The Constant Speed Power Take Off (CS-PTO) - a new concept for driving refrigeration units (patent pending)

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This paper presents a novel Power Take Off system for power levels up to 25 kW. The system, intended for the refrigerated distribution truck market, was developed in order to comply with new restrictions concerning exterior noise, fuel consumption and emissions as well as to meet the demand for better performance of refrigeration units. With a Continuously Variable Transmission (CVT) the variable crankshaft speed of the trucks main engine is transformed into a constant speed. A large capacity generator is connected to the CVT and the generated voltage is constant and supplied to the refrigeration unit. This new concept is called the Constant Speed Power Take Off (CS-PTO)

With a specially developed ratio control system, the output speed of the CVT can be controlled within the available ratio coverage of the CVT. This enables optimisation of the rotational speed of the connected generator with respect to required electrical power, overall efficiency and life-span of electrical and mechanical components.

The new CS-PTO concept is developed and tested in the Automotive Laboratory of the Technische Universiteit Eindhoven and used to drive a refrigeration unit of the company Govers ET BV. After successful experimental results, the CS-PTO is implemented on trucks used for distribution of refrigerated goods. By means of the CVT, the generator speed is controlled to a constant value and the electrical power supplied to the refrigeration unit is optimised for maximum refrigeration capacity and noise emission.

As a result of the constant speed of the generator, the refrigeration unit functions at an optimal frequency and generates a constant refrigeration capacity. All components of the refrigeration unit of Govers ET BV function at their optimum, at constant speeds. This results in a constant refrigeration capacity that is always available when the primary diesel engine is running.

The maximum noise emission of the refrigeration unit is caused by high speeds of the compressor and fans. The CS-PTO supplies a constant and optimal frequency to the compressor and fans, resulting in lower speeds and less noise emission. The maximum noise emission of the refrigeration unit was measured and equals 57 dB(A).

The additional engine power required for the refrigeration unit has a positive influence on the fuel consumption. The implemented CS-PTO shows a reduction in fuel consumption of 5.6%, compared with an identical refrigeration unit driven by a generator without CS-PTO.

The CS-PTO proves to be a silent and fuel-efficient solution that is able to guarantee a constant generated refrigeration capacity, when the primary diesel engine of the distribution truck is running. With the new concept the future restrictions concerning fuel-consumption and noise-emission, as well as the increasing demand for a constant refrigeration capacity are met.
1. Introduction
Refrigerated distribution trucks need additional power for the refrigeration unit, next to the power needed for transportation of the goods. This additional power can be retrieved in several different ways, but two concepts dominate the refrigerated distribution market (1).

![Figure 1, market share of the two dominating concepts for refrigerated distribution](image)

A secondary diesel engine placed on the distribution truck (more than 85% of the Dutch refrigerated distribution market) is able to deliver additional power at any time and at a constant level.

The additional power can also be retrieved by a Power Take Off (PTO) from the primary diesel engine (less than 10% of the refrigerated distribution market). This way, no second diesel engine is needed, but the additional power is only available while the primary engine is running.

The future of the refrigerated distribution market involves new restrictions concerning emission of exhaust gases and noise (2). Next to these restrictions, the demand for systems that are able to guarantee a constant refrigeration capacity is increasing. With the future restrictions and increasing demand in mind, the two dominating concepts in the market are analysed.

1.1 Present Concepts
When the additional power for refrigeration of goods is generated with a secondary diesel engine, its constant crankshaft speed results in a constant generated refrigeration capacity. Because of the increasing demand for a constant refrigeration capacity, 85% of the market is using this concept. However, the costs of the secondary diesel engine with its additional fuel consumption are high, and it results in a significant contribution to the overall noise emission.

When the additional power is taken from the primary diesel engine, the additional costs and noise emission of a secondary power source are eliminated. However, the crankshaft speed of the primary diesel engine is not constant and therefore the generated refrigeration capacity is variable. Using this concept, the refrigeration unit is switched off at generator speed below 1500 rpm or above 4500 rpm. This results in no refrigeration capacity at very low (stationary) or high (above 1875 rpm) speeds of the primary diesel engine.
1.2 Analysis of New Concepts

Diesel engines for trucks are designed to meet future restrictions concerning fuel emission, fuel consumption and noise emission. By using the primary diesel engine as a power source for generating refrigeration capacity, the future restrictions concerning fuel emissions and fuel consumption are met.

