New Energy-Efficient Electromagnetic Clutch for Automotive Air Conditioning Compressors

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ABSTRACT

Even if the air conditioning is switched off, the internal combustion engine in today's cars continues to drive the common compressor. To avoid resulting power losses, the automotive industry aspires to apply electromagnetic clutches. When the air conditioning is used, however, CO_2-emission increases significantly because the electromagnetic coil consumes electricity. The CO_2-reduction per year is consequently very low, which is why new compressor clutches were developed that do not require a permanent electric power supply. Additionally, these clutches are characterized by low production costs, a simple functional principle and a small package.

1. INTRODUCTION

Air conditioning compressors with variable displacement nowadays are usually not equipped with electromagnetic clutches. When the air conditioning is switched off, the compressor is still driven at minimum displacement, which causes power losses and consequently additional fuel consumption. That is why the automotive industry seeks to apply electromagnetic clutches, that are already used for fixed displacement compressors. By applying such a clutch, the compressor can be stopped while the air conditioning system is not running, which avoids power losses and therefore reduces CO_2-emission. But when the air conditioning system is used, CO_2-emission increases significantly because the electromagnetic clutch consumes additional electricity.

For this reason, two innovative electromagnetic clutches were developed at Chemnitz University of Technology. These clutches do not require a permanent electric power supply.

2. DESIGN AND FUNCTIONING

2.1 Clutch Type A

As it is common practice today, the pulley is rotatably mounted on the compressor housing (Figure 1). The electromagnetic coil on the housing, too, does not require specific adaptions. A spring plate connects an adapter on the compressor drive shaft with a carrier disk. This disk is axially shiftable and can transmit a torque to the compressor drive shaft.

In the initial position, the spring plate keeps the carrier disk from touching the pulley. On the carrier disk are several locking elements, that are slidable in radial direction. A plastic cover protects the clutch mechanism from dirt.

When the air conditioning is activated, the electromagnetic coil is supplied with power, which pushes the carrier disk onto the pulley. As a result, a friction force develops between the pulley and the friction pads on the carrier disk. Thus the carrier disk and the compressor shaft are driven. When the compressor shaft reaches a particular rotational speed, the centrifugal force might move the locking elements outwards in radial direction. If the locking elements immediately snapped into the grooves that are integrated in the pulley ring, the clutch could be damaged because of the speed difference between the carrier disk and the pulley. To avoid this, an edge in the pulley keeps the locking elements from engaging with the grooves.

