INNOVATIVE FAN DRIVES FOR HYBRID TRUCKS

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SUMMARY

This paper explores the possibilities for using the main engine cooling fan to provide cooling air flow even when the internal combustion engine of a hybrid truck is stopped. The required functionalities, including fan engagement and disengagement, efficiency in several operating conditions and fail safe modes, are established and prioritised. Different solutions for the engine cooling fan drive are evaluated. The development of an innovative electro-mechanical solution is presented: The working principle, modelling, concept choices and mechanical and electrical dimensioning to reach the required functionalities are detailed.

INTRODUCTION

With ever-increasing fuel prices and forthcoming stringent regulations on the reduction of CO_2 emissions, the desire for better fuel economy in the truck sector continues to drive towards an optimisation of energy use. One solution enabling significant reductions in fuel consumption is the Hybrid Electric Vehicle [1, 2].

The development of HEVs brings additional technical constraints and challenges compared to conventional trucks. The additional hybrid driveline components must be installed and cooled. The use of the vehicle changes with the addition of new operating modes that can be hybrid modes, combining internal combustion (IC) engine and electric propulsion or full-electric modes. These new operating modes are challenging for engine accessories, especially during driving conditions when the IC engine is stopped.

Typically, in hybrid vehicles the cooling of the electrical components of the powertrain, such as the energy storage systems, power converters and electric machines, is assured by an auxiliary cooling system [3, 4, 5]. This is often due to the differences in cooling needs of electrical components and the engine. Electrically driven fans are used to meet cooling needs (thus assuring hybrid or electric drive modes), adding cost, weight and additional packaging constraints to the vehicle. A single integrated cooling circuit for the engine and HEV components is one possible solution [5]. One of the main challenges in the development of an integrated cooling system is the need for the fan to function during IC engine off conditions. This drives the need for an evolution of the main engine mounted cooling fan drive and is the subject of this paper.

Fan drives in truck applications are often mechanical with a direct link to the engine crankshaft via a belt, chain or gear set. The speed of the fan is therefore dependent on engine speed, with either a fixed or variable ratio. Variable ratios can be achieved using gear technology (combinations of gears and clutches) or viscous drives. In the case of viscous drives the fan speed control is through energy dissipation.

This article describes the development of a fan drive that enables a continued cooling air flow using the main engine cooling fan even when the IC engine is off. To achieve this, the fan drive should be driven both mechanically by the engine crankshaft and/or electrically with an electric motor. The following sections describe installation constraints and fan functional needs in hybrid or electric modes. Possible solutions are evaluated and an innovative electro-mechanical solution is presented. Additionally, the innovative "hybrid" fan drive described in this paper enables fan speed modulation through a regenerative rather than dissipative control of fan speed, in a direct move towards energy efficiency.

TECHNICAL SPECIFICATIONS

Constraints of vehicle installation & packaging

Typically, on truck applications the main cooling fan is located behind the heat exchanger. The fan drive supporting the fan is attached to the front face of the IC engine and is mounted either on a pulley or directly on the engine crankshaft as shown in Figure 1.

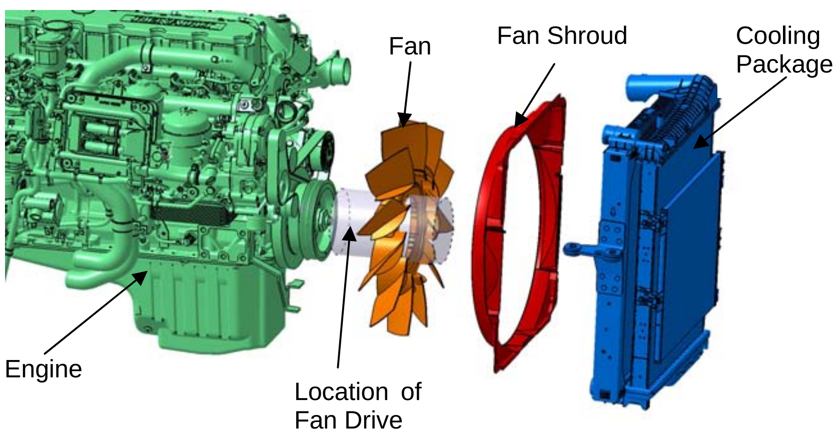

Figure 1: Exploded diagram of the cooling system to illustrate typical position of fan drive (mounted on crankshaft)

This paper focuses on a crankshaft mounted fan drive that must fit within the current drive volume. The available input speeds when the fan is driven mechanically by the IC engine, are therefore:

Table 1: Specification of Input Speeds

Mechanically driven	Input speed
Minimum	600 rpm
Nominal (i.e. maximum in normal operation)	2300 rpm
Overspeed (e.g. wrong gear shift during 10 seconds)	2650 rpm

Based on typical fan absorbed power values for medium-heavy duty trucks the power transmission requirements are assumed to be as follows:

- maximum fan absorbed power when mechanically driven of 20kW at 2300rpm engine speed.
- maximum fan absorbed power when electrically driven of 1.4kW at 1000rpm.