![Figure 2, Available power take off’s on distribution trucks from DAF Trucks NV](image)

Distribution trucks have a various number of available power take off’s (PTO's). The PTO's positioned behind the truck transmission are suitable for driving a new concept because of the available space. The transmitted torque of these transmission PTO's is intermitted when the transmission clutches are opened so a constant refrigeration capacity cannot be guaranteed. The engine and flywheel PTO are positioned on top of the transmission which result in design problems. The best option for driving the new application is a front-end PTO. These PTO's are able to deliver torque at any time, but are positioned in an area that has limited space for additional systems.

To meet the restrictions concerning the emission of noise, the generator driven refrigeration units of Govers ET BV are used, proven to be one of the most silent units in the refrigerated distribution market. When the generated refrigeration capacity is made independent of the crankshaft speed of the primary diesel engine, a constant refrigeration capacity can be guaranteed to fulfil the increasing demand. Different concepts that are able to eliminate this dependency are analysed and discussed.

**Electrical Concept**

The generated electrical power is transformed into a constant voltage and current with a desired frequency using power electronics. The voltage of the generator is led through a rectifier which is connected to a DC/DC converter with a capacitor in between. The output of the DC/DC converter is connected to a DC/AC converter, also with a capacitor in between. The output is a three phase alternating current at the desired frequency that can be directly supplied to the refrigeration unit. This concept will result in a constant refrigeration capacity, independent of the crankshaft speed of the primary diesel engine. However, the costs of power electronics for a 22 kVA generator are estimated at 10.000 Euro.
Hydraulic Concept
When the generator is mechanically attached to a hydro motor that is driven by a variable
displacement pump, the speed of the generator can be kept constant. This concept solves the
present problem and guarantees a constant refrigeration capacity. However, the costs are high
and the overall efficiency is poor because of hydraulic losses. Furthermore, the variable
displacement pump and hydro motor generate a lot of noise that exceed the noise from the
primary engine and compressor. Together with the environmental risks of hydraulics, this
concept is unattractive for driving a generator in refrigerated distribution trucks.

Mechanical Concept
A Continuously Variable Transmission (CVT) is able to transform the variable crankshaft
speed into a constant speed. CVT's are commonly used as automotive transmissions and their
efficiency measures 90 to 95%. The costs of this concept are relatively low. Therefore the
development of a new concept for driving refrigeration units on trucks is concentrated on this
mechanical concept.

2. The CVT-unit
For application in distribution trucks the new concept is preferred to be small, lightweight and
low in costs. The mechanical continuously variable transmission must be able to transmit the
required torques for the generator and must have an overall ratio that is able to cover the
speed range of the primary diesel engine. Furthermore, the response of its ratio control system
must be sufficient to compensate the variations in engine-speed by ratio change of the CVT.

2.1 Different Types of CVT
A wide range of CVT's is available with differences in shape and specifications, but belt
CVT's have the best shape and specification range for application in the engine compartment
of a distribution truck.

A belt CVT mainly consists of a belt and two pulleys (a primary or driving pulley, and a
secondary or driven pulley), called the variator. The ratio of the belt CVT is shifted by
changing the widths of the pulleys. Belt CVT's are available with metal belts, hybrid belts and
rubber belts.
Metal Belt CVT's
Metal belts used in CVT's, are available as a pull-belt as well as a push-belt. The Van Doorne push-belt transmits the power, mainly by pushing the secondary pulley. It consists of steel belt elements and rings made of sheet metal. The belt elements are positioned against each other and transmit the compressive forces needed for pushing the secondary pulley. The metal rings are used to transmit the tension forces existing in the belt during running. The belt is flexible and able to bend because of the multi-element structure and the sheet metal rings (3). Another metal belt CVT is the LuK chain (4), which transmits power by pulling the secondary pulley. This metal belt consists of long and short vertical chain links that are connected to each other by rocker pins. The pulley thrust is working on these retaining pins, while the tension forces are transmitted by the chain links. Both metal belts require oil lubrication to create a film between belt and pulley to prevent wear. Furthermore, the oil is used for cooling of the metal belt. To prevent slippage of the belt, the pulley thrust needs to be very high. This is done by hydraulic actuation and therefore metal belt CVT's are equipped with a hydraulic circuit, driven by a hydraulic pump.