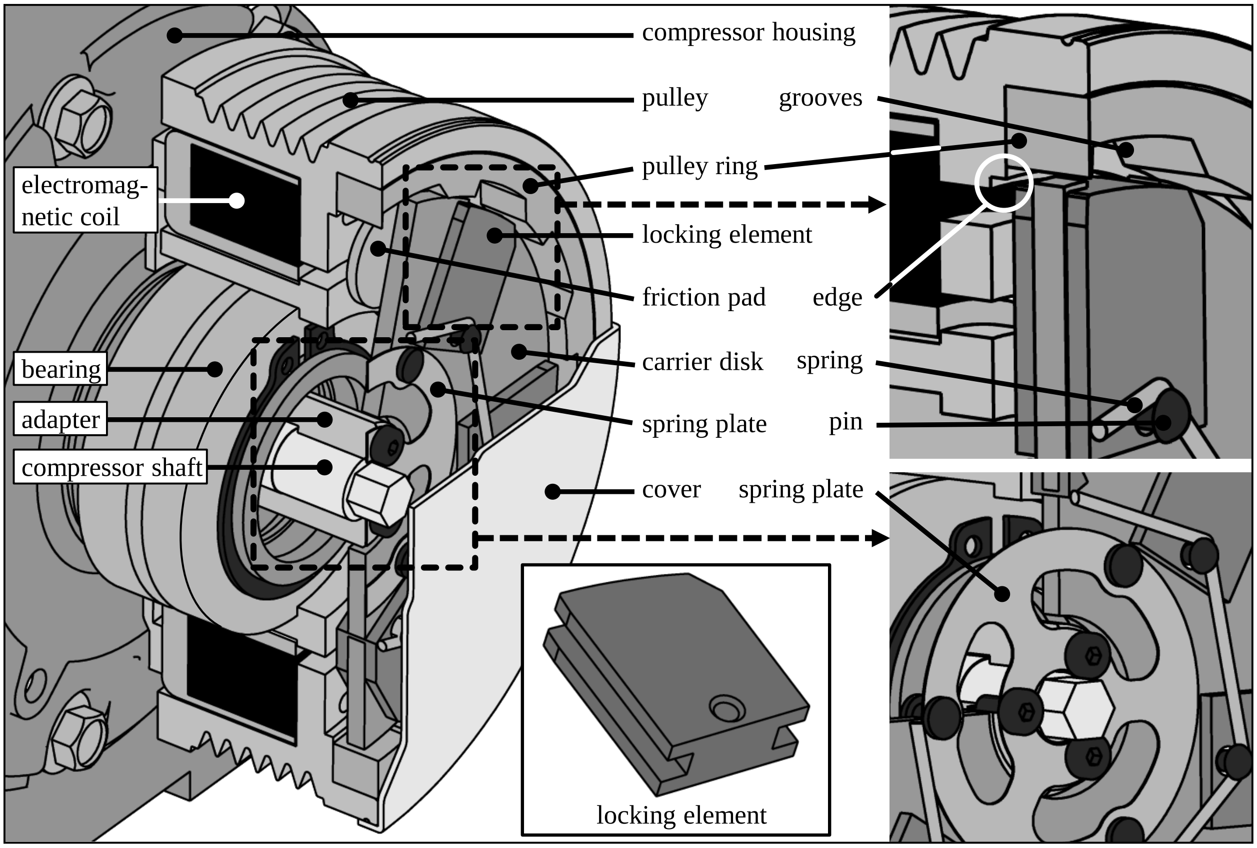


Figure 1: Clutch type A

The electromagnetic coil is supplied with power for a particular amount of time (e.g. 5 s) to make sure that the pulley and the carrier disk are in sync. When the power supply for the electromagnetic coil is cut off, the spring plate pulls back the carrier disk and the locking elements are detached from the edge in the pulley. The locking elements can now snap into the grooves because of the centrifugal forces. The torque can thus be positively transmitted from the pulley to the compressor shaft without electric power.

When the internal combustion engine is stopped, a spring pulls the locking elements out of the grooves and separates the pulley from the compressor shaft.

This type of clutch cannot be opened when the internal combustion engine is running. If the air conditioning is switched off during the ride, the compressor needs to be operating at minimum displacement as usual. However, simulations (Chapter 4) have shown that this disadvantage is insignificant compared to clutch type B (Chapter 2.2), that can be switched on and off anytime.

2.2 Clutch Type B

Another clutch type developed at Chemnitz University of Technology allows to switch the compressor on and off at any time while the car is running.

This clutch, too, is equipped with an electromagnetic coil and a pulley, which is mounted on the compressor housing (Figure 2). A specially designed clutch plate opens and closes the clutch. This clutch plate consists of a shift plate, a tooth washer and a blocking disk with its blocking elements.

A hub mounted onto the compressor shaft is equipped with a rotatable blocking ring, which has several teeth, that are alternately short and long. A spring plate connects the hub with the axially moveable clutch plate. A tooth ring on the front of the pulley can engage with the tooth washer. Thus the pulley is positively connected with the compressor shaft. As with type A, this clutch is protected by a plastic cover.

