HIGH SPEED DYNAMIC GEAR CHANGING

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The steady increase of oil prices together with a rising environmental concern has created a demand for more energy efficient transport solutions. One way of doing this is through the hybridisation of vehicles. By hybridising a combustion engine vehicle the operating point of the combustion engine can be kept closer to the maximum efficiency point for a longer period of time compared to conventional vehicles, which results in lower fuel consumption and emissions. Another major benefit is that brake energy can be regenerated and stored instead of being wasted as heat energy as in a conventional friction brake. Volvo has designed such an electric hybrid drive train concept called I-SAM; Integrated Starter, Alternator, Motor. This hybrid concept involves an electrical machine situated between the clutch and the transmission where space is limited. The motor has a high diameter to length ratio that results in an undesirably large moment of inertia.

An alternative placement of the motor is along side the transmission, rather than inline with it, and this is the case with the ExSAM concept (External Starter, Alternator, Motor). The benefits of changing the location of the motor is that the restrictions caused by the tight space in the driveline can be avoided and a longer more slender machine with faster acceleration times can be used. The ExSAM is connected via the power take-off (PTO) through a fixed gear setup directly onto the countershaft in the transmission.

The time it takes to change gears in a hybrid driveline can be significantly decreased with the assistance of the ExSAM. In order to change gears in a transmission the existing gear must be disengaged, the speed of the countershaft must be synchronized to match the speed of the new gear, after which the new gear can be safely engaged. In a conventional setup deceleration of the countershaft is achieved with a friction brake that can decrease the speed by 2000 rpm/s, acceleration is done with the help of the diesel engine and is significantly slower. As the ExSAM is connected to the countershaft it can be used to speed up the shifting process by actively steering the countershaft to the correct speed. In order to prove this, a test rig has been setup at Sibbhultsverken in Sibbhult, Sweden comprising a diesel engine, a Volvo transmission, the ExSAM and a flywheel on the output shaft. Power electronics from Vacon together with a CompactRIO system from National Instruments is used to handle the motor control.

The work can be divided into three main areas:

1. Establishing control over the shifting forks in the transmission
2. Programming a state machine in LabVIEW that executes the steps in a shifting sequence
3. Programming an application for the Vacon control unit for a safe and fast motor control

The Volvo transmission has a built in control unit that needs to be circumvented in order to be able to move the shifting forks that engage and disengage the different gears without interference. This is done by drilling a hole in the lid of the transmission and directly connecting the solenoid valves that move the shifting forks to an output module in the CompactRIO.

The motor control needs to be extremely fast in order to achieve a significant improvement compared to changing gears in a conventional driveline. This means that the program governing over the gear changing process is located on a field programmable gate array (FPGA) in the CompactRIO. This is programmed in National Instruments' LabVIEW, which is a graphical programming environment implementing parallel code execution. The signals used to open and close the solenoid valves are sent directly from LabVIEW to the transmission, unlike the motor control signals, which are sent via the Vacon control unit to determine the appropriate motor current injection.

Because the modules in the CompactRIO cannot send negative signals the isy current is mapped in the Vacon control unit so that 1.4 mA is interpreted as maximum negative current and 20 mA as maximum positive current. If the absence of a reference signal should occur, due to a loose wire for example, it is important that this is not interpreted as maximum negative current. For this purpose signals ranging from 0 mA to 1.4 mA are programmed to be interpreted as zero motor current to avoid the motor rushing uncontrollably in such cases. To avoid crossing this boundary accidentally due to signal noise a hysteresis has been added in the LabVIEW code to saturate the signal at 2 mA. These necessary safety measures come at the expense of a 10 % loss of resolution as the isy current is now mapped between 2 and 20 mA instead of 0 and 20 mA.

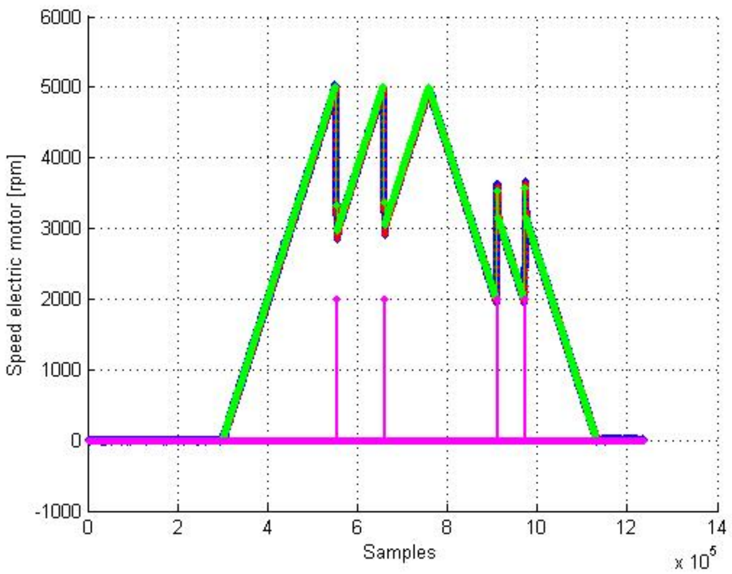

Figure 1. Graph of EM speed during gear changes in a drive cycle

Tests with the setup involve measuring the actual time of the synchronisation step and simulated gear changing drive cycles. The drive cycle can be seen in figure 1 where the first half of the graph shows an acceleration to 250 Hz in first gear, then gear changes to third and fifth both followed by accelerations. This simulates an acceleration of the output shaft whilst keeping the diesel engine working in the rpm range for economical driving. The second half of the graph shows a corresponding deceleration. The fastest recorded time for a gear change between first and third from 250 Hz is 318 ms.

Some delays in the shifting sequence are experienced when waiting for acknowledgement signals for the positions of the shifting forks. To try and minimize the effect of this delay the effected safety features were removed from the sequence and replaced with timeout indicators. With the timeouts set to 40 ms and starting in first gear at 250 Hz a series of gear changes were done, with the results shown in table 1.

Because the safety features are removed not all changes are successful but what can be seen is that it is possible to complete these changes much faster than before. The change from first to third gear can be compared with the results from the previous test and is just about 100 ms faster, an improvement of 31 %.

Timeout [ms]	First to Third [ms]	Third to Fifth [ms]	Fifth to Third [ms]	Third to First [ms]
20	250	-	-	-
40	270	160	220	330
40	220	220	280	-

Table 1. Results for gear shifts with low transmission safety

The goal is to prove that the ExSAM can be used to aid in the synchronisation process in a shift sequence in a hybrid vehicle. It is clear that this has been achieved when comparing the ExSAM synchronisation times with what is possible with the deceleration of 2000 rpm/s using the friction brake. A speed of 3345 rpm/s is reached and this, despite possibilities of being optimized further, is an irrefutable improvement.