Introduction of 48 V Belt Drive System

New tensioner and decoupler solutions for belt driven mild hybrid systems

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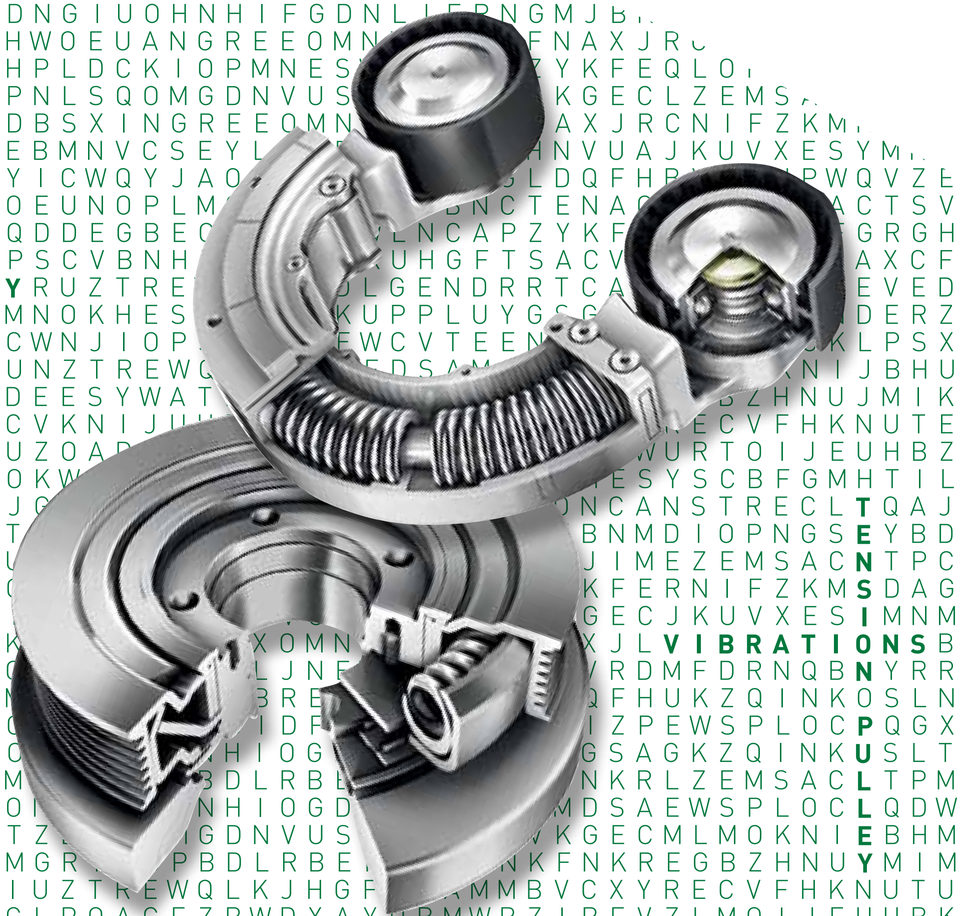


Introduction

The market for belt drives is in motion. At the 2010 Schaeffler Symposium, the focus was exclusively on conventional belt drives with pure load operation of the accessories [1]. Since then, systems with belt starter alternators have increased in importance for belt drive development. They serve to support additional functions like recuperation, boost operation, and engine starts, and thus offer advantages for the fuel economy and function of the engine.

The introduction of 48-volt electrical systems can mean a new boost for belt starter alternators. These enable an increased electric power output and mild hybridization of drives at justifiable costs. Through expanded functions – such as recuperation and electric boosting – considerable fuel consumption savings of up to 14 percent in the NEDC can be achieved.

The transmission of ever-increasing levels of power and torque means belts are subjected to higher dynamic loads. At the same time, vibrations are increasingly introduced into the belt drive, as more and more frequently engines with a reduced number of cylinders, but high mean pressures and thus high rotational irregularities are used. Innovative auto tensioners and crankshaft decouplers from Schaeffler are able to transmit the higher torques safely and also to reduce the vibration with the right design.

Conventional belt drives and belt-driven starter alternator applications

In modern internal combustion engines, the accessories are driven almost exclusively by V-ribbed belts. These belt drives and their automatic tensioning systems must meet the following requirements:

- Automated belt force adjustment during initial installation and maintenance (tolerance compensation of all drive components)
- Practically constant belt force over the entire life of the belt drive (compensation of belt elongation and wear)
- Practically constant belt force over the entire engine temperature range (compensation of heat expansion of all components that affect the drive)
- Reduction of dynamic belt force peaks in the drive
- Minimization of slip, noise, and belt wear
- Operating life increase for the entire belt drive system
- Optimum reliability of the entire belt drive system
- Minimization of friction losses in the entire system

Modern accessory drives, which are optimally adjusted to the entire system, are maintenance-free and can run for more than 240,000 km (nearly 150,000 miles).

Schaeffler offers a variety of products for the design of the front-end accessory drive. Mechanical and hydraulic belt tensioners provide a nearly constant belt force across tolerances, throughout the operating life and the entire temperature range of the engine, and also damp vibrations in the belt drive. Additional damping and decoupling of vibrations can be achieved by using decoupling elements. At Schaeffler, the OAP (overrunning alternator pulley) has therefore been in volume production since 1996 as a freewheel belt pulley on the alternator; the belt pulley coupler has been in volume production as a mechanical decoupler on the crankshaft since 2013. Schaeffler has been using the OAP (overrunning alternator pulley) as a mechanical decoupler on the alternator since 1996 and the pulley decoupler as a mechanical decoupler on the crankshaft since 2013 in volume production. In addition to individual components, Schaeffler also offers system development for the entire belt drive together with ContiTech (Figure 1).

