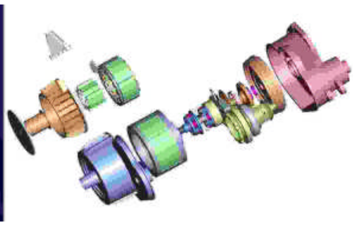
Advanced Electrical Drives for Vehicle Transmissions



Gears2005

Steve Cummins

BGA2005 RevA Annotated

Switched Reluctance Drives: - An Overview

- A ‘System’: comprising both motor and power converter.
- Robust in construction / straightforward in operation.
- Wide constant power range.
- Highly efficient.
- Compact format – easily integrated.

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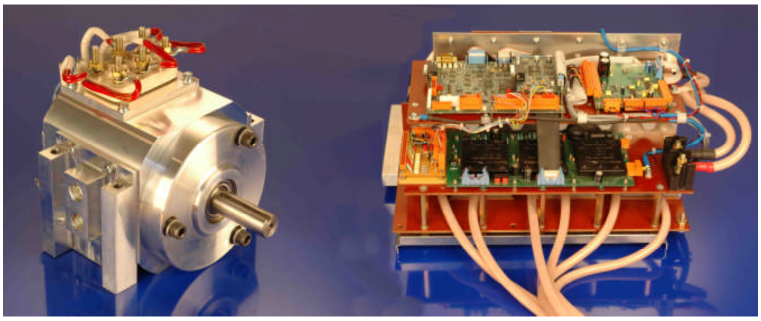
SR DRIVES

SR DRIVES Manufacturing



50kW water-cooled SRDrive® traction motor and 50kW – 180kW water-cooled power converter.

Switched Reluctance drives are a ‘system’ in that they comprise both a motor and a power converter. The function of the power converter is to convert the incoming voltage supply to a steady DC (direct current) voltage which is then switched across alternate sets of coils in the motor producing rotary motion.

The systems have no particular synchronous speed and as such offer high efficiency variable speed operation over a wide operating range. As will be seen in the subsequent slides, the motors are exceptionally simple and robust and the operation of the system as a whole is similarly straightforward.

Switched Reluctance Drives: - The Motor (Rotor)

- Simple rugged design – purely a stack of electrical steel laminations.
- No windings, rotor-bars, magnets or contacts of any sort.
- Cool running – losses are concentrated in the stator.
- Low-inertia – reduced reflected inertia in driven equipment.

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The simple SR Drive® rotor has many advantages over conventional types which utilise conductors on the rotor.

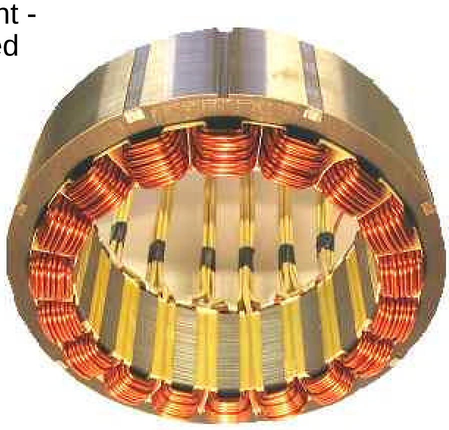
The simple and robust construction of Switched Reluctance motors offers high-performance in a compact package. The rotor construction comprises a stack of electrical steel laminations mounted about the motor shaft. There are no windings or rotor bars, no permanent magnets and no electrical contacts of any sort. The ‘salient’ construction of the rotor (having gaps between the poles – i.e. not a complete cylinder) creates a relatively low-inertia rotor allowing rapid speed response for a given motor torque and minimizing the risk of mechanical damage in large ratio gear-driven applications.

