Evaluation of Soft Switching for EV and HEV Motor Drives

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***Abstract*—Soft switching has the potential of reducing switch stresses and of lowering the switching losses as compared to hard switching. For this reason, several soft-switching topologies have been presented in the literature. Each topology has some advantages. Their operation, however, requires additional active and/or passive elements. This introduces additional cost and complexity. To understand the effectiveness of the soft-switching technique, when applied to electric vehicle (EV) and hybrid electric vehicle (HEV) systems, it may be necessary to first evaluate their system requirements and performance. This evaluation process would require knowledge of the vehicle dynamics. The vehicle load requires a special torque–speed profile from the drivetrain for minimum power ratings to meet the vehicle's operational constraints, such as initial acceleration and gradability. The selection of motor and its control for EV and HEV applications are dictated mainly by this special torque–speed requirement. As a consequence, this requirement will have a strong influence on the converter operation. This paper makes an attempt to evaluate EV and HEV running in both standard Federal Test Procedure 1975 city driving and highway driving cycles. A simplified analysis will be carried out for several of the most commonly used electric motors operating on the optimal torque–speed profile. Special attention is given to the converter conduction and switching losses. By analyzing the switching losses, and by assuming that an ideal soft-switching scheme will have zero switching losses, one can evaluate the improvement in the system efficiency if a soft-switching control is used. The relative significance of soft switching for EV and HEV systems will then be established.**

***Index Terms*—Electric vehicle/hybrid electric vehicle soft-switching evaluation, soft-switched electric vehicle/hybrid electric vehicle motor drives, soft switching.**

I. Introduction

POWER SWITCHES are an integral part of any power converter circuit. Unfortunately, they are also the major source of power dissipation in the circuit. This power dissipation is caused by two features. One is conduction voltage drop in the switch while the switch is conducting. Some devices, such as the metal–oxide–semiconductor-controlled thyristor (MCT) and the bipolar junction transistor (BJT), have lower conduction drops, hence lower conduction losses. Other devices, such as the insulated gate bipolar transistor (IGBT), and the metal–oxide–semiconductor field effect transistor (MOSFET), have medium to high conduction drops, hence, medium to high conduction losses. The other cause of energy dissipation in a power switch is the dynamics of the switching. Switching of current in the presence of a switch voltage and vice versa, commonly referred to as hard switching, causes power losses in the switch. The switching loss increases with the switching frequency. To reduce the switching loss, very fast devices are built. These devices have very fast turn-on and turn-off characteristics. However, high di/dt and dv/dt associated with this fast switching increase stresses on the switch and causes electromagnetic interference (EMI). To alleviate the difficulties associated with hard switching, the concept of soft switching was introduced. The main underlying principle in soft switching is to switch the power device at the instant when the switch current is zero, known as zero-current switching (ZCS), or switch the device when switch voltage is zero, known as zero-voltage switching (ZVS). In this way, both the switching loss and switch stresses can be reduced. Many soft-switched converter topologies have been presented in the literature [1]–[6]. The following are usually claimed with respect to the operations of the soft-switched converter topologies: 1) higher efficiency; 2) better device utilization; 3) reduced size of filtering elements; 4) higher power density; 5) reduced acoustic noise; 6) reduced EMI; 7) fast dynamic response; and 8) reduced torque and current ripple.

However, the operation of the soft-switched converters requires additional active and/or passive elements. This introduces additional cost and complexity. Moreover, some of the advantages listed above may be questionable and some may not be very critical for some applications. Therefore, it may be necessary to assess the effectiveness of soft switching compared to hard switching, in connection to specific applications. This paper, therefore, makes an attempt to evaluate soft switching for electric vehicle (EV) and hybrid electric vehicle (HEV) drivetrain applications. This evaluation is based on the systems performance and on the power converter requirements. First, knowledge of the vehicle dynamics will be needed. A study of vehicle dynamics reveals that the vehicle power train is required to exhibit a special torque-speed profile for minimizing the power requirement to meet the vehicle's operational constraints [7]. The selection of the electric motor and its control will be governed by this special torque–speed requirement. As a consequence, the converter operation will be greatly influenced by this special requirement. A simplified analysis is carried

Manuscript received March 12, 1998; revised September 7, 2000. Abstract published on the Internet November 15, 2000. This paper was presented at IEEE IECON'97, New Orleans, LA, November 9–14, 1997.