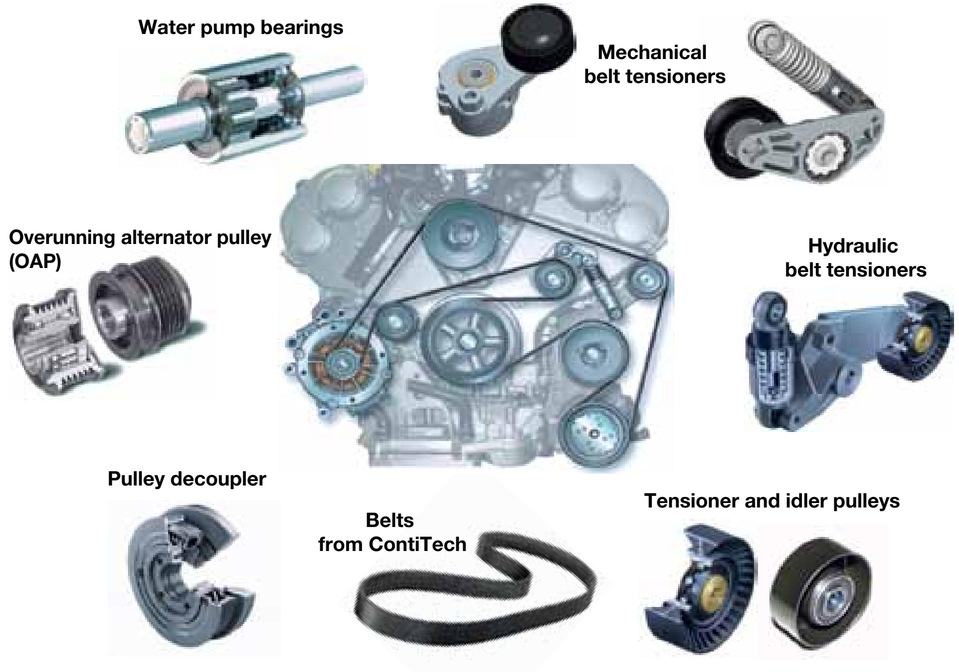


Figure 1 Schaeffler product portfolio for the belt drive

The function of conventional belt drives is characterized by the accessories being in load operation; the power is thus always transferred from the engine to the belt drive. In contrast, in applications with belt starter alternators, the power is transferred from the alternator to the engine at some operating points (alternator start and boost operation).

For conventional belt drives, tensioners with mechanical and hydraulic damping units are common. In addition, an overrunning clutch is often used on the alternator, which compensates fast torque changes when vibrations occur and thus reduces dynamics. This approach is not used in systems with belt starter alternators because the torque must be transferred in both directions, which makes the dynamics in the belt drive much more critical overall.

For starting via the belt, an expanded belt tensioning function is needed in order to allow a transfer of torque in both directions in the belt drive. This function is shown in Figure 2 based on two mechanical belt tensioners.

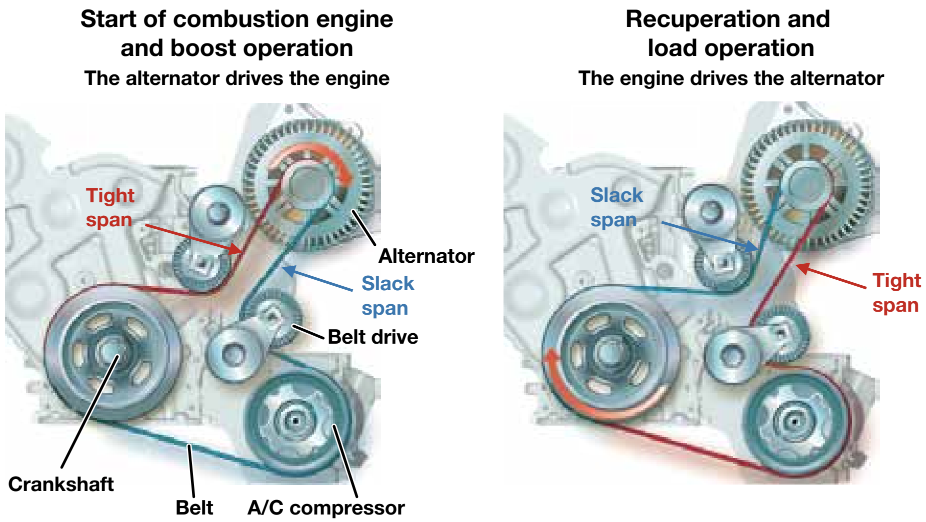


Figure 2 Belt drive load in boost and load direction

When the engine is driven by the alternator – in belt start or boost operation – the power is transferred via the upper run (indicated on the left as the driving run). For the load operation of the alternator (for example during recuperation), torque is transferred from the crankshaft to the alternator (right belt run, shown in the figure on the right as the driving run). The purpose of the tensioner system is to maintain the pretension in the entire system and to prevent the belt load from falling in the slack run.

Belt starter applications were already being researched extensively in the early 2000s [2]. However, development proved to be difficult due to the limited power of 12-volt on-board electrical systems and the unusually problematic vibration isolation. In 2005, Citroën was the first manufacturer to put an application with a belt starter alternator into volume production.

A new generation of belt starter alternators with significantly expanded functions has been in development since 2011. This is possible by using a 48-volt on-board electrical system, which provides up to 12 kW of power. The existing 12-volt on-board electrical system is connected to a voltage converter on the expanded 48-volt network, which includes a 48-volt battery with additional capacity and a 48-volt alternator in the belt drive. The increased capacity of the 48-volt network enables additional functions for the belt starter, which are shown in Figure 3. The expansion of the on-board electrical system to 48-volt in combination with a belt starter alternator is designated in general as a “mild hybrid,” which is positioned, in terms of functions and cost, between the existing 12-volt on-board electrical system and the full hybrid with a high-voltage power supply.