Rubber or Hybrid Belt CVT's
Hybrid belts consist of a heat resisting rubber, resin, aluminium alloy and advanced fibres, while a rubber belt mainly consists of heat resisting rubber and fibres. The specifications of a hybrid belt are higher and these belts are used in motorcycles and small cars (5), while rubber belts are mainly used in scooters, snow-mobiles and quad-bikes. The pulley width of the primary pulley is controlled by either electromechanical actuation (hybrid belts) or centrifugal actuation (rubber belts).

Comparison of belt CVT's
Because of the required hydraulic circuit with oil pump for actuation and lubrication, the size, weight and costs of a metal belt CVT are high compared to a CVT with a rubber or hybrid belt. As the area near the front-end PTO is limited, a small and lightweight CVT-unit is preferred. The maximum transmittable torque and overall ratio of the CVT's with a metal belt or hybrid belt are both sufficient for this application. CVT's with a rubber belt have a maximum transmittable torque and overall ratio that is not sufficient for this application.

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Table 1, Comparison of the different types of CVT

The specifications of the dry hybrid belt CVT are sufficient for this application and its overall efficiency is high (higher than 90% when the input torque above 20 Nm (6)). The costs of a dry hybrid belt CVT are relatively low (no hydraulics) and the required ratio control is not very complex because it is actuated electromechanically.
3. The CS-PTO Concept
By controlling the ratio of the dry hybrid belt CVT, the variable crankshaft speed of the primary diesel engine is transformed into a constant speed. This new concept is called the Constant Speed Power Take Off (CS-PTO).

3.1 The CS-PTO Components
Most electrical components of a generator driven refrigeration unit are designed to operate at a nominal frequency of 50 Hz, equivalent to a generator speed of 3000 rpm and a generated voltage that is equal to 400 V. At this frequency, the fans and compressor of the refrigeration unit require a total current of 15 A, which is equivalent to a load torque of 24 Nm.

When the refrigeration unit is switched on at a frequency of 50 Hz, a required peak current of 60 A is required from the generator. This results in a load torque of 96 Nm, which is higher than the maximum transmittable torque of the CVT-unit (74 Nm). Experiments showed that this peak current is dependent on the voltage frequency and by lowering the generator speed to 1850 rpm, the peak currents and load torque are lowered to 30 A and 48 Nm, respectively. Lowering the generator speed and voltage frequency to prevent high currents and torques at start-up, is called the soft-start.

The desired voltage frequency of the generator, results in a speed of the secondary pulley shaft that is equal to 3000 rpm and a nominal load torque at the secondary pulley shaft of 24 Nm. The ratio of the hybrid belt CVT is limited from 0.46 [-] to 2.20 [-], resulting in a speed of the primary pulley shaft that ranges from 1360 to 6520 rpm. The maximum torque at the primary pulley shaft yields 64 Nm, and occurs when the refrigeration unit is switched on and the speed of the primary pulley is 1360 rpm. Under normal conditions, the crankshaft speed of the primary diesel engine ranges from 600 to 2400 rpm. To guarantee the desired generator speed of 3000 rpm at all crankshaft speeds, a v-belt drive with a ratio of 2.4 is required. The speed of the CVT-unit its primary pulley shaft now varies between 1440 and 5760 rpm, which is within the required speed range.
3.2 The Ratio Control System
Variation in the crankshaft speed must be compensated by ratio change of the variator and therefore a ratio control system is developed to control the actuation system of the CVT-unit. If the actual output speed is lower or higher than the desired speed of 3000 rpm, the ratio is increased and decreased, respectively, by supplying a positive or negative voltage to the electromechanical actuation system. The actuation system of the CVT-unit is powered by an electric motor. The torque and speed of the electric motor are transmitted through two plastic gears and a spindle mechanism and result in a displacement of the moveable pulley flange of the primary pulley. The secondary pulley is equipped with a spring-activated torque cam, that ensures sufficient secondary pulley thrust. The CVT-unit is equipped with two revolution sensors (REV-sensors), measuring the speed of the primary and secondary pulley, and a sensor measuring the position of the primary pulley (PPS-sensor).