The absence of any form of conductor on the Switched Reluctance rotor means that the overall rotor losses are considerably lower than in conventional motors which utilize conductors on the rotor. This is especially relevant during start-up where, in the Switched Reluctance motor, the rotor losses are no greater than they are when operating at the rated condition. This permits a virtually unlimited capability for prolonged operation in the stall condition and for repeated starting under full-load. Such performance is often not possible with conventional drives because of the large electrical losses on the rotor and the subsequent rotor heating under such conditions.

The overall losses within the Switched Reluctance motor are concentrated within the stator where they are relatively easily dissipated: in the case of a standard totally – enclosed machine, by conduction through to the relatively cool exterior of the motor frame. The minimal rotor losses mean that the rotating parts of the machine, including bearings and lubricant, run relatively cool – often prolonging bearing and lubricant life.

Switched Reluctance Drives: - The Motor (Stator)

- Compact – short end-turns permit very high torque/volume ratio for an electrical drive.
- Reliable - independently wound coils have no overlap area.
- Good thermal management - losses are easily dissipated through the outer circumference.



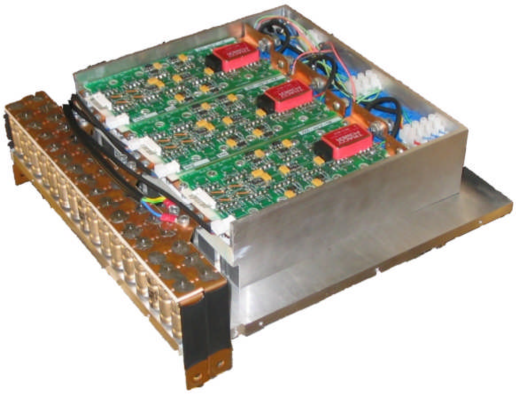
An SR Drive® stator for a vehicle traction application: note the small distance that the coils protrude from the lamination pack.

The stator is similarly straightforward, comprising a stack of steel laminations with a series of independently wound coils located around each stator pole. The coils themselves; being associated with just the one pole, have a very compact end-turn (the area of the coil protruding outside the stator pack). Since it is only the section of the coil within the stator pack that contributes to the torque produced by the motor, the end-turns represent 'dead-volume' within the motor and their small size in a Switched Reluctance motor allows the most efficient use to be made of the volume within a given motor frame size.

The stator coils; being independently wound and not a distributed winding like conventional ac machines, do not have an overlap area where conductors with a high potential between them pass over each other. This is a vulnerable area of conventional machines which is not present in a Switched Reluctance stator.

Switched Reluctance Drives: - The Power Converter

- Straightforward operation: Motor phases are simply turned on and off.
- Low switching frequency = minimal electrical losses, reduced EMI.
- Intelligent: speed/torque estimation without external sensors.



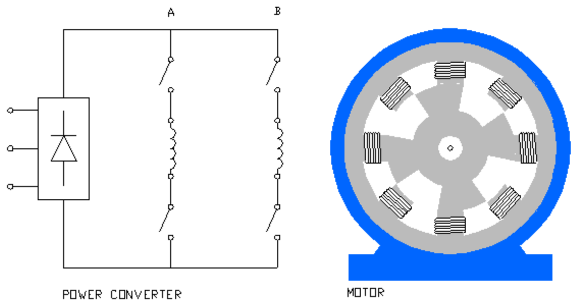
Watercooled 50kW SR Power Converter module.

The Switched Reluctance power converter provides a self-synchronous drive to the motor, simply switching the motor phases on and off at the appropriate rotor position.

When compared to an equivalent inverter drive, the switching frequency of the Switched Reluctance power converter is around an order of magnitude less. Lower switching frequencies mean lower electrical losses within the power converter, contributing to the relatively high operating efficiency of Switched Reluctance systems.

The power converter contains a 'Characterisation' map: a record of the optimum control parameters for the full torque/speed characteristic of the appropriate motor design. This ensures that the system performance is not only optimum across the whole load range but is also known at the outset.

Switched Reluctance Drives:
- Basic Operation (1)



Schematic representation of SR Drive® power converter and motor.