New challenges arise for the belt drive configuration due to the higher power transfer via the belt. This is shown in the following application example, a mild hybrid in a 1.6-liter four-cylinder gasoline engine with 130 kW power and a torque of 260 Nm in a mid-class vehicle (1,400 kg curb weight) with a 6-speed double clutch transmission.

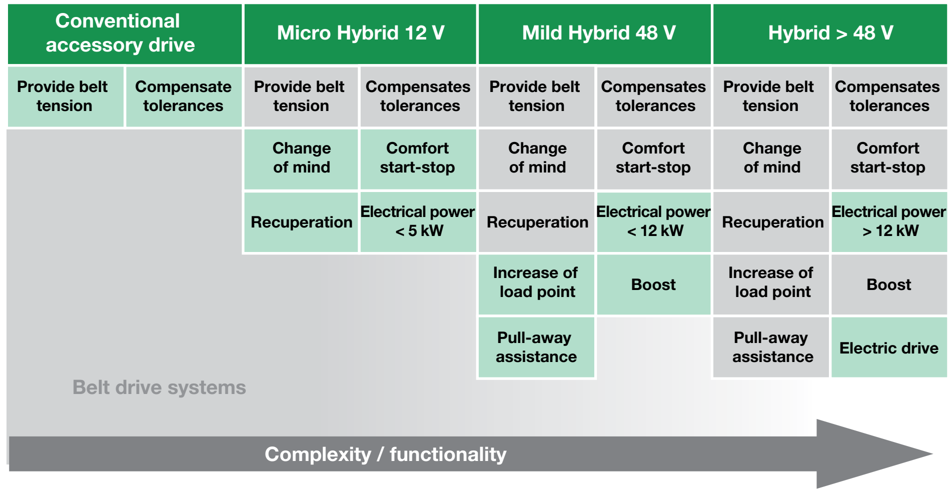


Figure 3 Functions of different hybrid stages

For the accessory drive system, a belt drive with air conditioning and a 180 A alternator is assumed. This technology combination is widely used among different manufacturers for mid-class vehicles. In expanding the belt drive to a 48-volt system, the air conditioning remains, however, the conventional alternator that previously allowed load-only operation is replaced with a 48-volt belt starter alternator. It thus becomes necessary to make an adjustment to the belt drive. The possible operating range for both alternator systems is shown in Figure 4.

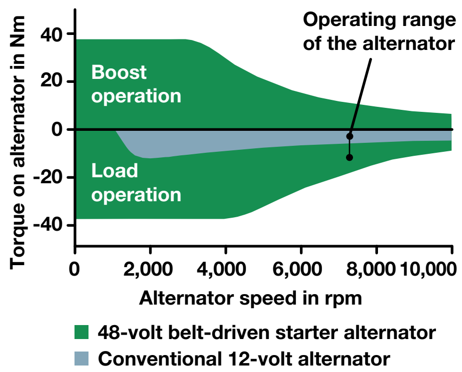


Figure 4 Operating range for a conventional 12-volt alternator and a 48-volt belt starter alternator

In order to obtain a representative depiction of drive performance, reference is made here to the WLTP cycle [3] (Figure 5).

The figure shows the power of the internal combustion engine and the 48-volt belt starter alternator for the example application. The ranges with recuperation (negative power range) and boost operation (positive power range) are easily recognizable from the alternator power signal.

The mild hybrid system offers the following advantages:

- Boost operation
- Recuperation
- Faster and more comfortable engine starts via the alternator, as well as
- Electric driving at low speeds (e.g., as a comfort function in stop-and-go operation or to prevent exhaust emissions in underground parking garages).

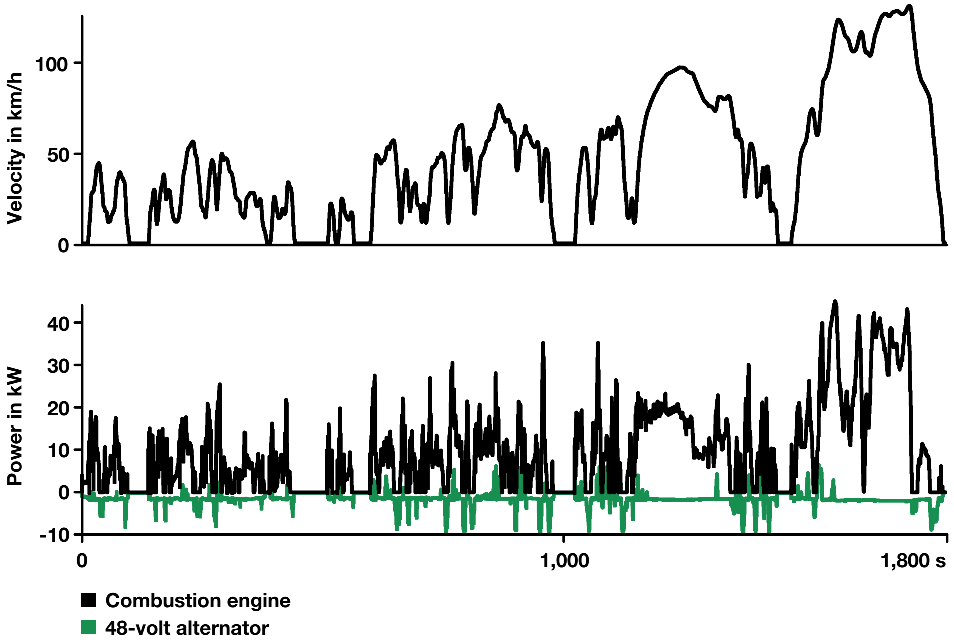


Figure 5 WLTP driving profile according to [3]

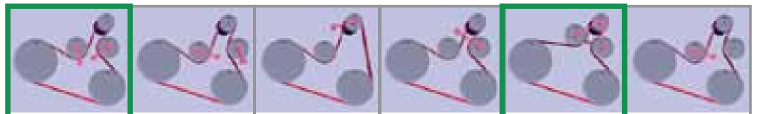
In contrast to the full hybrid, the electric motor is coupled with the internal combustion engine as a belt starter alternator in the mild hybrid. Recuperation and electric driving are only possible when the internal combustion engine is turning – the engine friction must thus be overcome, reducing the effective available power.