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Publisher Item Identifier S 0278-0046(01)01121-2.

out on a system level for induction motor, switched reluctance motor (SRM), and brushless dc (BLDC) motor operating on the optimal torque–speed profile [7]. Efficiency is a major issue, especially for EV operations. Hence, special attention will be given to the converter switching and conduction losses. By assuming that an ideal soft-switching scheme will have zero switching losses [8], and by calculating the converter switching losses for hard-switching operation, one can evaluate the improvement that an ideal soft-switching control would add to the system efficiency, expressed as gallons per mile. The loss estimation will be carried out for the vehicle running in both standard Federal Test Procedure 1975 (FTP75) urban driving and highway driving cycles. The relative significance of soft switching for EV and HEV systems will then be established.

II. EV and HEV Characteristics

A. EV and HEV Architecture

EVs use an electric motor for propulsion and battery as the only source of energy. These vehicles constitute the only commonly known group of automobiles that are classified as zero-emission vehicles (ZEV's). However, EVs suffer from range limitations. As a consequence, efficiency is a major issue for an EV, since it relates directly to the range of the vehicle. HEVs are classified as ultra-low-emission vehicles (ULEVs) and do not suffer from the range limitations imposed on the EVs. This is due to the fact that the power train combines more than one energy source to propel the vehicle. There are many different power-train configurations for hybrids, but, in general, they fall into two categories: series and parallel. In series hybrid, the internal combustion engine (ICE) is normally used to charge a battery pack through a generator, while the electric motor propels the vehicle powered by the battery. It is also possible to direct the ICE power directly to the wheels through the motor generator pair when the battery is fully charged. Thus, the engine can be decoupled from the wheel and always run in the optimal efficiency region. However, the several stages of energy conversion have their associated power losses. In contrast, the parallel hybrid system connects both the ICE and the electric motor in parallel. These two components directly provide the power to the wheel. In a series hybrid system, the electric motor behaves exactly in the same manner as in an electric vehicle. Therefore, the torque and power requirements of the electric motor are roughly equal for an EV and series hybrid, while, due to power sharing, they are comparatively lower for the parallel hybrid. The amount of power sharing in the parallel hybrid depends on the relative size of the ICE and the electric motor, and on the control strategy. For HEVs, electrical efficiency is not as critical as it is in the case of EVs.

B. Optimal Torque–Speed Profile for EV and HEV Drivetrain

Our recent study has shown that a vehicle can meet its performance requirements with minimum power rating if the power train operates mostly in constant power [7]. The power rating of a motor that deviates from the constant power regime can be as much as two times that of a motor operating at constant power throughout its speed range in a vehicle. The electric motor in its normal mode of operation can provide constant rated torque up to its base or rated speed. At this speed, the motor reaches its rated power limit. The operation beyond the base speed, up to the maximum speed, is limited to this constant-power region. The range of this constant-power operation depends primarily on the particular motor type and its control strategy. It is obvious from the previous discussion that an electric machine must be capable of performing a long constant-power operation in order to be suitable for EV and HEV applications. A range of six times the base speed in constant power would generally be required in order to reduce the power requirement to an appreciable level [7]. Clearly, for normal vehicle operation, the optimal motor will operate mainly in constant power range. In our study, therefore, special attention will be given to the converter operation for high-speed constant-power operation of the drivetrain. The specification of the power of the motor, along with its power factor (PF) of operation, will define the VA rating of the converter. Since different types of motors have different constant-power capabilities and have different PF of operation, the converter VA rating will be different for each motor.

C. Methods of Torque Control at Low Speed and High Speed

The method of torque control below base speed, when the back EMF is lower than the dc-bus voltage, is similar for all motors. It usually involves pulsewidth modulation (PWM) chopping of the current for the control of the torque. However, the torque control method above base speed, when the back EMF exceeds the bus voltage, is motor and control dependent. In the case of the induction motor, the usual practice is to begin field weakening once the motor speed exceeds the base speed. This way, the back EMF is not allowed to build up beyond the bus voltage. Nevertheless, in order to retain the PWM current control capability at high speed, the electric motor would need to enter the field weakening before reaching the base speed. This would, however, reduce the available torque at high speed. To maximize the torque capability at high speed, six-step mode of operation seems to be inevitable because of the limited bus voltage [9]. Torque control in this mode and smooth transition between current-regulated PWM mode and six-step mode becomes an important issue.

An SRM is a singly fed motor as is the induction motor. Both the excitation current and the torque current are fed through the stator. However, unlike the induction motor, no control method is known that can isolate the torque component of current from the field component of current. Hence, field weakening is not possible in the SRM. Operation in constant power is made possible in this motor by the phase advancing of the stator current conduction angle until overlapping between the successive phases occurs [10]. Due to the high backEMF, which cannot be weakened, PWM control of current is not possible in the extended speed range of operation.