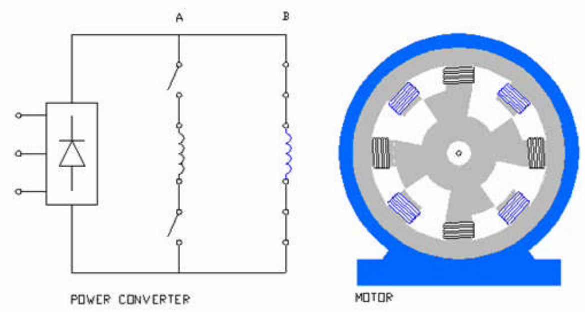
The operation of SR Drive® systems is very straightforward, consider the schematic view of the power converter and motor shown here.

The power converter takes the incoming mains supply and turns it into a DC voltage in exactly the same way as an inverter does. By closing both the top-side and bottom-side switch associated with a particular motor phase, we create an electromagnetic field within the motor that causes the rotor poles to align with the stator poles of that motor phase*.

The rotor position here is ‘aligned’ with the A phase. It can be seen from the diagram that the rotor pole is ‘stepped’ – the pole radius is greater on one side of the pole than it is at the other. The causes the rotor to have a slight angular offset in its ‘aligned’ position and is done to guarantee a particular direction of rotation of the motor – in this case anti-clockwise.

Imagine now that we were to energise Phase B by turning on the top and bottom switches in the power converter connected to motor phase B …. PTO

Switched Reluctance Drives:
- Basic Operation (2)



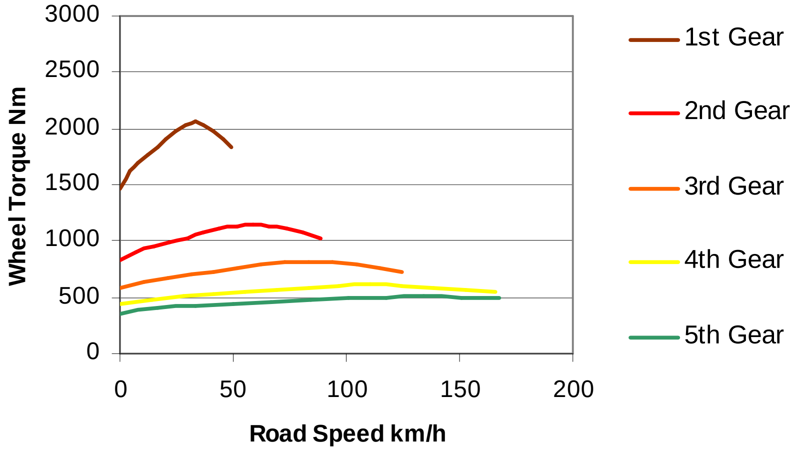
The rotor will move anti-clockwise until it reaches the aligned position of phase B, whereupon we turn off Phase B and again turn on Phase A.

The power converter is just alternately switching between Phase A and Phase B. By varying the duration for which the phases are turned on we can control the applied torque, and hence the speed, of the motor.

Note also that each motor phase is turned on only four times for every revolution of the motor. In an inverter; where the output switching is attempting to provide an sine-wave voltage to the motor, each phase may be switched on perhaps twenty or more times per revolution creating more switching losses than are evident in the equivalent Switched Reluctance Power Converter.

Switched Reluctance Drives:
- Wide Constant Power Range

- Conventional 6000rpm / 100hp drive with 5-speed gearbox, 4.25:1 final drive.