3.3 Comparison the CS-PTO with existing concepts
The most common concept in the refrigerated distribution market is a secondary diesel engine used for driving the refrigeration unit. This results in a constant refrigeration capacity at all times. The present concept using the primary diesel engine to drive the refrigeration unit, results in a refrigeration capacity that is linear dependent on the crankshaft speed. The variable refrigeration capacity is available at engine speeds between 625 and 1875 rpm. The new CS-PTO concept is able to generate a constant refrigeration capacity at all engine speeds (600-2400 rpm), but will only work when the primary diesel engine is running.

![Figure 5, Three concepts for driving a refrigeration unit with a capacity of 10 kW](image)

4. CS-PTO Performance Simulation
The performance of the CS-PTO concept is analysed with computer simulations. A comparison is made between a generator driven refrigeration unit, directly connected to the crankshaft of the diesel engine by a v-belt drive (reference concept) and a generator driven refrigeration unit, connected to a CS-PTO.

The European Transient Cycle (ETC) is used to simulate the variations of the primary diesel engine crankshaft speed during driving and together with dynamic models of the reference and CS-PTO concept, the resulting generator speed and fuel consumption are simulated.
Figure 6, The first part of the European Transient Cycle (ETC)

The ETC is divided into three parts, simulating driving in city traffic, rural roads and motorways, respectively. In city traffic, the variations in crankshaft speed of the primary diesel engine are the largest. Therefore, the simulations and experiments are concentrated on the first part of the ETC.

4.1 Efficiency measurements

The overall efficiency of the CS-PTO concept is determined by the efficiencies of the v-belt drive and CVT-unit. While the efficiency of the v-belt drive can be assumed constant (0.95), the efficiency of the CVT-unit is dependant on multiple parameters. To get an accurate model of the CVT-unit, the efficiency is determined experimentally on a test-rig. The efficiency is measured at different speeds, at different ratios and at different primary torques.

Figure 7, Measured efficiency of the dry hybrid belt CVT in ratio LOW
The experiments show that the efficiency is nearly independent of the primary pulley speed. The efficiency of the CVT-unit does vary from 90 to 95%, but that is mainly dependent on the transmitted torque and its ratio. At primary torques lower than 15 Nm, the efficiency of the CVT-unit drops significantly below 90% to values as low as 45%. This is not a problem as the primary torque of the CVT-unit will rarely drop below 15 Nm in the new CS-PTO application.

Figure 8, Simulated generator speed for both the reference and CS-PTO concept

4.2 Simulation Results
In the reference concept, the generator speed is equal to the crankshaft speed, multiplied by the ratio of the v-belt drive. This results in a large variation of the generated voltage. The control system connected to the refrigeration unit switches the unit off when it measures frequencies below 25 Hz and above 75 Hz, (generator speeds of 1500 and 4500 rpm, respectively) This is done to ensure a good performance of the compressor and prevent the electrical components from very high voltages. When the unit is switched off, it will not switch on for 20 seconds. This is done to ensure a smooth motion of all the components of the compressor in the refrigeration unit.
During the first part of the ETC the variation of the generator speed in the reference concept causes the refrigeration unit to be switched off for 63% of the total simulation time (see fig. 9). However, the CS-PTO concept ensures a constant generator speed of 3000 rpm, resulting in a refrigeration unit that is always switched on. The designed controller for the CVT-unit shows a good system response, resulting in a nearly constant generator of 3000 rpm in city traffic. The maximum deviation of the generator speed is limited by the present system dynamics and the designed controller, and measures 100 rpm.

