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Electrified Dynamic Skip Fire (eDSF): Design and Benefits

Mark Wilcutts, Masaki Nagashima, Kian Eisazadeh-Far, and Matthew Younkins Tula Technology Inc.

Keith Confer Delphi Technologies

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Abstract

Tula's Dynamic Skip Fire (DSF®) technology combines highly responsive torque control with cylinder deactivation to optimize fuel consumption of spark ignited engines. Through careful control of individual combustion events, engine operation occurs at peak efficiency over the full range of torque demand.

A challenge with skip-fire operation is avoiding objectionable noise and vibration. Tula's DSF technology uses sophisticated firing control algorithms which manage the skip-fire sequence to avoid excitation of the powertrain and vehicle at sensitive frequencies. DSF enables a production-quality driving experience while reducing CO2 emissions by 8-15% with no impact on regulated toxic emissions. Moreover, DSF presents a high value solution for meeting global emissions mandates, with estimated cost less than $40 per percent gain in fuel efficiency. DSF is slated for production on larger engines in the near future, and is in advanced development with automotive OEMs for four cylinder applications.

In a partnership with Delphi Technologies, DSF has been implemented in 1.8 L 4-cylinder GTDI vehicles, and has been shown to provide a smooth driving experience with substantial fuel economy benefits. Further, projects coupling DSF with hybridization are under way. Hybridization, projected to soon be in place on most new vehicles, offers opportunities for additional fuel economy gains for DSF via careful control of motor and engine torques to broaden skip-fire operation over the engine operating range.

This paper discusses design features and fuel economy benefits of coupling DSF with electric hybridization, dubbed eDSF. The fuel economy benefit synergies include enhanced vehicle kinetic energy recovery through decel cylinder cutoff, and expansion of DSF zone of operation using torque assist and torque smoothing. In the torque smoothing operation an electric torque waveform is introduced in concert with the skip-fire engine operation.

A fuel economy simulation study is described, and predictions of test-cycle reduction in CO2 emissions are presented. Hardware requirements for implementing an eDSF system are discussed, as well as preliminary simulation analyses of front-end accessory drives, relevant when eDSF is implemented in a P0 configuration.

1. Introduction to DSF

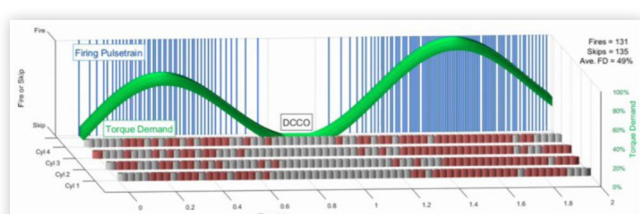
Dynamic Skip Fire (DSF®) is the ultimate control strategy for cylinder deactivation, updating engine displacement on a cylinder event-by-event basis. DSF provides dynamic downsizing, minimizing fuel consumption while delivering production-level noise and vibration. Prior publications have presented the DSF system [1-5] and associated DSF-affected functions; a brief description is provided here.

In DSF operation, the decision to fire or skip a cylinder is made immediately prior to each firing opportunity, with each firing opportunity considered in sequence. In most applications, when a decision is made to skip a cylinder, intake valves and exhaust valves are held closed, using conventional cylinder deactivation hardware. These valve deactivation mechanisms are the only additional hardware required to implement DSF. Thus, DSF can be implemented on DOHC four cylinder engines for approximately $40 per percent CO_2 reduction.

Figure 1 shows an example of DSF operation in a four-cylinder engine. A varying torque request is shown in green, which results in cylinders being fired (red) or skipped (grey). The combined firing pulse train for all four cylinders is in blue. When torque demand is near 100%, all cylinders fire. When torque demand is close to zero, 20% or fewer cylinders fire. When torque demand is zero or negative, no cylinders fire. This is termed DCCO, or deceleration cylinder cutoff.