Functionalities

The following graph shows the functionality required from the hybrid fan drive in terms of the output speed. Today's mechanical viscous fan clutch is indicated by the solid grey area. Additional functionalities are shown around this area and are numbered in order of importance.

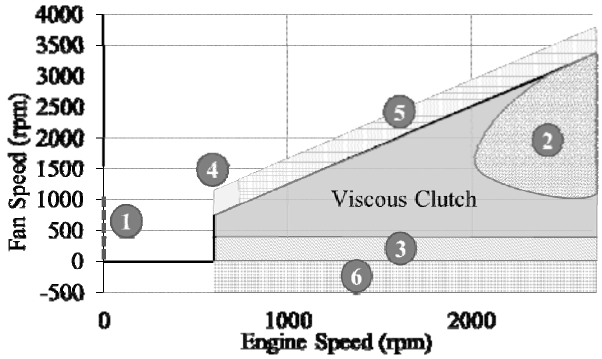

Figure 2: Required functionality in terms of output speed

Functionality 1: To achieve variable fan speed between 0 and 1000 rpm with IC engine off

This is the primary functionality to be achieved by the hybrid fan drive. The purpose is to provide cooling airflow when the IC engine is off. A variable speed between 0 and 1000rpm is required when the IC engine is stopped.

Functionality 2: To eliminate (or reduce) current restricted area (slip heat area)

The slip heat area (SHA) of viscous fans corresponds to the operating area in which the heat produced by the drive is higher than the cooling capacity of the drive. In this area silicon oil temperatures can exceed durability limits, leading to oil degradation. Fan modulation within the slip heat area is limited to short transients. The hybrid fan drive should eliminate or reduce this restricted area to allow a full modulation of the fan speed whatever the input speed.

Functionality 3: To eliminate (or reduce) clutch idle speed

The purpose of this additional function is to reduce energy consumption when airflow is not needed. This functionality is also beneficial in cold conditions to improve engine warm up, and is acceptable even if reducing airflow consumes energy.

Functionality 4: To 'boost' fan speed at IC engine idle speed

The purpose is to supply a higher fan speed when the IC engine is at idle speed. This functionality is typically beneficial for air conditioning where there is a high demand in cooling airflow to cool the condenser, especially when the truck is at standstill.

Functionality 5: To 'boost' fan speed throughout diesel engine speed range

The purpose is to provide a higher fan speed than the input speed reached in mechanically driven conditions, for the whole range of IC engine speeds. This functionality increases the engine cooling performance.

Functionality 6: To reverse the direction of fan rotation

The interest of this functionality is to blow debris out of the heat exchangers.

Fan engagement and disengagement speeds

In order to prevent temperature overshoots, the engagement of the fan and variation of fan speed should be rapid. Therefore, a minimum rate of change of speed is defined at 200rpm/s. For example, it must take 5 seconds at the most to increase the fan speed by 1000rpm.

On the other hand, a maximum acceleration is defined to minimise the fan noise perception. In electric mode, a hybrid vehicle is relatively silent, therefore it is imperative to consider the noise aspect in the development of the fan drive. While fan noise is mainly dependent on the fan speed and fan blade geometry, the fan clutch has an impact on noise annoyance by controlling fan acceleration. Thus a maximum rate of change of speed is defined at 600rpm/s. If we use the same example as above, a change of speed of 1000rpm should not be done in less than 1.66s.

Fail-safe modes

The system must be designed as fail-safe, so that if the electric system fails, the fan can continue to rotate at a certain speed to maintain a minimum level of cooling capacity.

SOLUTIONS

Mechanical fan drives today include viscous, continuously variable transmission (CVT), electromagnetic and simple on-off clutches. Most of these solutions could be combined with an electric motor to achieve the primary functionality. Although a detailed analysis of each solution is not the aim of this paper, Table 2 illustrates the requirements that are met by each solution.