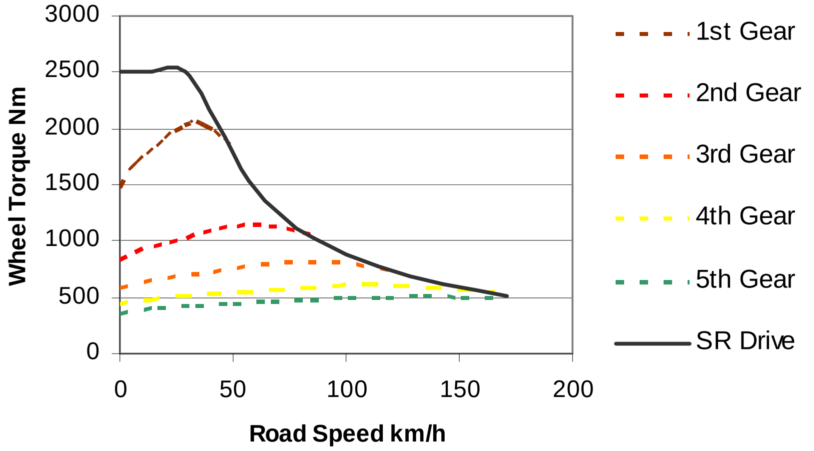
Comparison in speed/torque characteristic between a conventional 100hp 5-speed drive system and the fixed ratio SR Drive® system. Final drive ratio is 4.25:1 in both cases.

Switched Reluctance system have a very wide constant power range: the range of speeds over which their output can deliver constant power. Constant power capability over a very wide range of speed is possible.

To illustrate this point consider a conventional 100hp / 6000rpm vehicle engine with a typical 5-speed transmission and a 4.25:1 final ratio drive. The graph shows the relation in wheel torque and road speed for the vehicle. Maximum power in each gear ratio is represented by the right hand extreme of each line.

Switched Reluctance Drives:
- Wide Constant Power Range

- SR Drive® system 6500rpm / 100hp without gearbox, 4.25:1 final drive.

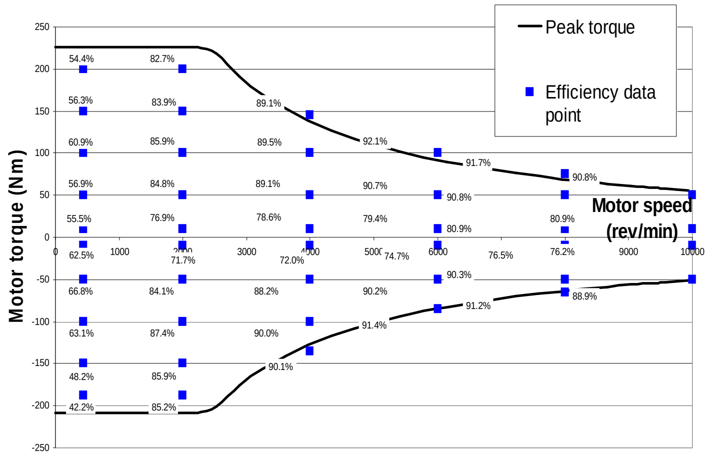


Comparison in speed/torque characteristic between a conventional 100hp 5-speed drive system and the fixed ratio SR Drive® system. Final drive ratio is 4.25:1 in both cases.

Consider now the performance of a 100hp / 6000rpm Switched Reluctance motor in place of the conventional engine and 5-speed gearbox but with the same 4.25:1 final drive. The 100hp maximum power curve for the Switched Reluctance motor is shown here in black and encompasses the maximum power points available from each of the five ratios. Constant power is available from wheel speeds of around 30km/h up to the vehicle maximum a 180km/h: a 6-fold constant power range.

Switched Reluctance Drives: - Highly Efficient

- High system efficiency.
- High efficiency maintained over virtually the full load range.



System efficiency data (Mechanical shaft power / electrical input power) for a 42kW vehicle traction drive.