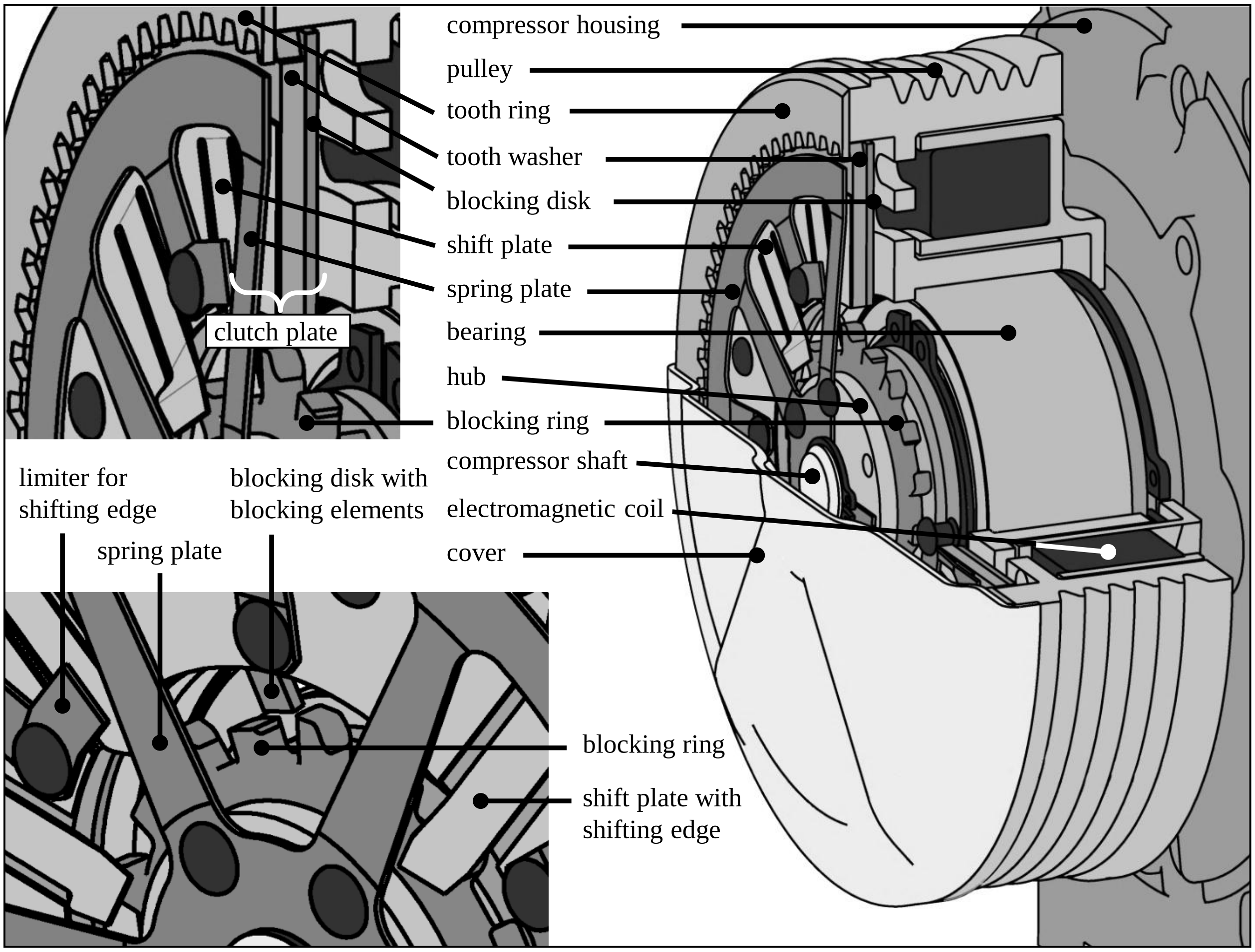


Figure 2: Clutch type B

When the clutch is open, the axial movement of the clutch plate is blocked because the blocking elements collide with the long teeth on the blocking ring (Figure 3a). Thus the tooth washer cannot engage with the tooth ring.

When the air conditioning is switched on, the electromagnetic coil is supplied with power, which pushes the clutch plate onto the pulley (Figure 3b). Thereby shifting edge i on the shift plate rotates the blocking ring by half a tooth pitch (Figure 3c). Because of the friction force between the pulley and the blocking disk, the compressor shaft is driven.

After a certain amount of time (e.g. 5 s), the pulley and the clutch plate are synchronized. The electromagnetic coil is switched off afterwards and thus the spring plate pulls back the clutch plate (Figure 3d). Simultaneously, shifting edge ii moves the blocking ring by another half tooth pitch (Figure 3e). The blocking elements can now pass the short teeth on the blocking ring and the tooth washer can snap into the tooth ring (Figure 3f). Consequently, the clutch is closed and the compressor can be driven without a permanent electric power supply.