The internal combustion engine can thus be run at operating points with greater efficiency, which results in optimized consumption in combination with the braking energy recovery and sailing phases. Current discussions involve fuel consumption advantages in the range of 4 % to 14 % [4, 5], depending on the base driving cycle, engine, and system tuning. At the same time, there is increased driving comfort for the driver due to a very comfortable start function, assistance for the engine from the boost operation, and the possibility of moving off under electric power only in stop-and-go operation.

Belt tensioner configuration for the mild hybrid with belt starter alternator

In the entire system, the mild hybrid offers a noteworthy advantage with regard to driving dynamics and fuel consumption, which is achieved with assistancefrom the internal combustion engine via the 48-volt belt starter alternator. This requires a suitable torque transmission in the belt drive, which differs from the tensioner and damper solutions for the conventional belt drive. In addition to the solution already presented with two individual tensioners, other tensioner systems are also conceivable, and are shown in Figure 6 with their different requirements.

From the classic solution with two mechanical belt tensioners, there are already a few systems in combination with 12-volt systems in volume production. An alternative design requires only one tensioner, which can swivel about the alternator's axis of rotation. These, known as decoupling tensioners, offer the greatest advantages. Figure 7 shows the function of the belt drive system for different operating points. A part of the WLTP cycle is shown in which boost and recuperation operation is used. An alternator start also takes place at the beginning of the depicted range.



	Two mechanical tensioners	Mechanical + hydraulic tensioners	Generator tensioner	Hydraulic tensioner in tight strand	Decoupling tensioner	Hydraulic tensioner in slack strand
Start function (generator start)	+	+	+	+	++	-
Operation under load	+	+	0	0	++	0
Packaging	-	-	+	0	+	0
Costs	+	--	0	0	0	0
Transient operation	+	+	0	0	++	-

Tensioner variants considered on the following pages

Figure 6 Design of different tension system solutions for the belt drive

Engine speed and vehicle speed are shown in the top diagram. The shifting of the double clutch transmission and engine irregularities due to the engine's ignition can clearly be seen from the engine signal. It is easy to tell the vehicle's operating mode from the torque of the engine and belt starter alternator (both shown as torque appearing on the crankshaft), shown in the middle. A positive torque on the belt starter alternator indicates boost operation; dips into the negative indicate vehicle braking with recuperation. To evaluate the dynamics in the belt drive, the hubload on the belt pulley of the belt starter alternator is shown.

Significantly higher dynamic loads can be seen for the system with two mechanical belt tensioners. The area of maximum transferable torque is limited, however, because the two tensioners in the belt drive cannot completely maintain the pretension. If the tensioner is adjusted so that the torque for the alternator start can be fully transferred, the result is a limit on the maximum possible recuperation torque. In this example, the belt slips above at an alternator torque of approx. 30 Nm during recuperation. Overall, these results show that the conventional design approach using two mechanical tensioners is not a match for the increased requirements. The belt drive is simply overloaded.

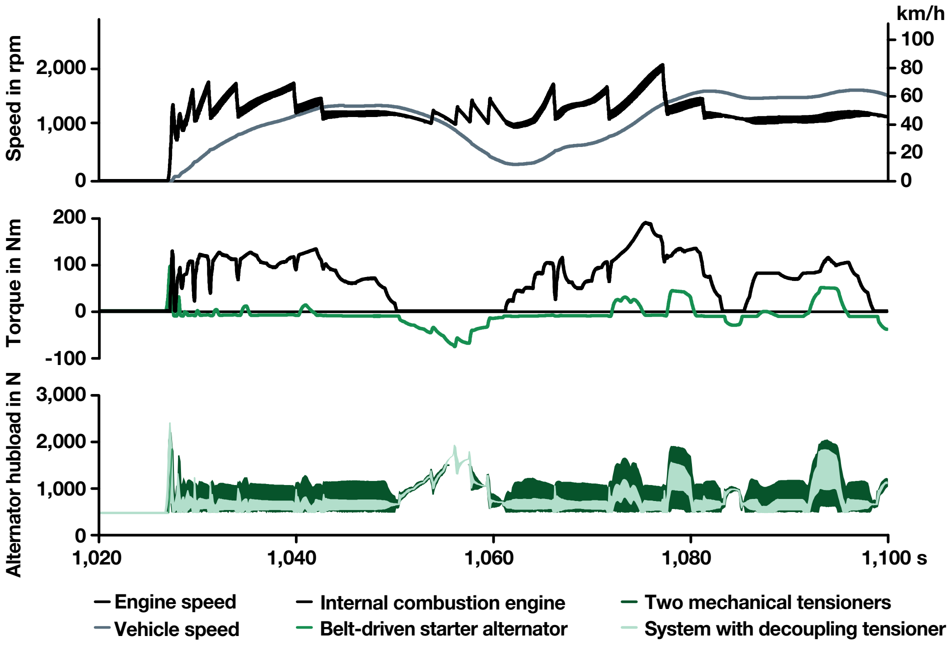


Figure 7 Function of the belt drive system in the WLTP cycle

By contrast, one decoupling tensioner on the alternator has distinct advantages. Improved retention of the pretensioned load in the slack run is one of these, as