Contrasted with conventional cylinder deactivation approaches, DSF avoids switching sets of cylinders on and off, since deactivation is continuously variable, avoiding large

FIGURE 1 Dynamic Skip Fire Operation



jumps in manifold pressure and other torque controlling quantities, which would need to be managed. Also, deactivating individual cylinders for extended periods of time is avoided. For the example in Figure 1, the longest period of deactivation for any particular cylinder is 20 cycles, or about 0.6 seconds. Over the two second time history of this example, the average firing density (FD) is 49%.

Fuel consumption is reduced substantially and is realized primarily through three mechanisms:

1. Elimination of most pumping losses
2. Improved combustion
3. Reduced oxygen saturation of catalysts during deceleration fuel cut events

In addition to the fuel economy benefits, transient response improvements are also possible since high intake manifold pressure is maintained, reducing the time to achieve the demanded torque on tip-ins.

Tula has integrated DSF into production automotive ECMs, in modern torque control architectures. Coordinated control of cylinder deactivation, throttling, camshaft phasing, and ignition achieves torque demand while maximizing fuel efficiency and managing NVH to production levels [2, 5], with very modest cost addition.

DSF requires a responsive valvetrain deactivation system to deactivate and reactivate the intake and exhaust valves of each cylinder independently. An example cylinder deactivation hardware system for overhead-cam roller finger follower (Type 2) valvetrains offered by Delphi Technologies, Inc. is described below.

Figure 2 shows the Delphi Technologies deactivation roller finger follower (dRFF) hardware. The dRFFs switch valve actuation between full and zero lift. Hydraulic pressure, routed through the lash adjuster, moves a spring-loaded pin in the body of the dRFF. When oil pressure is applied while on the cam base circle, it pushes the pin out of engagement. With the pin disengaged, the RFF follows the cam profile in lost motion. When the oil pressure is released while on the cam base circle, the spring forces the pin back into engagement and the dRFF then imparts the cam profile onto the valve stem for normal valve operation.

The oil pressure that drives the lost motion pin is provided through an electrically controlled Deactivation Control Valve

FIGURE 2 Deactivation Roller Finger Follower at peak cam lift, in Activated (left) and Deactivated (right) states

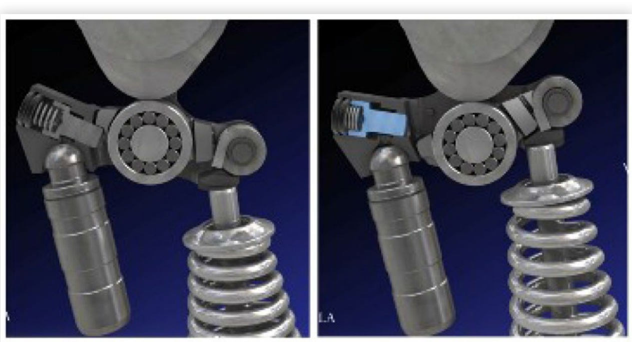


FIGURE 3 Deactivation Control Valve (left) and Deactivation Roller Finger Follower (right).

(DCV) shown in figure 3. Because intake and exhaust RFFs are on the cam base circle at different times, only one DCV, controlling all four intake and exhaust valves, is needed for each engine cylinder. The DCVs are similar to production two step oil control valves but have faster response time and higher durability since the number of deactivation cycles is much higher than in conventional cylinder deactivation, which changes state comparatively infrequently. These components comprise a compact, robust deactivation system that is highly responsive and maintains low friction characteristics.