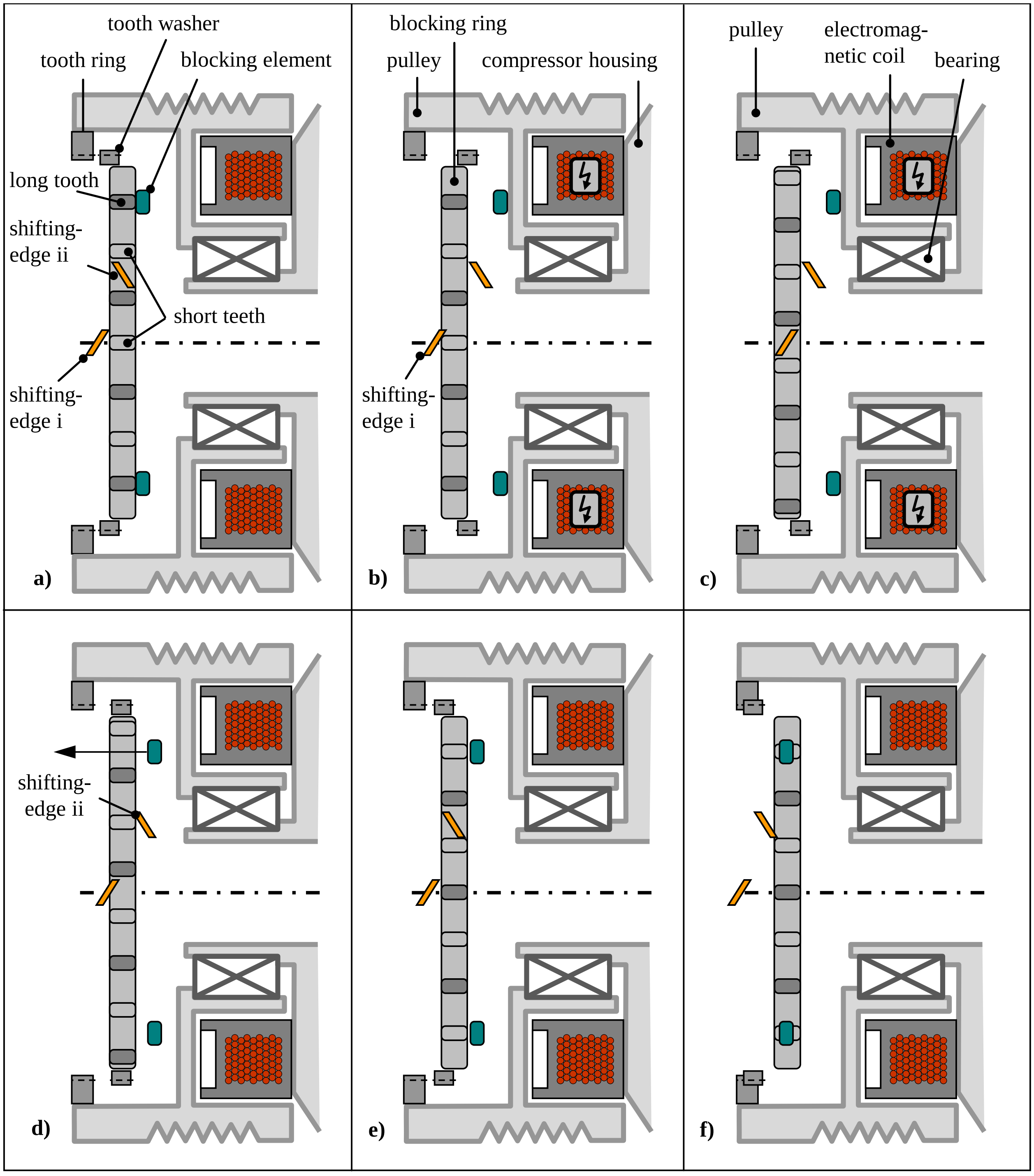


Figure 3: Closing procedure clutch type B

To open the clutch, the electromagnetic coil has to be supplied with power (Figure 4a) and thus the clutch plate is pushed onto the pulley, which moves the tooth washer out of the tooth ring (Figure 4b). This process separates the pulley from the compressor shaft. At the same time the blocking ring rotates by half a tooth pitch (Figure 4c). After the electromagnetic coil is switched off, the clutch plate moves backwards (Figure 4d), which rotates the blocking ring by another half tooth pitch (Figure 4e). The blocking elements cannot pass the long teeth of the blocking ring now (Figure 4f). As a result, the tooth washer cannot lock with the tooth ring. Contrary to clutch type A (Chapter 2.1), the compressor can be stopped while the internal combustion engine is running.