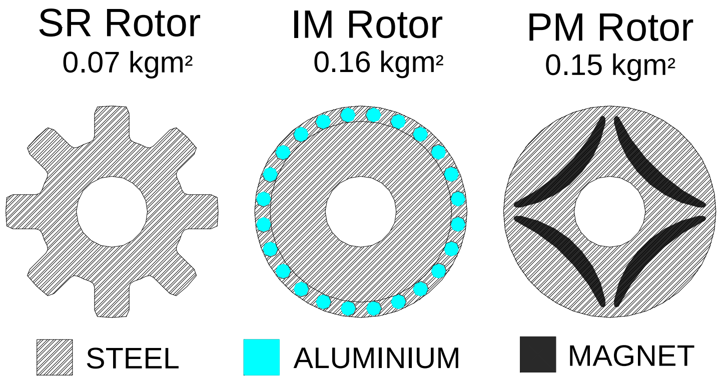
Switched Reluctance drives are very efficient. The minimal rotor losses in the motor and the low switching losses in the converter yield a high overall system efficiency. Moreover, because the systems are not designed to meet a particular synchronous speed, their high efficiency is maintained over a very wide operating range.

Consider the above plot of the system efficiency (motor shaft power/electrical input power). Spot point efficiency measurements are shown by the appropriate blue square. The figures are for a 42kW vehicle traction drive rated for both motoring and generating operation and show system efficiencies consistently in the band of 85% to 91% for all but very low power operation where fixed losses is the system become proportionally larger. Note the very close correlation between motoring and generating efficiencies for equivalent load points.

The figures here are true system efficiencies and include all motor and power converter losses, both electrical and mechanical.

Switched Reluctance Drives: - Low Rotor Inertia

- 'Salient' construction has gaps between the poles.
- Very-low inertia 30%-50% that of conventional motors.



Comparison of rotor lamination profiles for typical electrical machines, inertia figures assume 200mm OD, 60mm bore and 150mm stack length: SR Motor, AC Induction motor, DC permanent magnet motor.

The rotor of a Switched Reluctance motor has a 'salient' construction meaning that the rotor poles have gap between them. In the abscence of any windings on the switched reluctance rotor these gaps are not filled with conductor material or magnets and have the effect of removing a significant amount of mass from the periphery of the rotor. The effect is much reduced rotor inertia.

Consider the cross section view of typical rotor profile shown here. The induction machine and the permanent magnet machine are effectively a closed cylinder. In practice the induction motor will have an end-ring where the rotor conductors connect together hence its slightly increased inertia over the permanent magnet machine. It can be seen that for comparable lengths and diameter of active material in the rotor the Switched Reluctance machine is less than half the inertia of the conventional alternatives. The figures above assume a rotor diameter of 200mm, a stack length of 150mm and a bore of 60mm – broadly commensurate with the size of machine used in vehicle traction application.

Case Study - LeTourneau Inc
L1350 Wheel Loader – The Requirement

- LeTourneau Inc, Longview, Texas .
- The L1350 weights 180 tonnes, handles a 38 tonne payload.
- Continual service in open-cast mining applications.
- Conventional machines utilise four brushed DC traction motors.
- Brush and commutator wear in the traction motors entails significant down-time for inspection and replacement.

The L1350 weighs 180 tonnes and stands 6m tall.

LeTourneau Inc. are based in Longview Texas and utilize SR Drive® technology in their latest 50-series 'digital' loaders. The L-1350 electric wheel-loader is the first of its type to be fitted with Switched Reluctance motors, providing independent power for each wheel.

Stranding 6m high from ground to cab roof and more than 16 metres long, the L1350 weighs over 180 tonnes and handles a 38 tonne payload carried in a 21m³ bucket.

Typically the machines are used in open-cast mining applications throughout the world. Such applications demand almost continual availability as the provision of replacement machines to cover downtime is extremely costly.

Conventional machines use a brushed DC motor as a traction drive, one per wheel. The brushes and commutators require regular inspection and maintenance and presented LeTourneau with an obvious desire to move to a brushless solution for their traction drives.