2. Fundamentals of eDSF

Introduction

eDSF has three main synergies obtainable by operating DSF in conjunction with hybrid systems:

- Increased vehicle kinetic energy recovery through deceleration regeneration
- Expansion of DSF operation zone through judicious use of mild-hybrid torque assist
- Expansion of DSF operation zone through use of torque smoothing

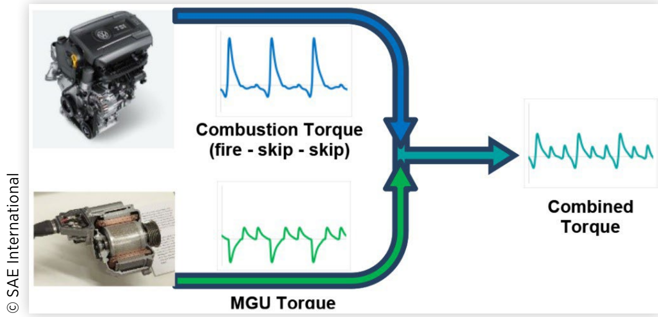
Enhanced Deceleration Regeneration

DCCO completely avoids pumping losses that normally occur during vehicle deceleration events when operating in deceleration fuel cutoff (DFCO) or in throttled mode. This provides an opportunity for additional coast regeneration by applying a small negative torque during deceleration, maintaining the same vehicle deceleration rates.

Expansion of DSF Operating through Torque Assist

Electrical torque assist provides additional torque primarily on launch. This creates a responsive drivability feel, which is especially important for downsized turbocharged engines. Because the torque assist also creates reduced torque demand from the combustion engine, it also provides additional opportunity for DSF operation. DSF has tremendously better fuel consumption of DSF at low loads compared with all-cylinder operation, so optimization of mild-hybrid control strategies that account for this can provide better overall fuel economy.

FIGURE 4 Torque Smoothing Principle



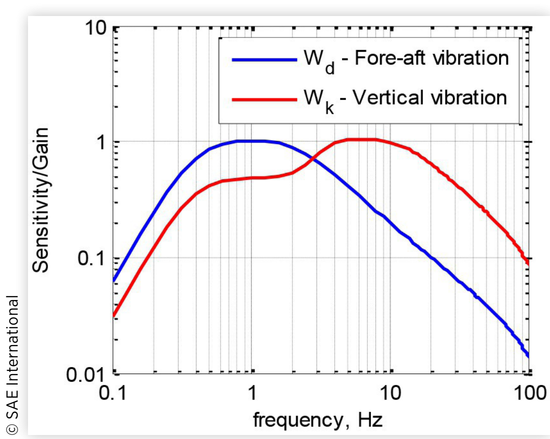
Expansion of DSF Operating through Torque Smoothing

Skip fire operation increases cylinder torque pulse magnitude for fired cylinders, and spaces the fired cylinder torque pulses farther from each other in time than all-cylinder operation. This introduces more low-frequency content in the torque excitations on the drivetrain and thus of the vehicle's chassis. The basic idea of eDSF is to use an electric motor-generator unit (MGU) to counter the low frequency excitation.

A countering torque waveform can be generated as conceptually shown in Figure 4. Here the large, wider-spaced torque pulses from combustion are partially captured by an MGU negative (generating) torque pulse, and stored in an energy storage device such as a battery or capacitor. During skipped cylinder events, this energy is reapplied on the powertrain in the form of a positive torque pulse or wave. In practice, the electric torque pulses only partially reproduce the missing combustion torque pulses, due to MGU torque and power limitations.

Lower magnitude pulses or waveforms that reproduce some of the characteristics of the skipped combustion torque pulses are used. In this manner, the lower frequency components of the resultant combined torque waveform are reduced as shown at right in the figure. The torque excitation spectral components are shifted to higher frequencies where vehicle attenuation characteristics generally better, and also less perceptible by humans. Figure 5 shows human whole-body

FIGURE 5 Human Sensitivity to Vibration, from ISO2631-1 [6]



vibration perception characteristics [6], in which the frequency range 0.5 to 12 Hz is the most perceptible in various directions of vibration.

This smoothing torque should be used optimally to obtain the maximum benefit of reducing perceived accelerations while minimizing energy losses in the process of storing and providing torque/power from the MGU to provide the best fuel economy benefit at each operating condition.