When the engine torque is high and the engine is running at high speeds, the contribution of the load torque of the generator is limited. Therefore, whether the refrigeration unit is switched on or switched off has a small influence on the fuel consumption. On the other hand, situations where the engine torque as well as the engine speed is low, the load torque of the generator and refrigeration unit have a large influence and positive influence on the fuel consumption. At low engine speeds a higher torque is taken from the crankshaft, the engine operates in a point with a lower break specific fuel consumption. Together with a better performance of the refrigeration unit, the simulations with the CS-PTO concept show an increase in generated refrigeration capacity per litre diesel fuel with 126%.

5. CS-PTO Experiments
To validate the simulation results, experiments with the reference and CS-PTO concept are performed on a test-rig. Reference measurements are made using the reference concept and performance tests of the CS-PTO are made with a full-size prototype with implemented ratio control system. The power source of the test-rig is a large capacity speed controlled electric motor. This large electric motor is used to follow the simulated engine speed prescribed by the first part of the ETC. Its capacity is sufficient to drive the generator and refrigeration unit and its speed range is equal to the speed range of the primary diesel engine.

Using the reference concept, the refrigeration unit is switched off for even a longer period (69% of the time) than follows from the simulations, resulting in less refrigeration capacity. When the refrigeration unit is running and the generator speed is equal to 3000 rpm, the nominal current of the 22 kVA generator is 15.2 A, resulting in a load torque of the generator
of 24.3 Nm. The measured load torque is in line with the approximate value of 24 Nm that was used for the concept design. The test-rig is adapted with the CS-PTO prototype and ratio control system to validate its simulated performance.

Figure 10, Experimental test-rig with the CS-PTO prototype

5.1 Experimental Results
The ratio control system proves to function correctly as well as the implemented soft-start strategy. The soft-start results in a low required peak current from the generator of 24.9 A (1.6 times the nominal current). The torque at the primary pulley shaft of the CS-PTO is dependant on the ratio of the CVT-unit and a maximum value of 64.1 Nm is measured.

Figure 11, Simulated generator speed for both the reference and CS-PTO concept
When the refrigeration unit is switched off, the generator speed is held constant at 1850 rpm. The 5 seconds delay in the controller is sufficient to guarantee a smooth start-up behaviour of the refrigeration unit. The electromechanical actuation system ensures that the change in desired generator speed from 1850 rpm to 3000 rpm is performed within 2.5 seconds. With the implemented soft-start strategy, the first part of the European Transient Cycle is simulated with the speed controlled electric motor. The applied ratio control system is able to keep the output speed constant at a mean 3000 ± 100 rpm.

When the heavy duty diesel engine is decoupled from the transmissions (clutches are open), the rotational speed of the crankshaft decreases instantaneously. This instantaneous drop in speed can not be compensated fast enough, by changing the ratio of the variator with the electromechanical actuation system. The drop in speed requires an instantaneous increase of the ratio that is limited by the dynamics of the variator. The secondary pulley is equipped with a heavy compression spring and torque cam to ensure enough axial pulley thrust and prevent slippage of the belt. When shifting towards low, this compression spring 'helps' the electromechanical actuation system by pushing the moveable pulley flange inwards. When shifting towards high, the electromechanical actuation system has to overcome the additional pulley thrust of the compression spring, requiring more electrical power. Therefore, an instantaneous increase of engine speed can be compensated more easily than an instantaneous decrease of the engine speed.

The measured generated voltage is linear dependant on the generator speed and therefore it shows the same behaviour. The required current from the generator is dependant on the rotational speed of the compressor and fans of the refrigeration unit. The drag of the fans is linear with their rotational speed, which is dependant on the generated voltage. Therefore, the course of the generator speed is recognized in the generated current.

Parallel to the performance measurements with the reference and CS-PTO concept, the maximum noise emission of the refrigeration unit was measured for both concepts. The noise emission of the refrigeration unit is mainly dependant on the rotational speed of the compressor and fans. The maximum generated voltage using the reference concept is equal to 500 V, resulting in high rotational speeds of the compressor and fans. The maximum noise emission measured during the experiments was 81 dB(A). The maximum generated voltage using the CS-PTO is equal to 415 V, resulting in much lower rotational speeds of the compressor and fans. The maximum noise emission measured during the experiments was 63 dB(A). Both measurements were performed on a refrigeration unit without noise insulation.

