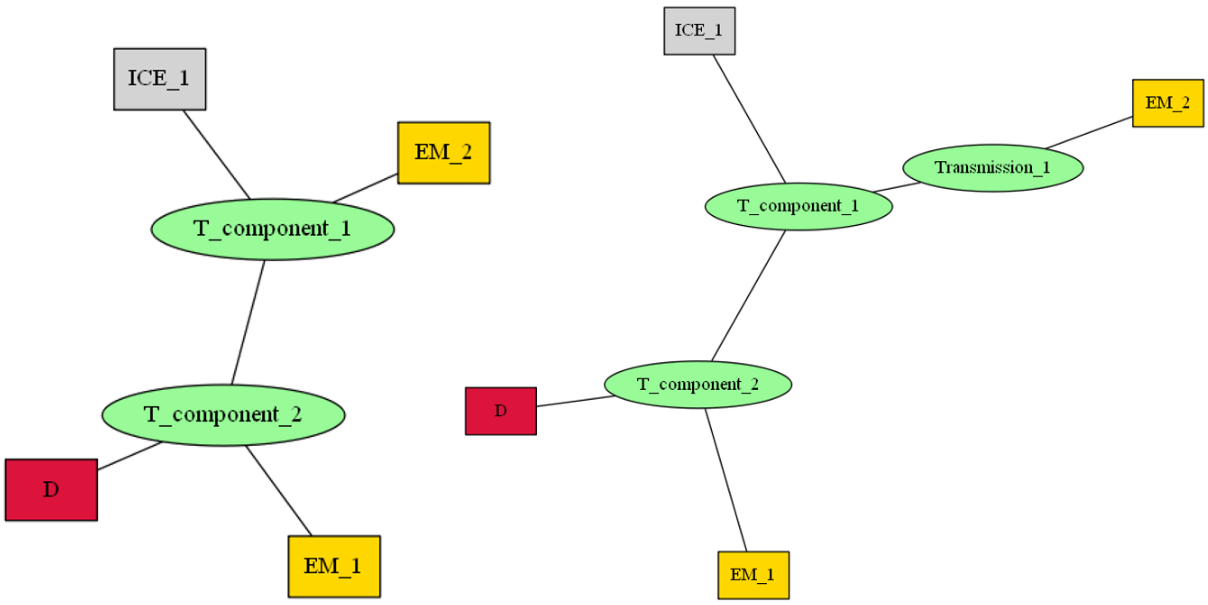

Figure 4: Topology pairing of two topologies that are classified as similar, diverting in one component.

The second pairing, displayed in Figure 5, differs in an additional transmission as well. Besides the transmission, there is also another EM integrated, which needs a T-component, to be integrated into the topology. Therefore, this topology pairing differs in three components. Regarding the right topology, the functionality of the left topology can be reached when the transmissions has a gear with the ratio of one, as explained in the first topology pairing. Additionally, between the added electric machine and its connected T-component, a clutch has to be integrated and opened, to enable the functionality of the left topology. It hasto be mentioned, that the numbering of the components is not taken into account and is therefore not of meaning in the similarity analysis.