Table 2: Functionalities of different fan drive solutions

Requirements \ Solution	Viscous clutch + Electric Machine	Pulley CVT + Electric Machine	Electro-magnetic clutch + Electric Machine	On-off clutch + Electric Machine	Electro-mechanical solution
Packaging constraints	X		X	X	X
Functionalities 2 to 6		X			X
Fan engagement / disengagement	X	X	X		X
Fail safe mode	X	X	X	X	X
Improved Efficiency		X			X

It can be seen that the electro-mechanical solution best meets the requirements as described previously. The electro-mechanical fan drive presented here is a continuously variable transmission (CVT) composed of a planetary gear driven by the engine and to which the fan is coupled. An electric machine connected to the third member of the planetary gear enables fan speed control independent from the engine speed. Full fan engagement is achieved by maintaining the third member stationary by closing a clutch. Using the same electric machine for both hybrid and electric modes gives a significant packaging benefit compared to the other solutions.

THE ELECTRO-MECHANICAL SOLUTION

Functional Description

The recommended design is to drive a planetary gear by mounting the planet carrier to the engine, the fan on the ring gear and both the electric machine (EM) and the clutch to the sun gear, as shown in the functional sketch Figure 3.

The functionality of a planetary gear is typically described by using an equivalent lever diagram in which the speed of the sun, carrier and ring gears are plotted on three parallel axes and the torque applied to sun, carrier and ring gears are represented by forces. The lever diagram Figure 4 represents an electro-mechanical fan drive with a ratio of 1.25.

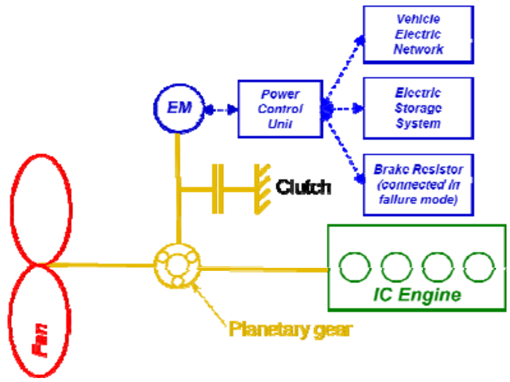

Figure 3: Functional sketch of the electro-mechanical solution with planetary gear

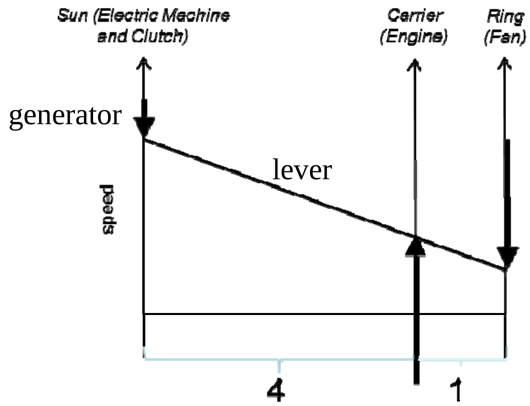

Figure 4: Lever diagram of the electro-mechanical fan drive with a planetary gear ratio of 1:1.25

It can be demonstrated that in such a diagram, sun, carrier and ring speeds are aligned, thus forming the lever. In steady state, the resistive torque applied by the fan to the ring gear is balanced by a resistive torque applied by the electric machine to the sun gear. This means that when maintaining the fan blade speed at a given level, the electric machine operates in generator mode. In the example chosen above, we can see,

$$\tau_{electric\_machine} = \tau_{fan} / 4 \qquad (1)$$

In order to increase fan speed, the resistive torque of the electric machine is increased. The torque applied by the electric machine during this transient phase balances fan resistance and fan inertia as well as the inertia of all rotating parts (the gears and the electric machine itself). Note that the electric machine is in generator mode during fan engagement.

Complete fan engagement is reached when the speed of the electric machine reaches zero as shown in Figure 5. In the chosen example, fan speed is 1.25 times engine speed. This steady state corresponds to the highest torque applied to the sun gear, but as the sun gear is not rotating, it does not transfer any power. This functionality is best met by closing the clutch as shown in Figure 5. This mode is the most efficient as the fan is driven by the engine through the gears.

To decrease fan speed, the resistive torque of the electric machine is reduced, typically put to zero.