5. CS-PTO Application
After the experiments, a second and optimised prototype is implemented in a refrigerated distribution truck, equipped with a data-acquisition system to measure the performance of the CS-PTO. The truck is used for distribution of refrigerated goods within the cities, to ensure large and fast variations in crankshaft speed of the primary diesel engine. During the hot summer of 2003 the CS-PTO was tested on performance in worst-case conditions.
Figure 12, Application results of the Constant Speed Power Take Off

The measured performance (Fig. 12) shows that the implemented CS-PTO guarantees a constant generator speed of 3000 ± 50 rpm, with an incidental drop in the generator speed of 150 rpm.

The additional power required for the refrigeration unit has a positive influence on the fuel consumption. At stationary engine speeds, the additional power taken from the crankshaft is relatively high, while at high engine speeds, the additional power taken from the crankshaft is relatively low. The implemented CS-PTO shows a reduction in fuel consumption of 5.6%, compared with the reference concept. Furthermore, the generator speed is held constant at 3000 rpm and therefore the refrigeration unit is not switched off as a result of generator speeds that are too low or too high. The refrigeration unit is working whenever the primary diesel engine is running and produces 42% more refrigeration capacity in city traffic.

The maximum noise emission of the refrigeration unit is caused by high speeds of the compressor and fans. The CS-PTO supplies a constant and optimal frequency to the compressor and fans, resulting in lower speeds and less noise emission. The noise emission of the refrigeration unit of Govers ET BV was measured by official institutes at a voltage of 400 V and a frequency of 50 Hz (equal to a generator speed of 3000 rpm). Its maximum noise emission was measured at 57 dB(A) and meets the future requirements concerning noise emission.

The CS-PTO is able to guarantee a generator speed of 3000 ± 50 rpm, resulting in a constant voltage frequency of 50 ± 1 Hz. As a result of the constant speed of the generator, the refrigeration unit functions at an optimal frequency and generates a constant refrigeration capacity. All components of the refrigeration unit of Govers ET BV function at their optimum, at constant speeds. This results in a constant refrigeration capacity that is always available when the primary diesel engine is running. During distribution of refrigerated goods in city-traffic with many stops and door-openings, the air temperature in the trailer is kept significantly lower than with the reference concept (see Fig. 13).
6. Conclusions
The CS-PTO is a silent and fuel-efficient solution that is able to guarantee a constant generated refrigeration capacity, when the primary diesel engine of the distribution truck is running. With the new concept the future restrictions concerning fuel-consumption and fuel-emission, as well as the increasing demand for a constant refrigeration capacity are met.

The CS-PTO is able to generate more refrigeration capacity and therefore the capacity of the generator and refrigeration unit can be smaller, reducing the overall costs and of the system. The generator runs at a constant speed independent of the crankshaft speed, preventing high voltage frequencies to the refrigeration unit and lowering the noise emission of the compressor and fans. Furthermore, the life span of all electrical components is enlarged. The peak currents and torques in the total driveline are limited by lowering the generator speed, before the refrigeration unit is switched on. With this implemented soft-start strategy the maximum transmittable torque of the CVT-unit is not exceeded.

7. Recommendations
To improve the performance of the CS-PTO even more, all components of the driveline (especially the generator and refrigeration unit) have to be optimised in the field of efficiency. The total efficiency of the generator and refrigeration unit must be analysed in order the find the optimal generated frequency. Furthermore, the CS-PTO has to be submitted to an endurance assessment to analyse wear and performance.

The power taken from the crankshaft of the primary diesel engine influences the fuel-consumption and is linear dependant on the generator speed. The fuel-consumption of the primary diesel engine can be optimised by adapting the power taken from the crankshaft, using the ratio control system.
The CS-PTO is designed for application in refrigerated distribution trucks. The principle of a constant speed power take off can be utilized for many more applications. An analysis of the range of CS-PTO application must be performed.

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