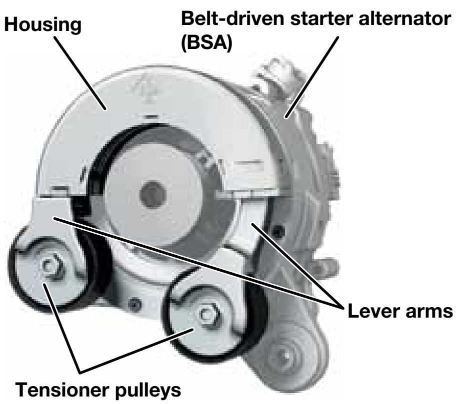


Figure 8 Overview: Decoupling tensioner design

are the significantly lower dynamic loads in the belt drive due to engine excitation. By introducing this type of decoupling tensioner, the dynamics in the belt drive can be managed and the functional advantages are fully achieved with the mild hybrid system. These requirements correspond to a decoupling tensioner recently developed by Schaeffler, which is illustrated in Figure 8.

The tensioner consists of a housing which is connected to the electric motor by a plain bearing and can be rotated by 360° about the electric motor's axis. A tensioner pulley is permanently fixed to this housing. The second tensioner pulley is located on a moving lever and is spring-mounted against the housing by means of an arc spring assembly. This allows the tensioner pulley to create the necessary belt pretensioning load and to compensate tolerances in the belt drive (Figure 9).

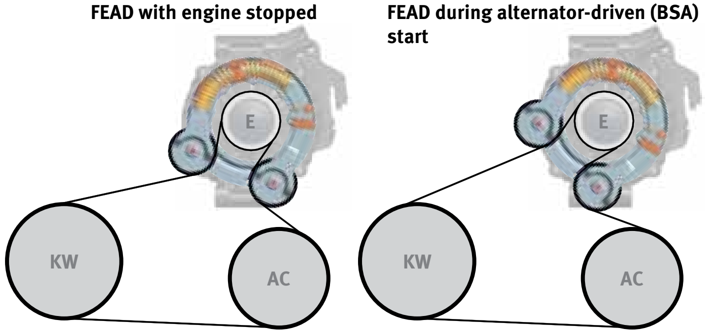


Figure 9 Function of the decoupling tensioner, alternator start with decoupling tensioner

Depending on whether load torque is being applied to the electric motor (alternator operation or recuperation) or it is generating torque (belt start, boosts), the driving run occurs in either the right or the left belt run and the slack run is on the other side. The reciprocating movement of the entire tensioner about the electric motor's axis causes the driving half of the tensioner to be pressed away from the drive and the other tensioner pulley to automatically retension the slack side by means of the the geometric connection, so that it is pushed into the drive. In a solution with two independent tensioners, this geometric connection does not exist, which leads to the slack side tensioner receiving no additional support from the driving half tensioner for tensioning the slack side (Figure 10).