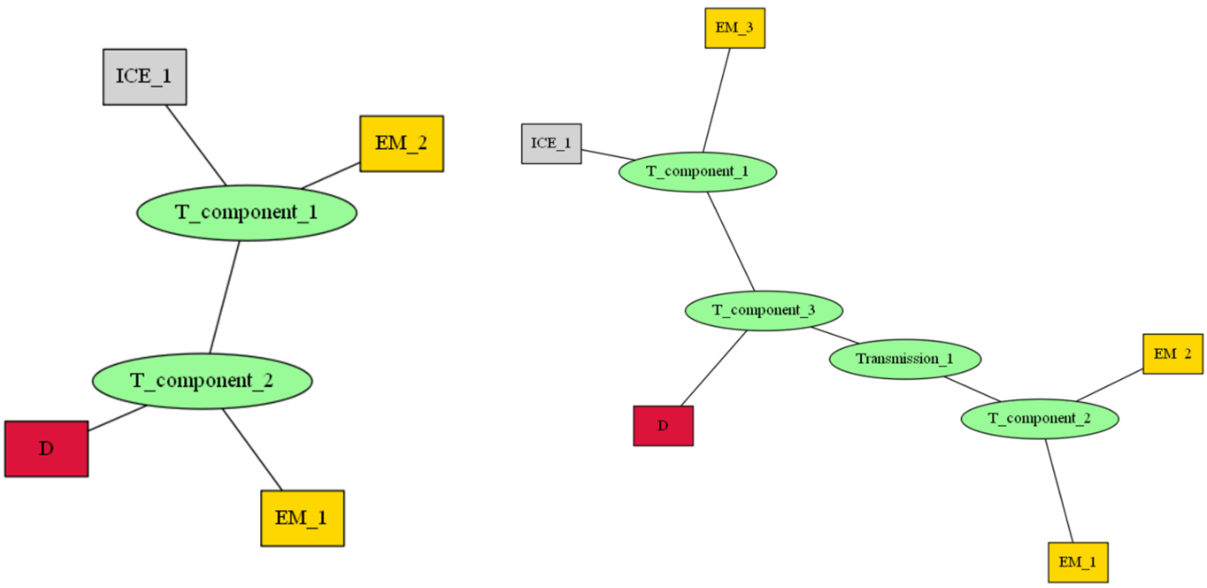

Figure 5: Topology pairing of two topologies that are classified as similar, diverting in three components.

The third pairing, displayed in Figure 6, differs in the number of components only in one component, an additional transmission. Despite this distinction, two component types are arranged different within the topologies, which makes it difficult to see the similarity of the two topologies. At this point, the modelling of the topologies within this method has to be taken into account and the topology category, which is parallel in this case. As mentioned before, the T-components are modelled as loss-free parts of a transmission, where the torque is added, in parallel topologies for the torque addition. Therefore, all components that are

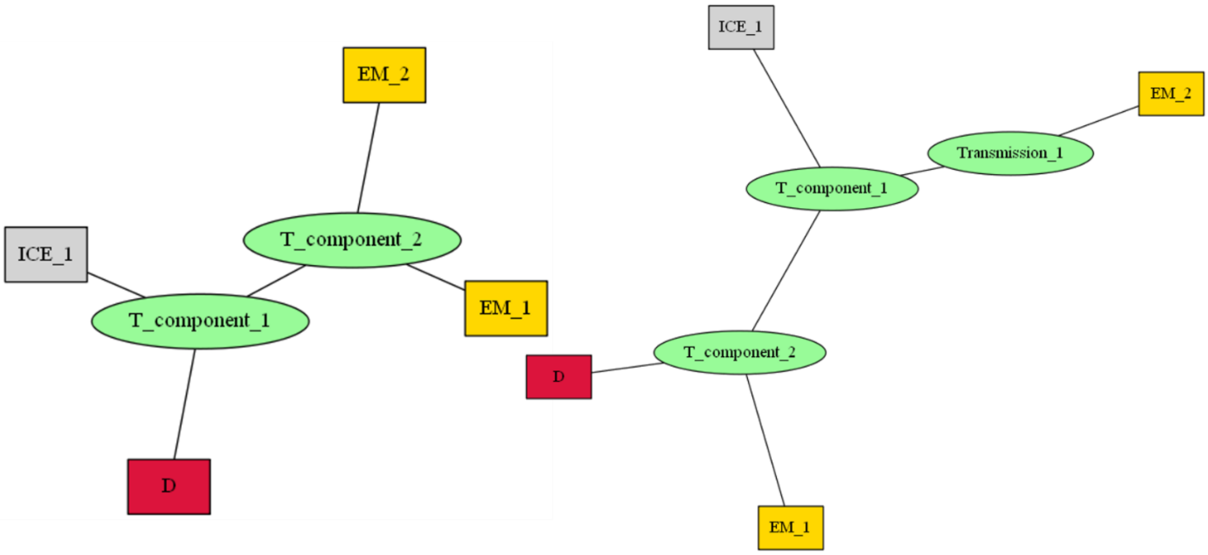

Figure 6: Topology pairing of two topologies that are classified as similar, diverting in switching of the component arrangement and adding of a component.