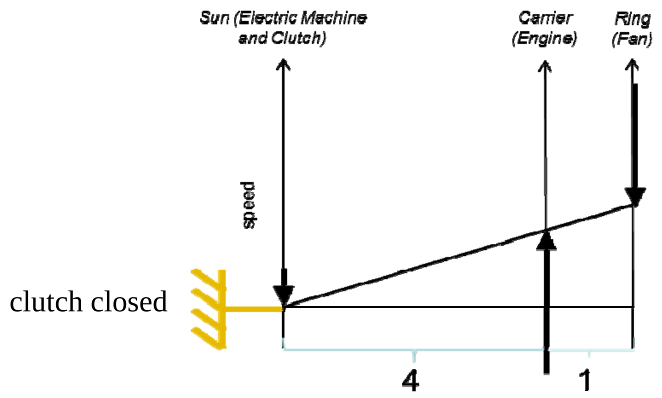

Figure 5: Lever diagram for complete fan engagement

How to drive the fan electrically when the engine is off (primary functionality)

The fan can be driven electrically when the engine is off as shown in Figure 6. The carrier acts as a fixed point, the resistive torque of the stalled engine being significantly higher than the torque applied to the carrier. The planetary gear acts as a gear ratio between electric machine, in motor mode, and the fan. In the example, it enables an operation of the electric machine at a speed four times higher than the fan speed (e.g. at 4000rpm to obtain a fan speed of 1000rpm), thereby avoiding less efficient low speeds on the electric machine. Note that this electric mode can be used to reverse fan rotation.

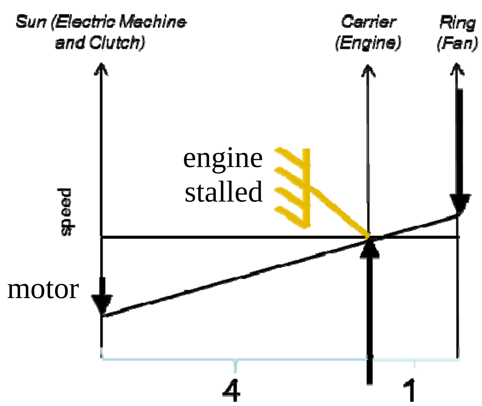

Figure 6: Lever diagram for fan driven electrically during IC engine off

How to achieve a reduced idle speed of the fan

If no electric torque is applied by the electric machine, the fan speed will drop, only damped by the inertia of the rotating parts, until the internal resistance of the system (gears, bearings, lubricant, seals) balances the resistance of fan blade. This steady state is the idling state. Figure 7 shows the estimation of the fan speed versus engine speed assuming standard levels of internal resistance. The foreseen trend is that the idle speed reached with the electro-mechanical drive will not be lower than that of the best current viscous drives (approx. 300rpm) as the resistance of the gears will remain greater than the resistance of an emptied working chamber of a viscous drive. The resulting power consumption remains moderate: 180W due to a fan speed of 500rpm reached for an engine speed of 2000rpm.

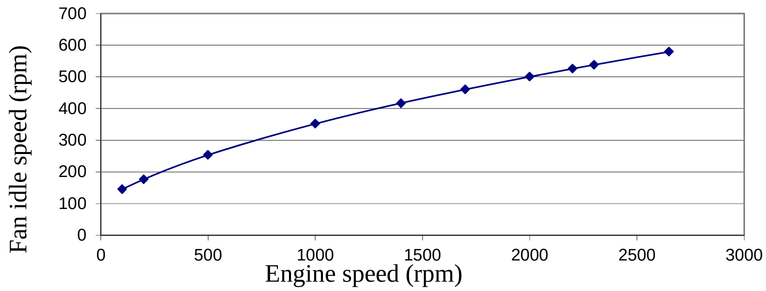

Figure 7: Graph of fan idle speed (rpm) as a function of engine speed (rpm)

How to avoid fan rotation in cold start conditions

Reducing fan speed to levels lower than the idle speed requires compensating the internal resistance of the system with the electric machine.

This leads to a specific operating range of the electric machine in motor mode at very low torque (a fraction of a Nm) and at high speeds. See "Sum up of technical choices and dimensioning of components / Electric machine and power electronics".

How to meet the other functional requirements

The electric machine can be used in motor mode and reverse speed, when the engine is on, to boost fan speed above complete engagement speed. The electric machine can also be used in motor mode and forward speed, when the engine is on, to reverse fan rotation. These functionalities are not addressed further in the following paragraphs, which focus on the functionalities that most influence concept choices and component sizing.