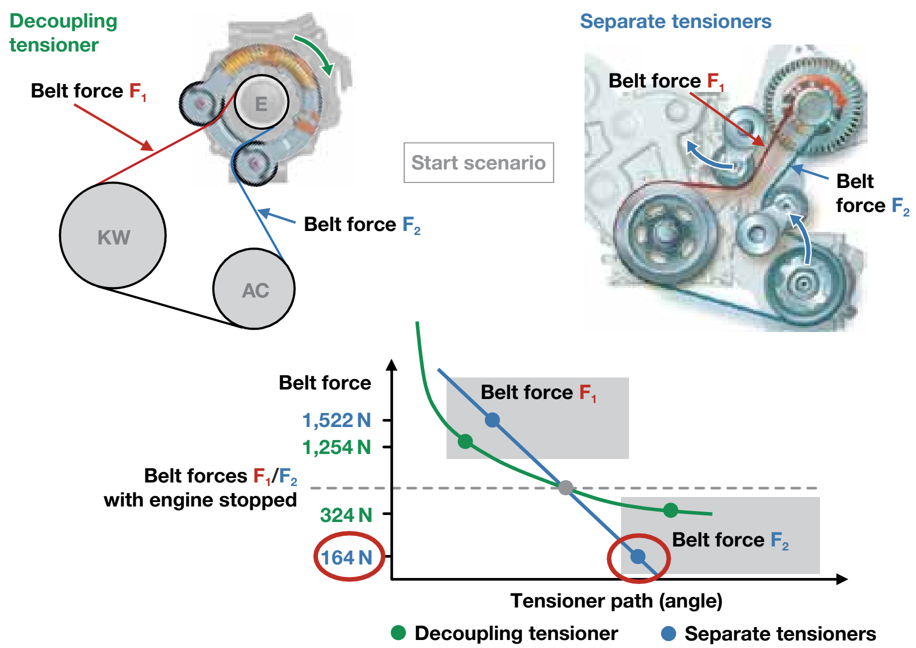


Figure 10 Comparison of the belt tension during engine start

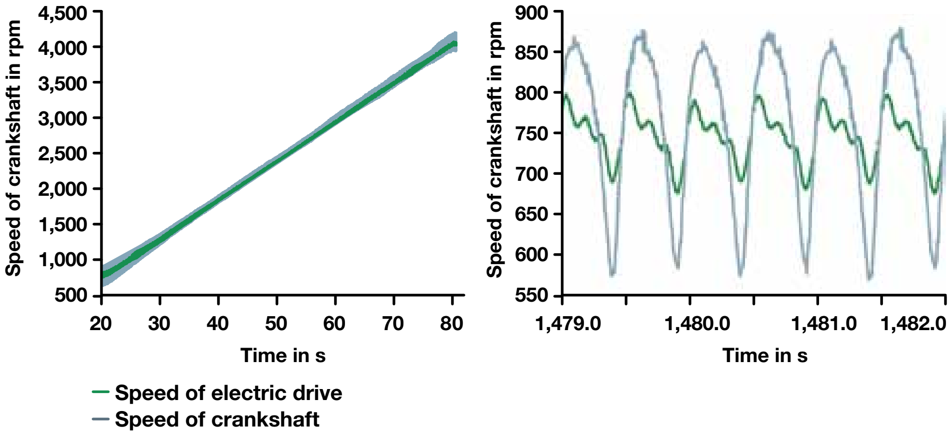


Figure 11 Decoupling effect of the tensioning system

Figure 11 clearly shows the additional decoupling effect of the tensioning system: Only a small portion (green) of the rotational irregularity introduced into the drive from the internal combustion engine (grey) reaches the electric motor shaft via the reciprocating movement of the decoupling tensioner.

This decoupling effect is sufficient for many belt drives with belt starter alternators. The use of advanced decoupling measures is still necessary because of increased rotational irregularities as a result of smaller engines with higher specific power and a lower number of cylinders.

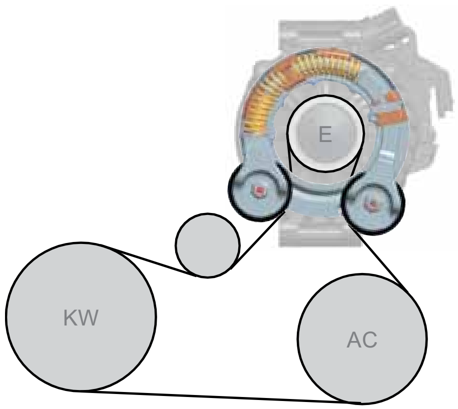


Figure 12 Layout of the belt drive

Belt starter systems with crankshaft decoupling

When power is transferred between belt starter alternator and engine, the decoupling tensioner automatically damps vibrations in the belt drive due to its design. This function is dependent on the belt drive layout and the position of the accessories as well as on the internal combustion engine excitation. The example of a mild hybrid drive with a highly turbocharged 2-liter four-cylinder diesel engine (470 Nm engine torque, 140 kW engine performance, in a mid-size, upper-class vehicle with a six-speed double clutch transmission) shows the necessity of an additional decoupling of the belt drive by means of a crankshaft decoupler. Figure 12 shows a layout based on

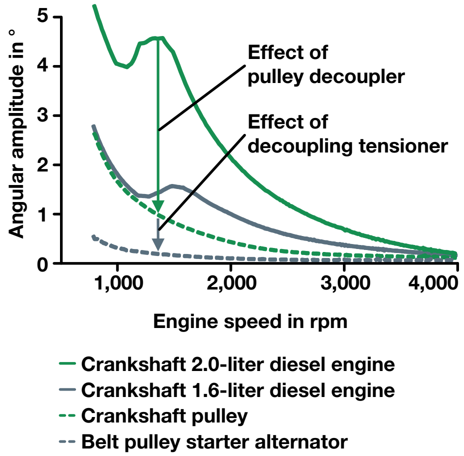


Figure 13 Engine dynamics of the example application

the assumption that the geometry is limited by the available installation space. This means an additional guide pulley is required in the belt drive and the working range of the decoupling tensioner is limited as a result.

Figure 13 shows the vibration angle of the engine on the front crankshaft end as a function of the engine speed. This engine has a significantly greater belt drive excitation via the crankshaft than the 1.6-liter gasoline engine application from the first part of this paper. The increased irregularities of the internal combustion engine excite the belt drive to higher vibrations, which can no longer be managed by a decoupling tensioner alone. Therefore, to reduce vibrations, a direct decoupling on the crankshaft must be used via a decoupled belt drive (dashed line).

The dynamics in the belt drive are reduced to an acceptable value by crankshaft decoupling. Whether crankshaft decoupling is necessary for a belt drive depends on such parameters as the crankshaft excitation, belt drive layout, and accessory loads.

The relevant criteria for a decoupling on the crankshaft are:

– The decoupling of the belt drive in theoperating range and
– The transmission of the alternator torque for alternator start, boost, and recuperation operation.

These requirements can be covered with the LuK pulley decoupler (PYD). This decouples the belt drive from the rotational irregularities of the internal combustion engine, with a specifically designed arc spring isolating the belt pulley from the crankshaft. The PYD is mounted directly on the crankshaft. It usually also contains a torsional vibration damper, which is needed to limit the natural vibrations of the crankshaft in the upper speed range to a level permissible for durability and acoustic comfort (Figure 14).