connected to each other with T-components between each other can be exchanged. This can be compared mechanically to a shaft, where all components are connected to. As it does not matter where the torque is applied to the shaft, as long as there is no transmission in between, an exchange of the components does not influence the functionality. For that reason, the topologies of the third pairing are from functional and mechanical view only differing in an added transmission, which is not that easy to recognize without the explanation, mentioned in this section.

The previously described topology pairings were also shown in the performed study with development engineers. The description of the study and the results are presented in the next chapter.

4 Study with development engineers

4.1 Aim and procedure of the study

The aim of the customer study is to verify to what extent the tool is considered applicable by potential users.

Problems in the handling and usefulness of the tool are to be recognized and suggestions for possible extensions are to be found. In addition, the usefulness of the tool itself will be questioned and alternative purposes discovered.

Furthermore, the integrated similarity analysis will be examined by users and evaluated afterwards.

In order to fulfil the objective of the customer study, various survey methods are used. Since the tool is still in the development phase, a qualitative survey is chosen in which research is carried out very close to the user in order to filter out the relevant variables for applicability. The framework of the survey is a kind of interview in which a ready-made questionnaire is filled in and an experiment is carried out.

The questionnaire starts by checking the level of knowledge of the respondents on hybrid vehicles. This check is carried out by closed questions that have predefined answer options and the respondent is asked to tick the answer that best matches his or her knowledge. Based on this, the interviewer can explain certain backgrounds if the interviewees state that they are not aware of them. This ensures that the required basic knowledge, on which the input masks of the tool are based, is available to all participants. The closed questions also facilitate the evaluation of the study.

The main part of the questionnaire deals with the applicability of the tool, which is classified using the parameters clarity, comprehensibility and meaningfulness. Since the tool itself is very extensive and therefore difficult to evaluate as a whole, it is divided into three different levels, which are examined with the help of an experiment. The first stage consists of the two input masks, which have to be operated after starting the tool. The outputs generated by the tool after the synthesis, simulation and evaluation of the topologies act as the second stage. The similarity analysis performed after the output of all found topologies represents the last stage.

In the experiment, the test persons are confronted with the same use case, which they are to implement in the tool. The outputs of the tool are presented to the participants in written form. After each step, the participants are asked to complete the corresponding part of the questionnaire - i.e. input, output and similarity analysis. If attitudes, statements or questions are expressed orally, the interviewer records them in minutes in handwriting in order to be able to better reconstruct the written key point answers of the questionnaires in the evaluation.

In addition, the interviewer is always available to help the respondents, as the similarity analysis is still relatively rudimentary and therefore not intuitively understandable.

The questions asked in this part of the questionnaire are open. This means that the respondents are not limited by answer specifications, but can express their individual opinions on the above-mentioned parameters of applicability.

Finally, so-called social-demographic characteristics are recorded in the questionnaire. These show the test persons' experience in the field of drive system technology. In order to obtain a differentiated result at the end of the evaluation, persons with different levels of knowledge are interviewed as part of the customer study.