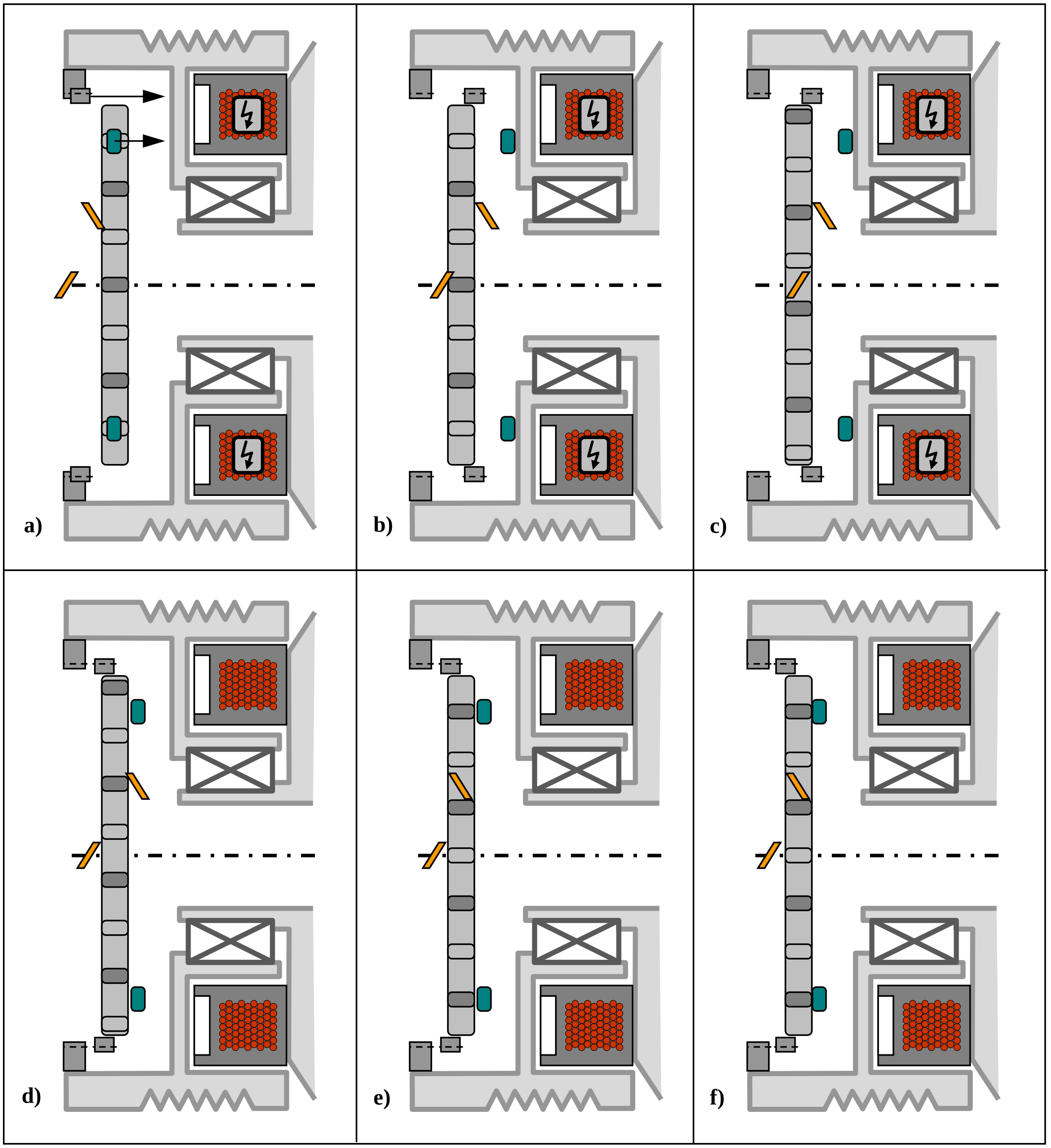


Figure 4: Opening procedure clutch type B

3. SIMULATION MODEL

In order to simulate and optimize air conditioning systems, for all components of the refrigeration cycle, geometry and process-based models were developed, which will be described in the following (Baumgart 2010, Baumgart and Tenberge 2010).

The compressor model is based on an externally controlled air conditioning axial piston compressor. The model considers the dynamic behavior of the discharge valves and the suction valves in a very detailed way because said behavior has a great influence on the compressor characteristics. Using the equations of the valve motion as well as the thermodynamic and fluid processes in the cylinder a system of equations can be developed, whose solving allows the simulation of the processes in the compressor. Furthermore all acting forces and torques in the compressor are calculated, that determine the required driving power. With this model for instance the refrigerant mass flow, the refrigerant temperature at the compressor outlet and the above-mentioned driving power can be predicted for any operating point.

In addition to the compressor model, detailed models for the heat exchanges (evaporator and condenser) as well as the expansion valve have been developed.

For a holistic consideration of the air conditioning system it is necessary to describe the temperature behavior in the passenger cell. For this purpose a cabin model has been developed, which considers all heat transfer mechanisms in the passenger cell and the heat input caused by solar radiation for each cabin elements including shadowing effects by other components. The model also takes into account the influence of the driver caused by convection, heat radiation, breathing and transpiration.

All mentioned models were validated through extensive measurements.

By combining the models for the compressor, the heat exchangers and the expansion valve, the refrigeration cycle can be described depending on the

- compressor speed,
- relative compressor displacement,
- velocity profile of the air flow at the condenser inlet,
- air temperature and relative humidity at the condenser inlet,
- air volume flow at the evaporator inlet and
- air temperature and relative humidity at the evaporator inlet.

The compressor speed depends on the combustion engine speed, which was taken from driving cycle data. These data are based on an urban, an extra-urban and a highway driving cycle (Table 1).

Table 1: Driving cycles

	Urban	Extra-urban	Highway
Distance [km]	8.49	37.25	255
Average speed [km/h]	23.8	68	91.44
Duration [min]	21.37	32.87	167.33

The velocity profile of the air flow at the condenser inlet is determined with a CFD software for many relevant vehicle speeds.

The air state at the condenser inlet is equated to the state of the environmental air. The temperature and the humidity as well as the solar radiation, which is relevant for the cabin model, were taken from weather data for Germany and Italy.

The air mass flow into the passenger cell depends on individual settings of the air conditioning. The respective data for the simulation are detailed in Deh (2003).

The relative compressor displacement is calculated for each time step as follows: First the difference between the cabin temperature and the desired comfort temperature is calculated by using the cabin model. From this difference the required air state at the evaporator outlet is determined and then used to calculate the relative compressor displacement iteratively with the help of the model for the refrigeration cycle.

Thus the model provides the

- air temperature and humidity in the passenger cell,
- compressor driving power and
- relative displacement of the compressor

in dependence of the time.

With the compressor driving power, the additional fuel consumption and CO_2-emission can be determined.

The here presented investigations are based on an air conditioning system with an externally controlled seven-cylinder compressor with a maximum displacement of 160 cm³. The transmission ratio of the belt drive between the combustion engine and the compressor is 0.741 (into higher speed). Similar compressors are standard components in car types such as Audi A3 and Volkswagen Golf. The assumed geometry properties of the passenger cell conform to a medium-sized car.