3. eDSF Strategy

Energy Management

The simplest energy management strategy for eDSF, conceptually, is a charge-maintaining strategy in which no net storage or depletion of battery charge occurs over time. In this mode, charge in the energy storage device is maintained by an increase in combustion engine torque mean value to account for losses in the MGU, inverter, and ESS.

DSF and eDSF have several synergies with mild-hybrid functions such as torque assist and decel regeneration as described earlier. More sophisticated energy management strategies can be contemplated that optimize drive cycle fuel consumption through more intelligent choice of the storage and release of energy from the ESS.

Electric Torque Smoothing

Electric torque smoothing extends DSF by allowing skip-fire sequences that would have noise or vibration characteristics normally exceeding NVH targets to become acceptable. Fuel consumption is improved due to greater utilization of skip-fire operating conditions that have lower fuel consumption.

During the drive cycle, fire-skip sequences are continually changing, along with the electric torque smoothing waveform. Generally the torque smoothing waveforms are bandwidth limited to the frequency range most perceptible as described in section 2.

4. Hardware Implementation Requirements

Micro or mild hybrid configurations in P0, P1, P2 locations are appropriate for eDSF.

The eDSF torque smoothing function may pass a significant amount of power bidirectionally through the MGU, inverter and energy storage system (ESS) in a round-trip path from negative (generating) torque pulses through the MGU, inverter and ESS, and then back out to positive (motoring) pulses on the crankshaft or drivetrain. So that energy/power losses in this roundtrip are small enough to result in a fuel consumption benefit in performing the torque smoothing function, all components in the path should have high efficiency, and their bandwidth of operation should be high enough to cover the frequency content of the mitigation waveforms.

Motor-Generator Unit

MGUs are designed for high efficiency within cost constraints of the target application. There are several technologies of automotive traction MGUs in the current market, including permanent magnet synchronous machines (PMSM), AC induction machines (ACIM), and switched reluctance machines (SRM). Generally, PM machines have higher power to volume ratio than other types and thus for P0 applications are more easily packaged underhood in today's vehicles' cramped engine bays, if at somewhat higher cost due to the rare-earth magnets typically employed.

Figure 6 shows a conceptual map of MGU one-way efficiency vs. MGU torque and rotor speed, integrated with an assumed inverter control strategy. The stator winding arrangement and construction affects the shape of this map, in particular the corner speed between torque-limited operation and power-limited operation. Depending on the planned duty cycle of the MGU, appropriate stator winding should be chosen.

The MGU used in this study has efficiency in the range 88-95% for the range of torques and speeds relevant to eDSF.

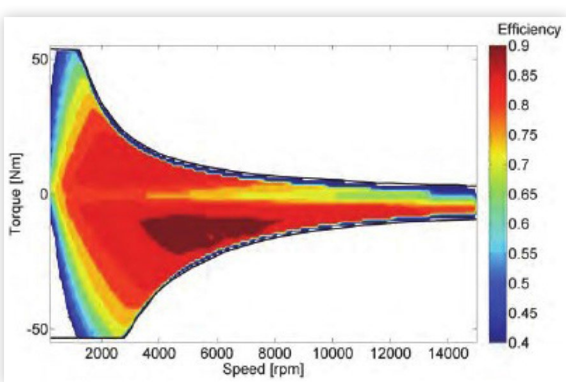
The rate of change of current, and thus torque in a PM machine is related to the stator inductance to resistance ratio, however with closed-loop current control in the inverter, the motor parameters become less relevant to torque response speed. In most cases these dynamics are far faster than required for eDSF application.

Inverter

The inverter is a key component in the eDSF system. Modern vector control, or field-oriented control (FOC) algorithms provide high-performance, high-bandwidth, low loss torque control, when properly configured with correct machine parameters.