4.1 Results of the study

The study was carried out with different participants. It was assumed that the test persons had some prior knowledge in the field of hybrid vehicle powertrains, otherwise the useful operation of the tool would not be guaranteed. It must also be taken into account that the potential users of the tool are trained development engineers who master these basics. Nevertheless, care was taken to ensure that the participants were diverse in terms of career and experience in drive system technology in order to obtain a meaningful result with regard to the applicability of the tool. The participants had work experience in the field of drive system technology from half a year to 25 years. In addition, they were at various stages of their careers from a bachelor of science degree to a doctorate in industry. On average, the group dealt with drive system technology on an almost daily basis.

The input made by the user before the synthesis and simulation of the topologies is carried out is unanimously evaluated as understandable and clear. Only instructions for menu navigation would facilitate intuitive operation. According to the interviewees, all parameters needed to determine a new hybrid topology optimized for the application were also taken into account.

The tool's outputs are generally comprehensible and meaningful for all test persons. Helpful suggestions were given, which can be subsequently incorporated into the tool in order to make it more suitable for use by other persons.

Opinions differed on the similarity assessment. The concept of similarity was unanimously recognised as meaningful, but it was depending to the similarity category, whether the similarity between topologies was recognized without further hints or not. Three different categories of topologies similar to the tool, as introduced in the chapter before, were presented to the respondents in writing.

The first category consisted of the addition of a type of component, which in the study corresponded to the installation of one or more multi-stage transmissions with one stage with a gear ratio of one. The next category included the installation of several types of components such as the installation of gearboxes (as described for the first category) and the addition of an electric motor, which could be separated from the rest of the driveline by a clutch. The exchange of two component types within the topology as well as the installation of one component type represented the third and last category.

The first category was clearly recognizable as similar for all participants except one participant. During the survey, the participant expressed the opinion that the installation of a multi-stage transmission would no longer be similar for him. According to him, the strategy, consumption, comfort, installation space and power flows changed depending on the characteristics of the transmission. Based on this assumption, he could/must therefore also classify the following categories as not similar. For him, the installation of one or more transmissions was the decisive factor in identifying two topologies as not similar. Nevertheless, the test person was able to clearly identify the so-called combination points (interfaces between the two similar topologies at which they can be mechanically merged) for each similarity category and knew how the combination points could be implemented mechanically.

The remaining participants can be divided into two groups, those who could see the similarity of the second category and those who could also see the similarity of the third category. However, this classification was based on a basic explanation of the similarity and the examples given by the interviewer. From this it can be concluded that in order to recognise the similarity between two topologies, a certain level of information must be available so that the user can deal with the output of the tool and further develop the results on this basis. The required information, which was collected from all interviews, is the mechanically possible implementation of the combination points, the different mechanical characteristics of the T-components as well as the reference to the modelling of the T-components as loss-free.

The meaningfulness of composing similar topologies in relation to overall efficiency was also assessed differently. The sample can be divided into three equal groups. One third can estimate whether the combinations make sense according to their own statements. The second third has an idea of which parameters they can use to estimate the overall efficiency of the composite topology, and the last third lacks certain clues for evaluating meaningful combinations. Both the second and the last third insisted on a simulation of the combined topology in order to give a meaningful assessment of the overall efficiency.

All respondents would use the tool in the early stage of the product development process [8] to generate a hybrid topology concept. One participant also said that the tool could also be used after the product creation process by reading in an already found topology and finding a similar one.

Accordingly, the application possibilities of the tool were recognized by all participating persons.

5 Summary and Outlook

The paper describes an approach to identify topologies for hybrid electric vehicles within the development process and how to merge the best topologies in order to gain topologies with more functions. The reduction of complexity in the development is achieved by supporting the developer with a framework that considers the boundary conditions and gives the developer a ranking of the best solutions. With a methodical support, the development engineer shall be able to combine the best topologies of the synthesis process to even better topologies.

As the participants were supported by explanations and examples, these will be integrated in the methodical framework. In addition to these amendments, it was suggested to develop a principle sketch library and to convert the graphs into principle sketches so that the user can better comprehend the results functionally. This representation could also make it easier for users to recognize similar topologies and their interfaces.

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