During the simulation, the air conditioning was "switched on" when the comfort temperature in the passenger cell could not be reached through environmental air only. By means of the dew-point-temperature of the cabin air and the window temperature it was checked whether the windows were about to mist up, in which case the air conditioning was "switched on" as well.

For the simulation the above-mentioned driving cycles (Table 1) were exemplarily distributed (Table 2) over a complete year with a total distance of 15,901 km.

Table 2: Distribution of the driving cycles

Cycle	Frequency	Starting time
Urban	4 times a week	9.00 a.m.
	4 times a week	3.00 p.m.
	2 times a week	1.00 p.m.
	2 times a week	5.00 p.m.
	2 times a week	10.00 a.m.
	2 times a week	2.00 p.m.
Extra-urban	1 time a week	9.00 a.m.
	1 time a week	3.00 p.m.
Highway	every 5th week	9.00 a.m.
	every 5th week	3.00 p.m.
Total distance [km]	15,901	
Average speed [km/h]	39.4	
Duration [min]	403.3	

4. RESULTS

4.1 CO_2-Reduction by Applying a Conventional Electromagnetic Clutch

By applying a conventional magnetic clutch, the compressor can be disconnected from the belt drive when the air conditioning is switched off, which reduces power losses and CO_2-emission. However, CO_2-emission increases with the air conditioning activated because of the additional electric power demand of the electromagnetic coil. This power demand was assumed to be 40 W in the simulation. A typical alternator map was used in the model to determine the resulting additional driving power.

The CO_2-savings that can be achieved by applying the conventional electromagnetic clutch were determined for each ride (Table 2) with the simulation model described in chapter 3. For a better understanding the results are summarized for every month in Figure 5.

Figure 5a illustrates the monthly CO_2-reductions under German environmental conditions. The diagram makes it clear that the conventional clutch allows CO_2-reduction only in cold months, when the air conditioning is used very rarely. In the summer, however, CO_2-reduction even increases because of the permanent power consumption by the electromagnetic coil. Under Italian environmental conditions, CO_2-reduction is only possible in February; the other months show a significant increase in CO_2-emissions (Figure 5b).

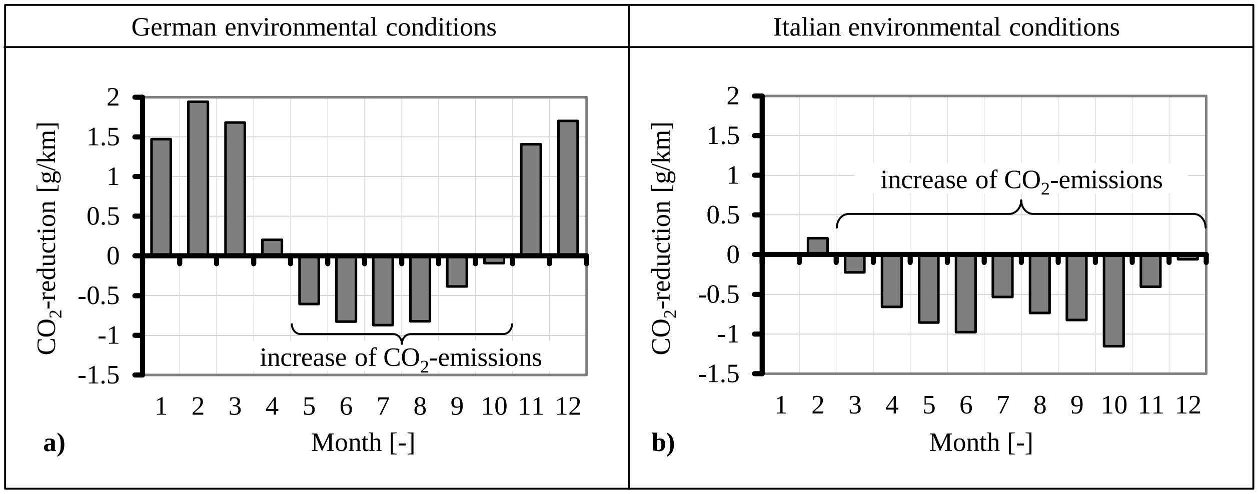


Figure 5: Monthly CO_2-reduction achieved by applying a conventional electromagnetic clutch (in relation to clutchless compressor)

4.2 CO_2-Reduction by Applying the New Electromagnetic Clutches

Figure 6a details the monthly CO_2-reductions, that can be achieved under German environmental conditions by applying the new electromagnetic clutches, in relation to the clutchless compressor. Under wintery conditions both clutch types (A and B) show saving potentials similar to those of the conventional electromagnetic clutch (cf. Figure 5a) because the compressor can be deactivated, which prevents power losses.

Furthermore it becomes evident that the new clutches do not cause additional CO_2-emission in the summer, contrary to the conventional clutch because both clutches (A and B) do not require a permanent electric power supply. However, the saving potentials of clutch type A are fairly low under summery conditions due to the fact that the air conditioning is activated most of the time then. Since clutch type B can be opened anytime, in contrast to clutch type A, CO_2-reduction is slightly higher (Figure 6a, white bars).