As implemented in many traction inverters, this bandwidth is artificially limited and/or detuned, since torque control bandwidth above 5-10 Hz is not typically needed or wanted in traction applications. Thus a challenge of using common commercial inverters is overcoming artificial limitations that were intentionally or unintentionally introduced in the inverter software. In some implementations, although the FOC algorithms would be capable, the input processing, in

FIGURE 6 PMSM Inverter-Integrated Efficiency Map Example



the form of CAN bus message processing, is done at a low sampling rate, or includes intermediate downsampling or filtering of the input torque requests, which make the inverter software less capable of achieving the modest bandwidth requirements of eDSF torque smoothing. Overcoming these limitations could require reworking the input signal processing, current control loops and/or software tasking architecture to remove or adjust these bandwidth limiters.

The electronic hardware components themselves are rarely the bandwidth limiting factor since high frequency switching control is employed.

In terms of efficiency, the losses in the inverter hardware consist of the Rds(on) of the power FETs under load and FET driver switching losses when idle. For high performance inverters running at higher than 10 kHz PWM frequency, MOSFETs, which have >96% efficiency are typically employed.

Inverter software can also introduce inefficiency when operated at high torque control bandwidth, if filtering in the estimation and control algorithms do not keep pace with commands.

Energy Storage System

Because of the possibly large amount of oscillating positive and negative power demands, the hybrid energy storage system efficiency is important. Generally, capacitors have lowest round trip losses in the range 97-99% at 48 V. Supercapacitors, having many low-voltage modules in series may have higher equivalent series resistance (ESR) and thus marginally lower efficiency.

Modern lithium-ion batteries also have very good efficiencies on the order of 94-96% round trip for 48 V types, at room temperature and above. An important constraint of these batteries is their capacity to source and sink current, depending on the battery chemistry, construction and temperature.

Optimized configurations including combinations of capacitors and batteries can be contemplated. For the simulations presented here, only a 48 V lithium-iron-phosphate battery was assumed.

5. Simulation Study

Powertrain and Vehicle Model

A drive cycle fuel economy prediction model was created consisting of a combination of an engine/vehicle model with an engine/transmission controller model.

A vehicle model representing a VW Jetta with DSF-enabled 1.8 L turbocharged engine was developed for drive cycle fuel consumption projection. Table 1 shows specifics. Inertias and mechanical efficiencies of powertrain components are accounted for.

Important model outputs are the combined hybrid powertrain torque, vehicle acceleration, fuel consumption, and ESS state of charge.

As a routine part of powertrain integration with OEM vehicle platforms, noise and vibration related hardware is

TABLE 1 Target Vehicle and Powertrain

Vehicle	2015 Volkswagen Jetta SEL with US EPA test weight class and retarding force coefficients.
Engine	1.8 L GTDI EA888
Transmission	6-speed automatic with torque converter and torque converter clutch

optimized, particularly with respect to torsional mitigation, exhaust system design and engine mounting hardware. Devices may be included such as centrifugal pendulum absorbers, dual mass flywheels, and tilgers. For simulation purposes, it was assumed that a vibration mitigation hardware device was incorporated in the powertrain in addition to the stock torque converter and torque converter clutch. The same mitigation hardware was assumed for all simulations presented here.

Hybrid System Model

Data sheet information for the MGU and battery were used to create models containing MGU motoring/generating efficiency maps and battery charge/discharge efficiency maps. With these models the state of charge of the battery is tracked.

Controller Models

The torque demand is provided by a driver model which incorporates vehicle and powertrain characteristics to calculate accelerator pedal and brake pedal inputs and corresponding powertrain and brake system torque demands to follow the vehicle speed target trace for each test cycle within +/−3 km/h.

Control strategy models calculate commanded firing density, cylinder torque, and MGU torque to satisfy demanded powertrain torque, along with transmission gear and TCC slip. The MGU torque level is used to modify torque commands to the combustion engine and friction brakes.

The controller model minimizes fuel consumption for a given engine torque, subject to constraints on predicted noise and vibration. In the fuel consumption minimization, losses in the MGU, inverter and ESS are accounted for by an increase in the mean-value engine torque command. To simplify this calculation in the controller model, a constant value of 75% roundtrip efficiency is used.