Case Study - LeTourneau Inc
L1350 Wheel Loader – The Solution

- Four 300kW SR Drive® systems employed, one for each drive wheel. Motors are independently driven but co-ordinated from a central controller.
- The SR Drive® motors; being brushless, increase inspection/service intervals from 500hrs to >20,000hrs.
- Their flat torque characteristic and greater speed range virtually eliminates the risk of stalling and has shaved precious seconds of loading time.

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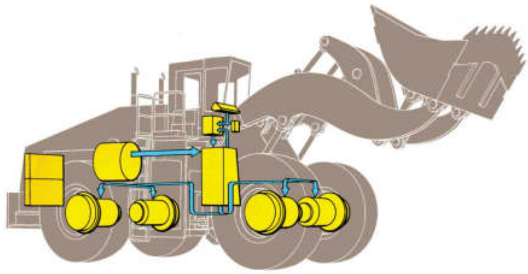


Exploded view of the SR Drive® traction motor and locations of the complete traction system on the vehicle.

Four SR Drive® B40 traction motors are employed on each vehicle and are coupled to each traction wheel via a 141:1 three-stage planetary reduction gearbox. Each motor has a separate power converter and the individual systems are coordinated from a central control unit.

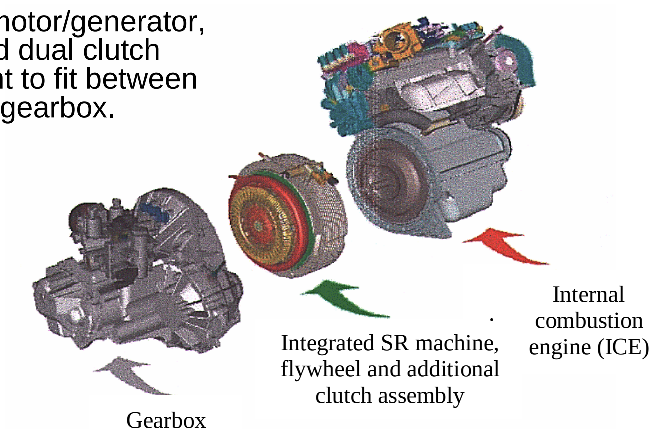
The B40 traction motors are rated at around 300kW continuous output and are around two-thirds the size of the conventional DC motor they replace. Their high torque availability and rapid response dramatically enhances the loader performance providing exceptionally high tractive effort whilst minimising wheel slip and tyre wear.

The use of SR Drive® motors has completely removed the need for brush inspection/replacement and commutator re-work procedures, increasing the inspection/service intervals from every 500 hours to upwards of 20,000 hours.

In use, the SR Drive® equipped wheel-loaders shave valuable seconds off each pass allowing more material to be loaded per shift than for an equivalent conventionally driven machine.

Case Study – ELMAS
Mild Hybrid Drive – The Requirement

- Greater fuel economy sought through:
  - Torque assist during pull-away
  - Regenerative braking
- Integrated motor/generator, flywheel and dual clutch arrangement to fit between engine and gearbox.



Exploded view of ICE, Motor-generator and Gearbox.

SRD have worked with Volvo, Fiat Auto and other partners on a European project to produce a mild hybrid-electric powertrain. An SR Drive® motor-generator with a novel dual clutch arrangement is integrated between the engine and transmission to provide pull away assist and regenerative braking in order to improve fuel economy. One of the clutches is integrated into the centre of the rotor of the switched reluctance motor-generator. This presents a challenge in that high specific output of the motor-generator must be maintained with minimal space for the active material.

Case Study – Fiat Auto
Mild Hybrid Drive – The Solution

- 15kW SR Drive® motor/generator provides up to 120Nm torque assist during launch.
- 25% cost saving compared to other technologies.
- Anticipated 10% improvement in fuel efficiency.