Figure 6b shows the results for Italy. Because of the very warm weather conditions, the air conditioning is running most of the time. Thus the saving potentials of the new clutch types are low in relation to the clutchless compressor. However, the clutchless compressor causes higher CO_2-emission because of compressor power losses, even though during CO_2-emission measurements in the New European Driving Cycle the air conditioning is switched off. To avoid these losses during the afore-mentioned CO_2-measurements, the here presented clutches are clearly preferable to the conventional clutch because the latter causes higher CO_2-emission when the air conditioning is running (cf. Figure 5).

Figure 6c illustrates the saving potentials of the new clutch types compared to the conventional clutch under German weather conditions. Since the air conditioning is not used most of the time under wintery conditions in Germany no significant savings can be achieved compared to the conventional type because the compressor is mostly separated from the belt drive. However, the new clutch types do not require a permanent power supply when the air conditioning is activated, which results in significant CO_2-savings in the summer.

Figure 6d details the results for Italian weather conditions. Because the air conditioning is activated most of the time the conventional clutch causes additional CO_2-emission in nearly all months (cf. Figure 5b) due to the permanent power supply. For this reason the new clutches allow considerable CO_2-reductions.

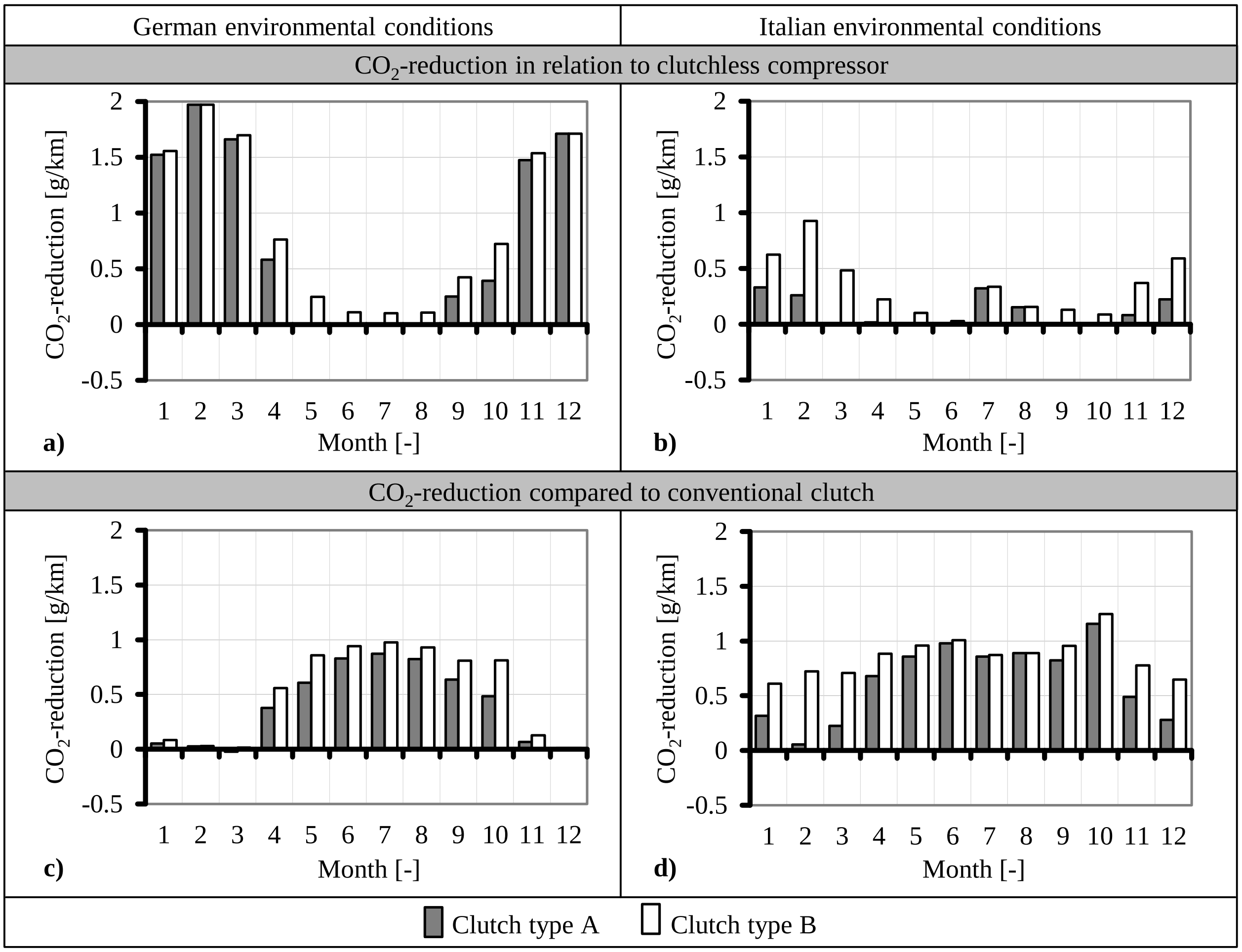


Figure 6: Monthly CO_2-reduction achieved by applying the new electromagnetic clutches