Regarding operation of the mild-hybrid functions, simple models for regenerative braking and torque assist were included. For regenerative braking, the maximum regeneration was applied, subject to MGU power and torque constraints, and battery charge current constraints.

Torque assist is applied when battery state of charge (SoC) is above 40%, subject to MGU torque and power limits, and battery charge current limits. For each simulation a 48 V battery SoC initial condition is used that matches the final SoC.

Sophisticated energy management strategies that optimize drive cycle fuel consumption through intelligent choice of the storage and release of energy from the ESS were not included in this simulation study.

A transmission controller model following the stock vehicle shift schedule was included, and for this study a constant TCC slip target was used for all conditions.

Engine stop/start was assumed for all simulations.

Fuel Economy Simulation Results

Figure 7 shows predicted fuel economy for the eDSF system vs. DSF without electrification and all-cylinder operation with mild-hybrid electrification, on US Metro-Highway, NEDC, WLTC and JC08 test cycles. The reduction in fuel consumption of the eDSF system over base all-cylinder operation ranges from 12.1% to 18.5% depending on drive cycle. The reduction of fuel consumption of eDSF over 48 V mild hybrid operation ranges from 8.3% to 11.0%. The synergy between eDSF and mild hybrid vehicles results from increased regenerative braking, made possible with the near-elimination of engine pumping losses, and the increased operating region of eDSF over base DSF.

Although the simulation results are dependent on vehicle chosen, MGU and battery constraints, component efficiencies, mild-hybrid strategy, battery capacity, and other factors, they are believed to be typical and are similar to the results that have been measured [7] which will be described in future work.

FEAD Simulation Results

In a P0 configuration, the MGU is attached to the crankshaft at the front-end accessory drive (FEAD). The high-magnitude, reversing torques applied to the belt require that the FEAD be adequately engineered to maintain consistent contact between the driven pulleys and the belt over the full eDSF operating range.

A typical FEAD tensioner system consists of two pulleys, one on either side of the MGU that are spring loaded and to some degree coupled to each other as shown in Figure 8. This

FIGURE 7 CO2 Emissions Reduction by Drive Cycle for DSF, All-cylinder with Mild Hybrid and eDSF vs. Base All-Cylinder Operation without Electrification

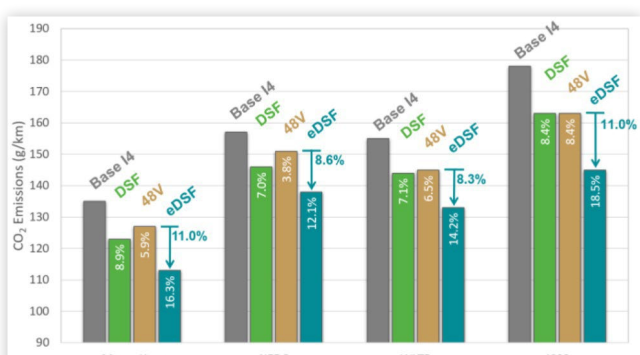
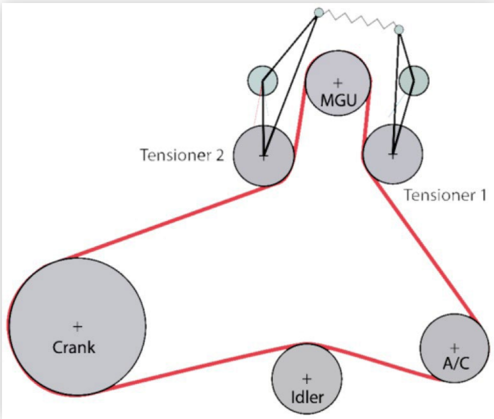


TABLE 2 Target Vehicle Hybrid System

MGU	12 kW power constraint, 44 Nm torque constraint, P0 with 2.2 pulley ratio
ESS	48 V, 8 Ah Lithium-iron-phosphate battery

FIGURE 8 Bidirectional FEAD Tensioner Arrangement



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arrangement keeps the belt adequately wrapped and ideally in non-slipping contact around the MGU pulley.