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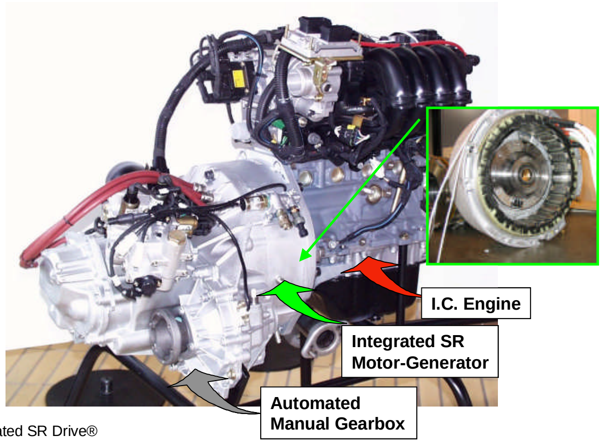

ICE and drive train showing integrated SR Drive® Motor Generator.

The result was a design which met all of the performance requirements and was demonstrated to be the most cost effective solution when compared with other electric drive technologies, being some 25% below alternative systems. The system yields an anticipated 10% improvement in fuel economy.

Key performance data for the switched reluctance motor/generator unit is as follows:

Stator lamination diameter = 284mm.

Stator active length = 55mm.

Rotor lamination bore = 197mm.

Air-gap length = 0.4mm radial.

Minimum battery voltage for full performance = 107V.

Low speed peak torque = 120Nm for 60s.

Low speed continuous torque = 70Nm.

Base speed for 15kW motoring = 1200rpm.

Maximum design speed = 6000rpm.

Case Study – Renault
Split Torque System – The Requirement

- Infinitely variable transmission system utilises two motors coupled through an epi-cyclic gearbox.
- Provides automatic transmission without the losses of a conventional torque converter.
- Enables engine to be run around its peak efficiency point at all times.

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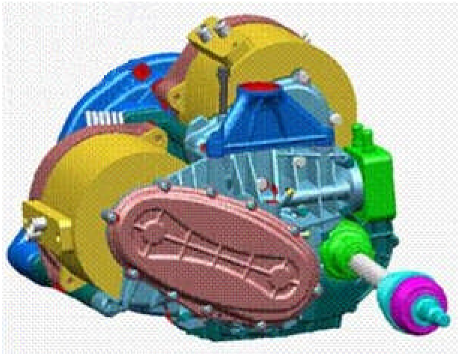
Infinitely variable transmission equipped diesel engined Renault Laguna.

SRD have developed the electrical drive system for a Renault Infinitely Variable Transmission (IVT). The main power source for the vehicle remains as a diesel combustion engine but the fixed transmission is replaced by a two-stage epi-cyclic gearbox which also links two SR Drive® motor/generator units. The intention of the system is that the transmission ratio between the engine and the final drive becomes continuously variable allowing the engine to be operated close to its peak efficiency at a constant speed around 2000rpm. Vehicle speed is then controlled by the two SR Drive® 'variator' machines whose maximum power output is a fraction of that (around a third) of that of the diesel engine. The overall vehicle efficiency is increased significantly by accomplishing an infinitely variable transmission with a combination of gears and small electrical machines as opposed to less efficient mechanical means such as conventional torque converters.

Case Study – Renault
Split Torque System – The Solution

- Two SR Drive® machines use liquid cooling and produce 25kW from 1800rpm to 11000rpm.
- Maximum peak torque of 135Nm.
- Position sensorless control provides a compact and rugged package for use in the engine bay.
- Prototype system currently under evaluation by Renault.
- Anticipated 10% improvement in fuel economy from the system.