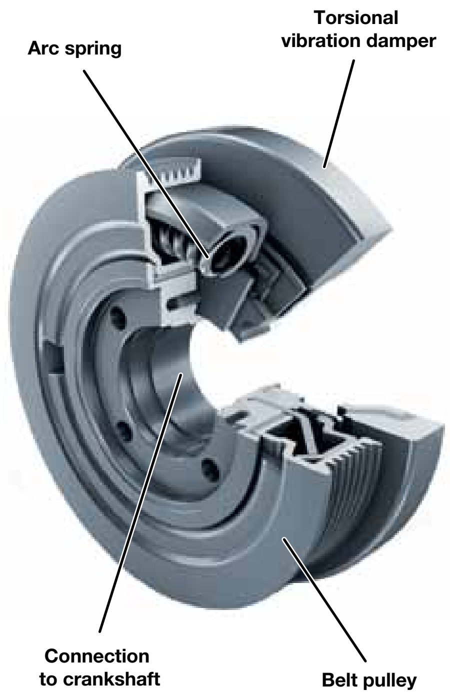


Figure 14 Overview: Design of the pulley decoupler

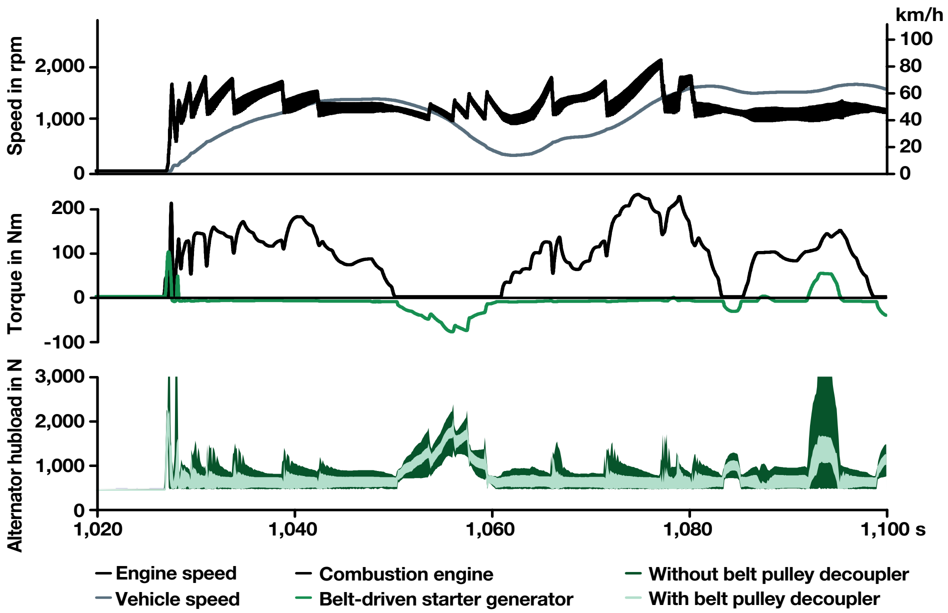


Figure 15 Function of the belt drive with belt pulley decoupler

The crankshaft pulley is decoupled from the vibrations of the crankshaft. Arc springs, such as those in a dual mass flywheel, are used for this, placed in a steel channel. From the crankshaft, the torque is transferred via a flange to the arc springs, which are supported on stops on the belt pulley. The torsion characteristics of the belt pulley decoupler can be flexibly influenced by the selection and combination of the springs used. The system function with the belt pulley decoupler is shown in Figure 15.

The function representation is analogous to Figure 7 with the engine speed, vehicle speed, and engine torque acting on the crankshaft and belt starter alternator and the hubload on the belt starter alternator pulley for the system variants with and without a belt pulley decoupler. In comparison to the system without a belt pulley decoupler, there is an additional reduction of the dynamics in the belt drive throughout the entire operating range.

In comparison with decouplers with elastomer springs, which use a rubber layer for resiliency, the mechanical arc springs have a significantly larger spring capacity and thus allow for the transmission of higher torques and power outputs. Thus, the increased power requirements for mild hybrid applications with belt start-stop can be covered. The characteristic curve can be flexibly adjusted by using multiple spring stages. This helps avoid resonances during engine start and driving operation.

The system is designed in a way that durability requirements are optimally fulfilled throughout the operating life. The design takes into account:

- More than one million engine starts through sailing and stop-start operation, depending on the application,
- A constant decoupling function over the engine's temperature range and vehicle operating life, as well as
- A decoupling of the belt drive throughout the functional range of the engine and alternator.

Air conditioning in the vehicle interior with the internal combustion engine switched off

With the increasing hybridization of the automobile, the amount of time during which the engine is actually running is growing shorter and shorter. This effect is already apparent from an examination of the WLTP cycle when considering sailing and stop-start operation, and, depending on the driving profile, is very much increased for city driving (Figure 16).

Measures that allow air conditioning of the car interior without the engine running include a latent heat storage unit in the air conditioning system, an electric AC compressor or a mechanical AC compressor that is positioned in the standard belt drive and is driven by the starter alternator.

Latent heat storage units provide the air conditioning function by means of a built-in heat storage unit and have a number of limitations regarding the maximum amount of storable energy. They must be charged regularly by running the engine. In contrast, electric AC compressors or AC compressors driven by the starter alternator allow for longer phases without the engine running.

The electric AC compressor, however, requires an additional electric motor and reduces the efficiency of the AC compressor when the engine is running, since losses also occur in this state due to the transfer of the power through the electric ower supply.

As an alternative to an additional electric motor, it is possible to use the existing belt starter alternator to power the AC compressor when the engine is not running if the belt drive can be decoupled from the engine.

This requires a clutch in the crankshaft pulley. Regardless of this comfort function, decoupling is necessary, as in the conventional belt drive. The decoupling is also used in the switchable pulley decoupler (PYDS) from Schaeffler to greatly reduce the dynamic torques that act on the separation coupling. This ensures acoustically and dynamically flawless operation.