The FEAD system can be simulated by creating a multi-body, planar representation of the belt, pulleys, and tensioner masses, spring constants, and damping factors. The combustion torques and/or rotational speed of the crankshaft and torque waveforms of the MGU are used to drive a dynamic simulation which can predict tensions in each span of the belt, slipping at the driven pulleys, and other factors.

Figure 9 shows example responses of torque at the crankshaft to torque applied at the MGU, adjusted by pulley ratio, with the tensioner system parameters set at values typical for a mild-hybrid application. There is some distortion of the torque waveform due to the dynamic response of the FEAD which is fundamentally a collection of springs, masses, and dampers.

Variation of parameters can be explored in simulation to optimize the belt and tensioner configuration. Parameters include the static pre-tension of the belt, belt number of ribs, belt stiffness, tensioner spring constant(s), and tensioner geometry. Figure 10 shows an example simulation output of losses in the tensioner system with parameters set at values typical for a mild-hybrid application. Losses in the FEAD system are due to a) sliding friction at drive and driven pulleys, and b) viscous dissipation in the belt. Unoptimized, there can be substantial peak losses for some operating conditions, generally due to slipping between drive pulleys and belt.

Output of a typical parameter study is shown in figure 11. In this study the spring constant of the tensioner is swept to determine its effect on efficiency of torque transmission

FIGURE 9 Crankshaft Torque Responses to Sinusoidal MGU Torque Inputs at Various Frequencies

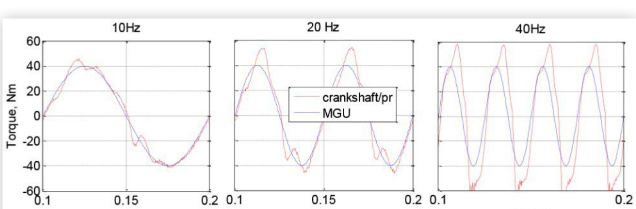

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FIGURE 10 FEAD System Loss Simulation Example (unoptimized)

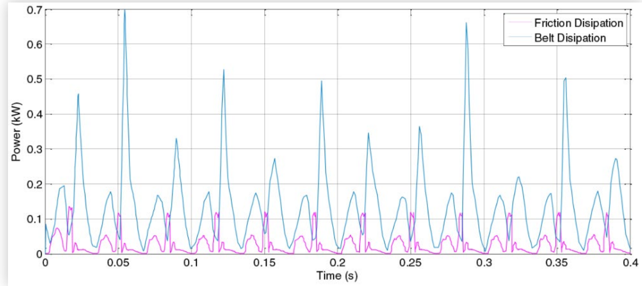

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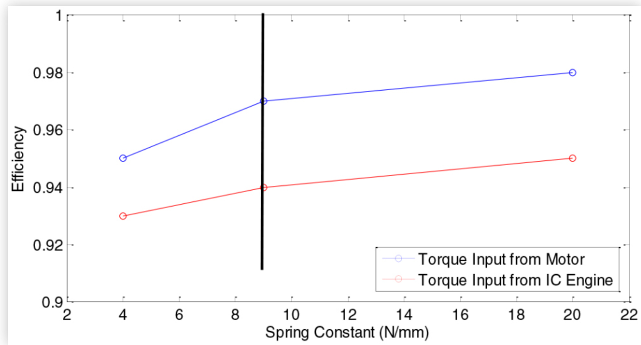
FIGURE 11 FEAD Parameter Optimization Example