From a dissipative system to a regenerative system

For a viscous drive, fan modulation corresponds to slipping: slip energy is dissipated as waste heat, Q_{waste} as in Equation 2 :

$$Q_{waste} = \tau_{fan} \cdot \left(N_{drive} - N_{fan}\right) \qquad (2)$$

Where τ_{fan} is the fan torque, N_{drive} the fan drive speed and Nf_{an} the fan speed. In the case of a crankshaft mounted fan, fan drive speed is equal to engine speed.

As previously discussed, the viscous fan drive modulation capabilities within the SHA are limited by the drive cooling capacity. In current designs, this cooling capacity is function of fan speed since the exchange surface is that of the housing to which the fan is mounted. In the example shown in Figure 8, in order to enable continuous operation of the fan at any speed for engine speeds up to 2200rpm, the cooling capacity of the drive must reach 4kW for a fan speed of 1700rpm.

In the case of the electro-mechanical drive, slippage power is regenerated into electric energy which is then utilised for electric consumers or stored for future use (e.g. to drive the fan electrically when the engine is off). Thus, instead of a dissipative fan modulation, the electro-mechanical hybrid fan drive concept is based on regenerative fan modulation. It can be demonstrated mathematically or numerically that the resistive power applied by the electric machine to the sun gear equals the slippage power and is thus equivalent to the heat that is wasted in viscous drives. This obviously leads to better energy efficiency.

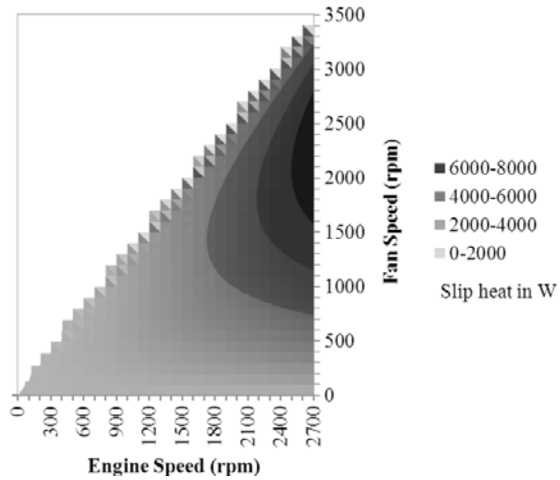

Figure 8: Slip heat of a viscous fan drive as a function of engine speed and fan speed (drive ratio 1:1.25)

In all these operating modes, the IC engine is the sole provider of energy. This energy is primarily transferred to the fan blade. Part is regenerated in the form of electric energy which is fed to the electric system and either used by electric consumers or stored for further use (typically for the electric drive mode). Only the internal resistances (mechanical and electrical) of the system lead to energy losses.

How to achieve a reduced slip heat area

Nonetheless, heat dissipation is, once again, the limiting factor. The losses in the electric machine, which is embedded in the drive, need to be dissipated. The order of magnitude of the heat produced is of 10% of the resistive power of the electric machine, on a wide operating range, with current technologies. This means the heat load of an electro-mechanical (regenerative) drive is ten times less than that of viscous (dissipative) drives. On the down side, maximum allowed temperatures of electric machines are lower than that of silicon oils used in viscous drives. The temperature differences that create the heat exchange are significantly in favour of the viscous drive.

The main desired functionality is to push the SHA above 2200rpm. Resistive power applied to the ring versus fan speed and engine speed is charted in Figure 9. 4kW peak / 3kW continuous are required to reach the desired functionality. Above maximum engine speeds of 2650 rpm, no cooling is required; this determines the maximum operating speed of the electric machine.

The SHA defines the sizing of the electric machine in continuous regeneration conditions.

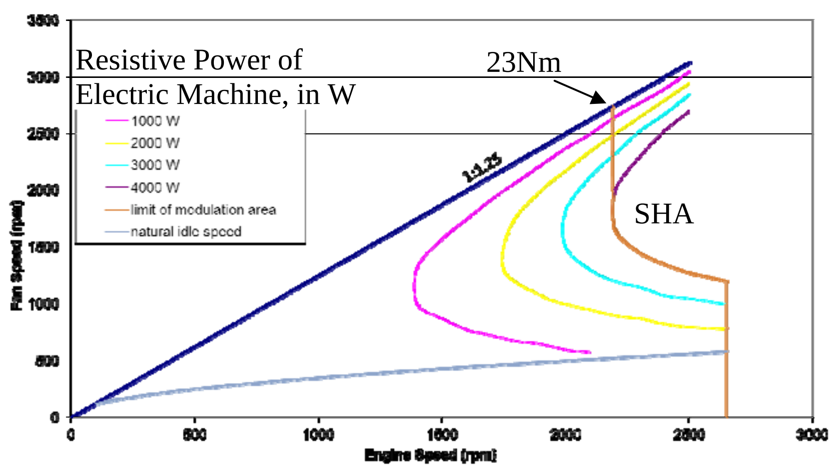

Figure 9: Slip heat area of the electro-mechanical fan drive (planetary gear ratio 1:1.25)