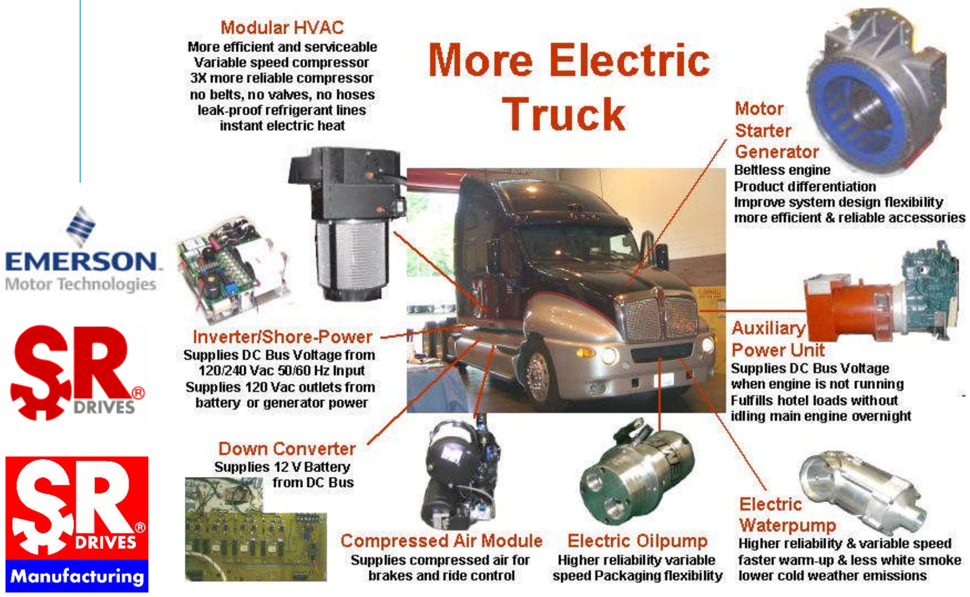
CAD image of Infinitely Variable Transmission system showing the two SR Drive® variator machines in yellow.

The electric machines use liquid cooling and have a continuous rating of 25kW from 1800rev/min to 11000rev/min. Each machine has an active diameter of 192mm and an active length of 160mm. A maximum torque of 135Nm is available for short periods of time. Position sensor-less control is used to provide a compact package suitable for use in the engine bay. Continuous current control enables a wide constant power region to be achieved for a DC bus voltage of 425V using 100A IGBT's* with a 70°C coolant temperature.

Prototype systems have been delivered to Renault for in-vehicle evaluation including fuel economy testing. The expected improvement in fuel economy is 10%.

**IGBT – 'Isolated Gate Bi-polar Transistor' a high efficiency semiconductor switching device.*

Case Study – Caterpillar Inc
Starter Generator – The Requirement



The US Department Of Energy provided funding to Caterpillar to investigate the benefits of increased electrical auxiliaries for highway trucks. Electrical auxiliaries include the oil pump, the water pump, the air compressor for the vehicle brake system and an electric HVAC system.

The heart of the system is the SR Drive® starter/generator unit which is mounted between engine and gearbox inside a modified flywheel housing. The intention of the starter/generator is to provide a direct-drive capacity to both start the engine and generate the required electrical power for the various auxiliaries.

Case Study – Caterpillar Inc
Starter Generator – The Solution

- Integrated Starter Generator provides:
  - Engine starting
  - Power to auxiliaries
- 340V 1200Nm 30kW unit located in modified flywheel housing.
- Sensor-less position control.
- Required no maintenance intervention since commissioning in 2003 and extensive road testing since.

Compact SR Drive® rotor fits within the space envelope of the existing motor flywheel.

SRD supplied a 340V, 1200Nm, 30kW crankshaft mounted SR Drive® starter-generator to start the engine and supply power for the vehicle electrical auxiliaries.

Position sensor-less control is used to provide rapid engine starting and vehicle power generation. The system has been shown to be robust in the vehicle environment and has required no maintenance intervention since the truck was commissioned in 2003.

Several on-highway tests have confirmed a fuel economy benefit. Work is underway to improve this by increasing the functionality of the ISG to provide engine assist.

Switched Reluctance Drives: - Summary

- Robust construction / straightforward operation
- Wide constant power range
- High efficiency over wide speed range
- Compact and cost effective

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The aim of this presentation has been to provide an overview of SR Drives® and to outline their numerous benefits and proven track-record in vehicle traction applications.

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