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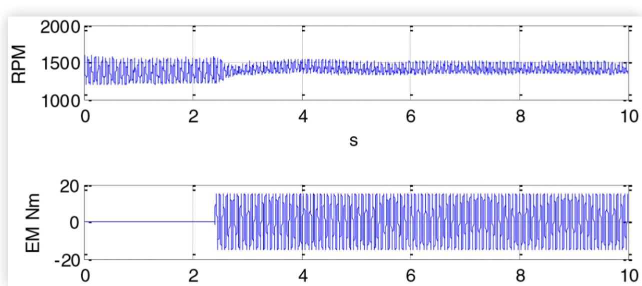
through the FEAD. After simple optimizations of this type, losses, particularly those of the maximum-loss operating conditions, are significantly reduced, without exceeding the maximum rated span tensions of the belt.

6. Vehicle Results

NVH Measurements

Figure 12 shows an example vehicle measurement when the MGU torque smoothing waveform is turned on. Here, torsional variation magnitude is reduced by roughly half through application of a 15 Nm amplitude torque waveform.

FIGURE 12 eDSF Torsional Variation Reduction Example Data



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7. Further Opportunities and Future Work

In this study an overly simple approach for torque assist control was employed that simply used energy in the battery whenever SoC was above a certain level. A better strategy would be to optimize the assist operation by targeting where it will provide the most improvement in fuel economy, taking advantage of DSF and eDSF fuel consumption characteristics. This could also more significantly improve mild-hybrid I4 fuel consumption since it is more sensitive to operating condition than DSF operation.

In general, offsets of the combustion engine torque both positive and negative, with corresponding offsetting of the MGU torque, can be used as another available fuel economy optimization knob.

Improvements in the ESS by including capacitors would reduce roundtrip losses in the battery, making its efficiency less important.

One further item worthy of note is the possible decrease of battery energy depletion during engine start, by keeping some cylinders deactivated, reducing pumping losses. This could be significant on drive cycles incorporating many stop-start events.

The eDSF system is currently being implemented on a VW Jetta vehicle platform. Operation of the system in vehicle will provide subjective feedback of vibration and noise as well as response data that can be used to improve the NVH related calibrations, optimizing the operation for fuel economy, as well as likely reveal additional operating constraints that will be included in control strategies and calibrations.

8. Summary/Conclusions

eDSF takes advantage of components already existing in mild or micro-hybrid powertrains, to provide projected drive cycle fuel consumption reduction over base all-cylinder operation ranging from 12.1% to 18.5% depending on drive cycle. The reduction of fuel consumption of eDSF over 48 V mild hybrid operation is predicted to range from 8.3% to 11.0%. These gains come with little or no change to hardware requirements, and provide a compelling value proposition for enhanced fuel economy in electrified vehicles.

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Contact Information

The first author can be reached at
mark@tulatech.com

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Definitions/Abbreviations

ACIM - Alternating Current Induction Machine
CAN - Controller Area Network
DCCO - Deceleration Cylinder Cutoff
DFCO - Deceleration Fuel Cutoff
DOHC - Double Over-Head Cam
DSF - Dynamic Skip Fire
ECM - Engine Control Module
eDSF - Electrified Dynamic Skip Fire
ESR - Equivalent Series Resistance
ESS - Energy Storage System
FEAD - Front-End Accessory Drive
FET - Field-Effect Transistor
FOC - Field-Oriented Control
FTP - Federal Test Procedure
GTDI - Gasoline Turbocharged Direct Injection
JC08 - Japan Cycle 2008
MGU - Motor-Generator Unit
MOSFET - Metal Oxide Semiconductor Field-Effect Transistor

NEDC - New European Drive Cycle
NVH - Noise, Vibration and Harshness
OEM - Original Equipment Manufacturer
PMSM - Permanent Magnet Synchronous Machine
PWM - Pulse Width Modulation
Rds(on) - Drain-Source Resistance, On
SoC - State of Charge
TCC - Torque Converter Clutch
US EPA - United States Environmental Protection Agency
WLTC - Worldwide harmonized Light vehicle Test Cycle

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