How to reach wanted engagement/disengagement speeds

As for other fan drive technologies, fan engagement speed is directly related to the drive capacity and is a transient operation at maximum braking power. This transient phase dimensions the electric system in peak power.

A model was developed to simulate fan engagement using a braking power of 3kW for input speeds of the engine up to 1900rpm. For engine speeds above 2000rpm, Min(30Nm;4.5kW) is applied when fan acceleration becomes too low.

Note that, to reach sufficient acceleration of the fan, it is necessary to apply a resistive power somewhat higher than the 4kw required to operate at the border of the SHA.

Fan acceleration resulting from the simulated control strategy is pictured in Figure 10.

Up to engine speeds of 1700rpm, 3kW is sufficient to stay above the lower acceleration limit. The applied resistive torque can be adjusted to reach a given acceleration curve. Less torque can be applied to slow the fan engagement, especially at low engine speeds.

Above engine speeds of 1700rpm, the lower acceleration limit is no longer reached with 3kW. Up to engine speed of 2000rpm, applying 4,5kW for less than 5s is sufficient to reach this acceleration criterion. This would result in transient operation of the electric machine between 3 and 4,5kW.

For engine speeds between 2100 and 2200rpm, although the lower wanted acceleration can no longer be met, fan engagement times remain comparable to that of the current viscous drives. The longest engagement time is of 22s at 2200rpm engine speed. The maximum resistive power of 4,5kW is applied less than 15s in all cases.

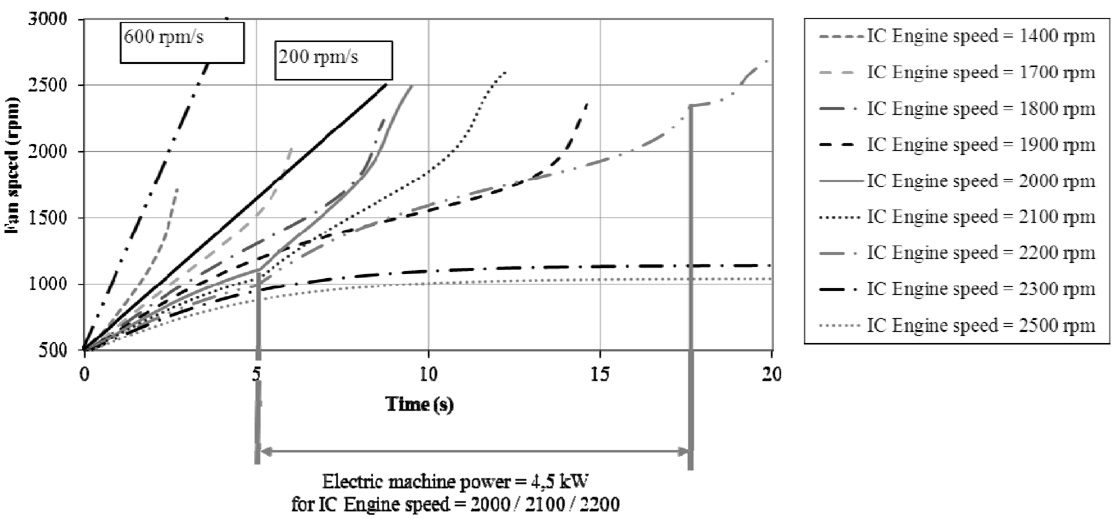

Figure 10: Fan acceleration resulting from the simulated control strategy

The planetary gears are also dimensioned in this transient phase.

Fan disengagement is achieved by reducing the resistive torque of the electric machine, down to zero. Fan deceleration speed when no torque is applied by the electric machine is calculated by the balance between inertias of the various rotating components. In theory, if a very fast deceleration were needed, the electric machine could be operated in motor mode (in the same operating quadrant as for the cold start operation). In practice this is not envisaged.