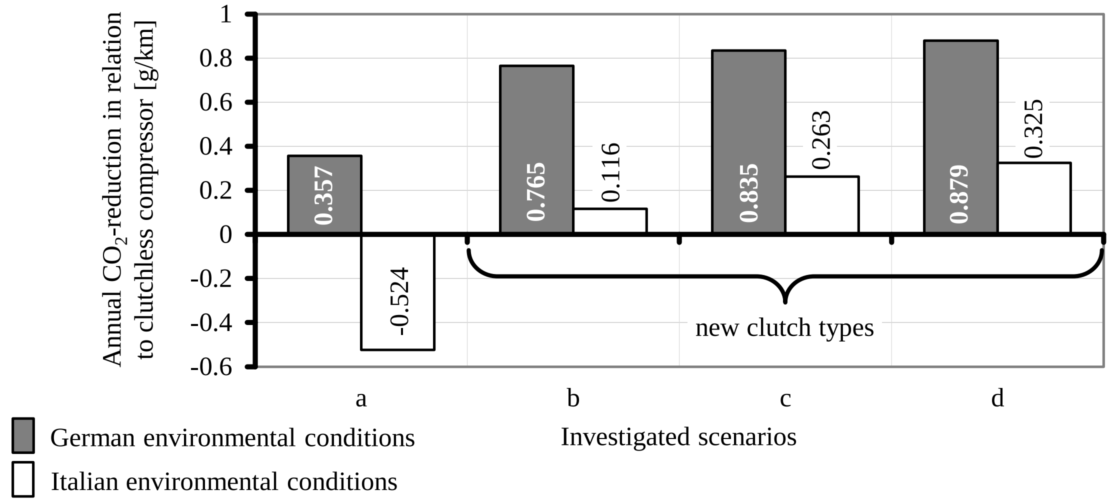
Figure 7 details the annual saving potentials of the compressor clutches in relation to the clutchless compressor. As can be seen, the conventional clutch allows an annual CO_2-reduction of only 0.357 g/km under German weather conditions (Figure 7a, grey bar). Under Italian conditions, though, the annual CO_2-emission even increases by 0.524 g/km (Figure 7a, white bar).

With clutch type A the saving potential can be more than doubled under German weather conditions (Figure 7b, grey bar) and under Italian conditions an annual CO_2-reduction of 0.116 g/km can be reached instead of an additional CO_2-emission (Figure 7a, white bar).

As already described in Chapter 2.1, clutch type A can only be opened when the internal combustion engine stands still. When the air conditioning is switched off during the ride, the compressor of a conventional car cannot be stopped by using this clutch type. The compressor then needs to be running at minimum displacement.
When this clutch is used in a vehicle with a start-stop system, however, clutch type A will be automatically opened by a spring (see Figure 1) when the engine stops (e.g. at traffic lights). If the driver has switched off the air conditioning before, the clutch will not be closed when the engine is restarted until the air conditioning is activated again.

As can be seen in Figure 7c, clutch type A in combination with a start-stop system allows a slightly higher CO_2-reduction compared to a car without such a system. In the simulation it was assumed that the start-stop system has been activated at each stop.

With clutch type B, the compressor can be switched off anytime. As expected, this results in the highest CO_2-reduction (Figure 7d).



a = Conventional electromagnetic clutch (electric power demand = 40 W)
b = Clutch type A (Chapter 2.1)
c = Clutch type A used in a vehicle with start-stop system
d = Clutch type B (Chapter 2.2)

Figure 7: Annual CO_2-reductions achieved by using the compressor clutches (in relation to clutchless compressor)

5. CONCLUSIONS

The investigations have shown clearly that by applying the conventional electromagnetic clutch, compressor power losses can be avoided when the air conditioning is switched off and thus CO_2-emission can be reduced. However, the permanent electric power consumption by the electromagnetic coil causes a significantly higher CO_2-emission when the air conditioning is activated (e.g. in the summer). Thus the annual CO_2-emission even increases by 0.524 g/km under Italian environmental conditions (Figure 5).

For this reason, two new clutch types have been developed at Chemnitz University of Technology. These clutches do not require a permanent electric power supply, neither opened nor closed. Moreover, they are characterized by low production costs, a simple functional principle and a small package. As the simulations have shown, these new clutch types allow considerable annual CO_2-reductions compared to the conventional clutch (Figures 6 and 7).

As a next step, the here presented clutches will be built as prototypes and then tested. Afterwards, they will be further optimized for serial production.

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