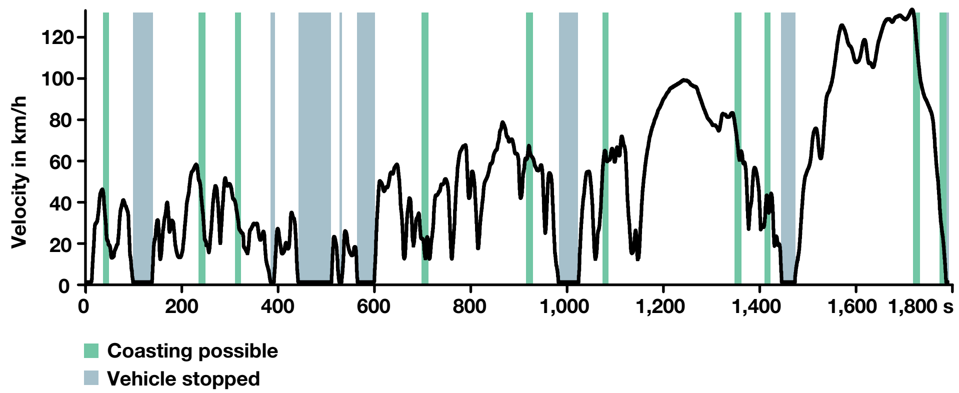


Figure 16 Example application in the WLTP cycle

The switchable pulley decoupler is mounted directly on the crankshaft (Figure 17). Like the standard decoupler, it has a vibration damper to reduce the torsional vibrations of the crankshaft and arc springs to isolate the belt drive from the rotational irregularities caused by the combustion process. This means that all of the advantages of conventional pulley decouplers are retained. A clutch unit is also fitted between the arc springs and belt pulleys.

The belt drive can now be turned freely while the engine is stopped by disengaging the clutch unit. The mechanical AC compressor can thus be operated autonomously despite the engine being stopped. For the restart, the belt drive is slowed down to a near standstill and the clutch is engaged. During normal driving operation, both boost and recuperation torques can be transmitted.

The switch unit can be integrated into the existing space of the decoupler – it results in a more compact design with low weight.

Figure 17 Design of the switchable belt pulley decoupler

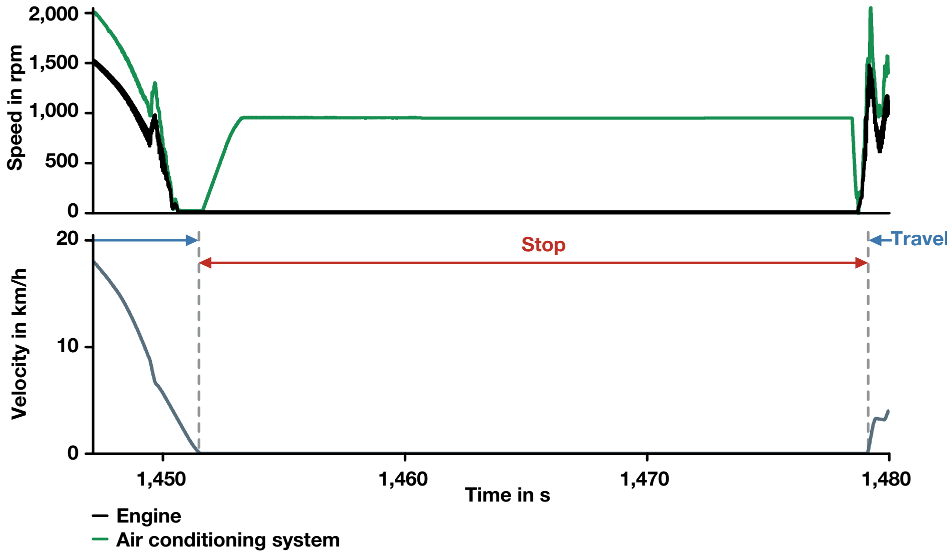


Figure 18 Function of the decoupler during AC operation while driving and with the engine stationary

Figure 18 shows the function of the switchable pulley decoupler based on individual points in the WLTP cycle for the example application. The decoupling of the belt drive makes the operation of the AC unit possible even when the engine is at a standstill. When the engine is running, the belt drive is isolated from irregularities by the crankshaft decoupling as in the non-switchable design.

In addition to the advantages in the belt drive arising from crankshaft decoupling, such as the reduction of dynamic loads and lower frictional losses by decreasing the pretension in the belt, the switching function allows further advantages. AC comfort is maintained both while the engine is stopped and in sailing operation – this also results in a further CO_2 benefit because the periods of time during which the engine is switched off may be extended.

Summary and outlook

Compared to just four years ago, [1], systems with belt starter alternators now play a more important role in belt drive development. This is primarily due to the development of 48-volt mild hybrid systems.

Mild hybrid systems can contribute to improvements in driving dynamics and fuel economy. However, they also lead to new requirementsfor belt drive design. Decoupling tensioners and pulley decouplers, whether switchable or not, are not just expanding the current Schaeffler product range for belt drives (Figure 19). Innovations are also expanding the design options for mild hybrid systems with a belt starter alternator.

Now that the first systems with belt starters with 12-volt systems are on the mar-

Figure 19 Overview of the Schaeffler product portfolio for belt drives

ket, new developments are driven by the expectation that belt starter alternators will become significantly more important in the coming years because of the change to 48-volt mild hybrid systems and – in addition to the conventional belt drive – will play an expanded role in the future. The requirements for belt drive design will increase to a greater or lesser extent, depending on the engine class. These can be met individually with products from Schaeffler – from the reduction of vibrations with the decoupling tensioner and the completely decoupled belt drive with standard air conditioning function through to switchable belt pulley decouplers.

Schaeffler is focusing on a system approach in belt drive development in which the interactions of the individual components within the entire system are taken into account. This approach is gaining significance due to increasing requirements. Therefore, the development of belt drives in the future will take the interactions with the entire vehicle system more closely into account. This focus on the whole system includes the interactions of the individual components and their use over the vehicle's operating life. While up to now systems have been designed based on individual operating points, these increased interactions are now shifting the focus to accounting for entire trips and the use of the vehicle by different drivers over the life of the vehicle. The interactions in the entire system can be incorporated into development using Schaeffler's unique expertise. For vehicle manufacturers, Schaeffler offers the advantage that during belt drive development, the design of the individual components can be optimally tailored to each other.

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