How to meet fail-safe requirements

Initial thinking was to close the clutch in case of failure of the electric system. It can be demonstrated simply that this would lead to sizing the clutch – and clutch actuator - as current fan clutches (such as pneumatically or electromagnetically actuated dry clutches). The weight, size and cost would in that case penalise the electro-mechanical concept. The drawback of using a clutch is the extremely short transient phase (typically a fraction of a second). This leads to peak dynamic torques that not only impacts clutch sizing but also the sizing of the whole system (including the planetary gear) and of the engine components to which the fan drive is mounted.

In consequence, the preferred solution to reach fail safe requirements is a brake resistor. The capacity of the brake resistor can be optimised to the cooling level requirement, depending on the application.

Sum up of technical choices and dimensioning of the planetary gear

A study performed by Ampère Laboratory, Lyon [6] has recommended a standard “type I” planetary gear as it fits functional needs and packages well. It has been dimensioned with the dynamic loading due to fan engagement.

Sum up of technical choices and dimensioning of electric machine and power electronics

The speed range of the EM is given by the kinematics of the planetary gear: maximum EM speed is reached when IC engine speed is the highest and fan speed is the lowest.

Table 3: Maximum speed and operating quadrant of electric machine vs engine speed and fan speed

engine speed		fan speed		EM speed	EM quadrant
(rpm)		warm up feature	idle		
nominal	2300	0		11500	motor
			540	9340	generator
overspeed	2650	0		13250	motor
			580	10930	generator

The warm-up feature (lowest fan speed) adds severity as it increases the EM speed. As both nominal speed and overspeed occur mainly for short periods (and as the latter seldom occurs), it can be argued that avoiding airflow in these conditions has a negligible impact during cold start. In consequence, 11000rpm is the order of magnitude for a realistic maximum EM speed.

In generator mode, forward speed (Quadrant 4), the EM continuous torque versus speed is dimensioned by the need to maintain a given slip between fan speed and engine speed throughout the operating area (cf. Figure 9).

- Maximum torque of 23Nm is reached when fan reaches full engagement at 2200rpm engine speed (calculated from the lever diagram, Figure 5).
- Maximum torque curve follows the 3kW limit of the SHA.

The EM peak torque is dimensioned by the maximum fan engagement speed at high engine speed (see “How to reach wanted engagement/disengagement speeds”), leading to 30Nm/4,5kW.

In motor mode, reverse speed (Quadrant 3),

- The most severe conditions correspond to driving the fan electrically when the engine is off. The maximum fan speed required (1000rpm in reverse speed) leads to a continuous mechanical power of around 1.4kW applied by the EM to the sun gear.
- Boosting the fan when the engine is off also requires operating in this mode. It is chosen not to use this requirement in the dimensioning of the electric machine.
- In motor mode, forward speed (Quadrant 1),

- The cold start enabler of holding the fan stationary is the sole requirement driving the need to operate the electric machine in this mode, putting extra requirements on the power electronics although power levels are low (up to around 500W).

Note: Quadrant 2 is not used.

These electric machine specifications are summed up in Figure 11. The typical characteristic of a current 28V/100A alternator from the automotive industry is also pictured as a known reference.

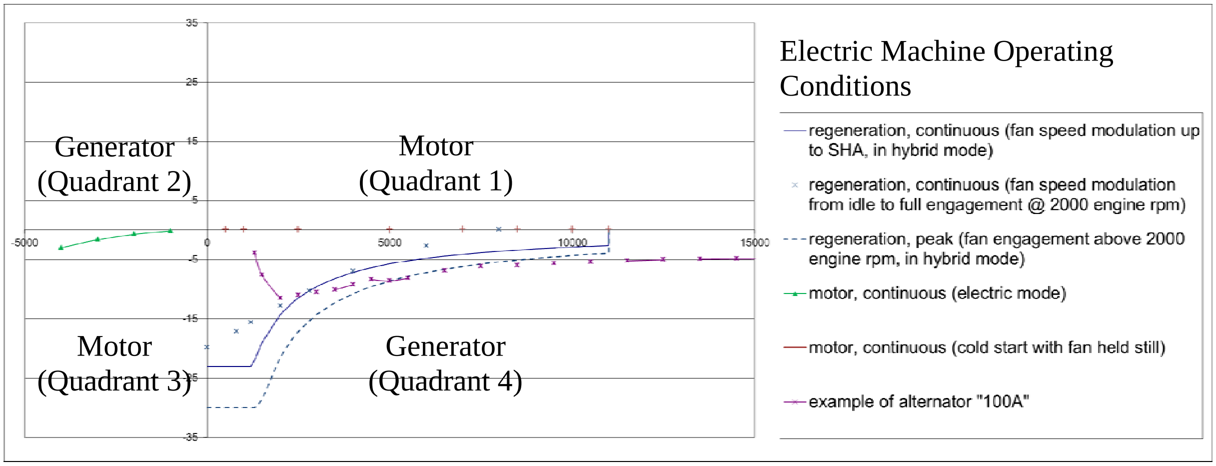

Figure 11: Graph of torque as a function of speed for the electric machine

Clutch

It has been chosen not to rely on the clutch for transients. The synchronisation being achieved with the electric machine, the function of the clutch is solely to maintain the fan fully engaged. The resulting torque is moderate, up to 23Nm at 2200rpm engine speed (calculated from the lever diagram, Figure 5) and the heat losses are negligible (no friction). All types of clutches can potentially meet this simple requirement, including dog clutches.

Design and packaging solution

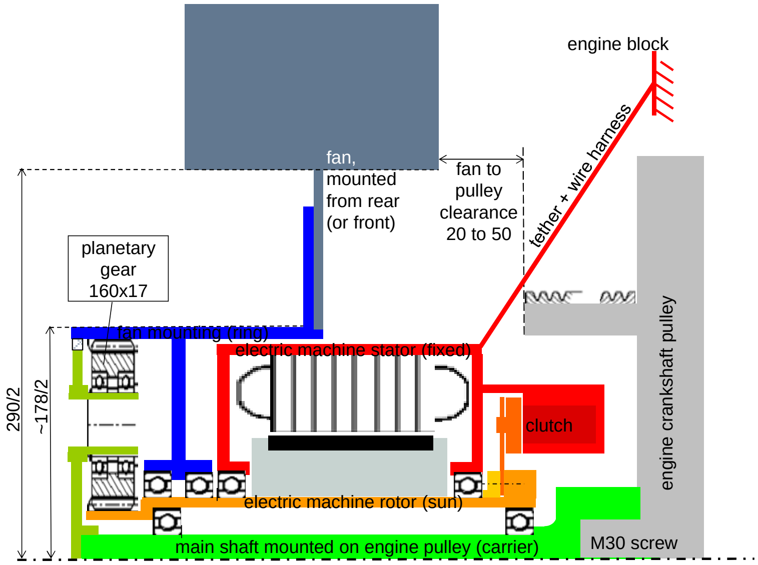

Figure 12: Illustration of the electro-mechanical solution packaging

DISCUSSION

The electromechanical solution meets the primary function of a hybrid fan drive: fan speed modulation both when the engine is on and when the engine is off (with limited fan speed). Its strengths are: Improved energy efficiency by replacing energy dissipation with energy regeneration, unlimited modulation possibilities with limitations only due to the sizing of the electric system. Its limitations are: Idle speed reduction is limited by the internal mechanical resistance of the system. The elimination of the SHA and fan engagement speed are limited by the sizing of the electric system. The fail-safe mode is limited by the sizing of the brake resistor system. This innovative fan drive could also enable some improvements in noise perception by limiting fan acceleration in transient phases, so that the engagement of the fan and variation of fan speed would be smooth at all times. The next steps in the development of this concept are to analyse the electric energy balance (generation versus consumption) to enable the sizing of the electric system in terms of the energy storage system. This could also lead to possible downsizing of the vehicle alternator. The brake resistor system must be sized. An alternative design with a second electric machine mounted to the ring to enable more independence from the electric system of the vehicle can be investigated. Energy management strategies must be developed and finally the detailed development of the product must be performed. In the long term, the expected advances in electric machines (cost reduction, compactness) will increase the attractiveness of this concept.

CONCLUSIONS

This paper presents an innovative electro-mechanical hybrid fan drive that combines the functionalities of current viscous drives and electric drives while fitting inside the packaging constraints. The electric machine is integrated directly in the fan drive. It is used to control fan speed when the fan is driven by the IC engine as well as to drive the fan during electric or hybrid vehicle modes. As the electric machine is used in generator mode, the fan drive generates electricity during fan modulation, increasing efficiency compared to conventional dissipative viscous fan drives. This concept has a high potential for improvement due to the expected advances in electric systems (compactness and cost reduction of electric motors, power electronics and energy storage systems). The option to introduce a second electric machine would make it less dependent on the electric network of the vehicle. Ultimately, this concept will enable complete freedom in fan actuation, making it an attractive solution for non-hybrid vehicles.

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