Operation of the BLDC motor in the extended speed constant-power range is similar to the SRM. Due to the presence of the permanent-magnet field, which can only be weakened through the production of a stator field component, opposing the rotor magnetic field, field weakening is difficult in a BLDC motor. Extended constant-power operation is possible through the advancing of the commutation angle [11]–[13].

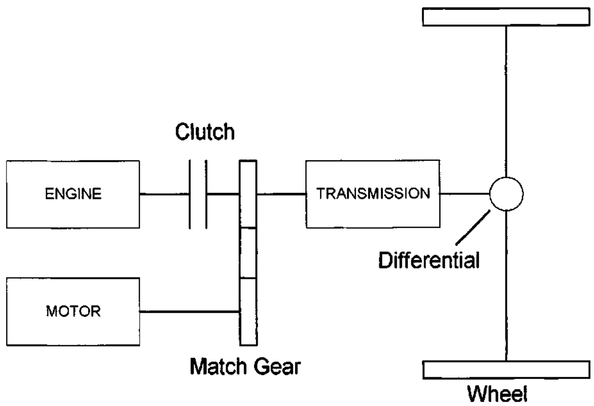


Fig. 1. Configuration of an electrically peaking hybrid (ELPH) vehicle [14].

In summary, one can see that the torque control method dictates the number of switchings performed by the converter. Consequently, it will influence the switching losses. Hence, the torque control scheme of each motor will be studied in this paper, in an attempt to estimate the switching losses for EV and HEV application.

III. EV and HEV Drivetrain Model Considerations

In this section, some vehicle characteristics, motor, and power converter considerations for modeling EV and HEV drivetrains are presented. The main objective is to calculate the converter switching and conduction losses for both systems. A simulation program, with simplified models, was implemented using an ACSL simulation package. In the simulations, the IM, BLDC motor, and SRM are considered. The drive cycles are in the form of lookup tables.

A. Vehicle Configuration

In this study, a parallel HEV configuration of a typical four-seat passenger car is considered, as shown in Fig. 1 [14]. The vehicle characteristics are given as follows:

- 0–26.82 m/s (0–60 mi/h) in 10 s;
- vehicle mass of 1700 kg;
- rolling resistance coefficient of 0.013;
- aerodynamic drag coefficient of 0.29;
- wheel radius of 0.2794 m (11 in);
- level ground;
- zero headwind velocity;
- engine size of 1.0 L (35 kW);
- maximum speed of 161 km/h (100 mi/h);
- gear ratio of the engine of 4.5815.

The system mode of control assumes the ICE is providing the base power for cruising the vehicle, while the electric motor is used to provide the peak power during acceleration and hill climbing [14]. The ICE size is determined based on this mode of control. The electric motor size, however, depends on the particular motor in use, on the optimal motor control, and also on the above mentioned system mode of control. The detailed analysis of it can be found in [7]. In the case of the EV, however, the battery pack has to provide both peak and cruising power for the vehicle. Hence, the electric motor, and its corresponding inverter, must be designed for the maximum vehicle power. In this paper, it is roughly assumed that each motor power for the EV system is equal to the ICE power added to the motor power of the corresponding HEV case. This approximation can be considered reasonable if one calculates the minimum motor power for the EV, in the resistanceless case [7], and takes into account that, here, the system is not resistanceless.

B. Motor Considerations

The drive cycles for the urban, as well as for the highway driving, are extremely long. The implementation of a full-order model of each motor, although possible, would be very time consuming. The dynamics of the drive cycles, used in this simulation, are not very fast. Hence, we used the time average model for each motor, while calculating the converter losses.

Table I lists the rated characteristics of each motor and their corresponding inverters, used in this paper, for the HEV and EV simulations. With this data, the torque–speed profile of each motor is obtained by following the procedure described in [7]. The rated power of a motor in a vehicle traction system depends on its corresponding torque-speed profile. A longer constant-power range makes it possible to reduce the rated power requirement of the motor for a particular vehicle acceleration. The power ratings in Table I produce a 0–26.82 m/s per 10 s vehicle acceleration, during the constant-power ranges of each motor. Each motor model, in this paper, has different constant-power capability.

Fig. 2 shows the optimal torque–speed profile of the simulated SRM used here. This motor has a 6–4 geometry and a 6-to-1 constant-power range. The static characteristic of this motor is obtained using the finite-element (FE) analysis. The SRM favors high-speed operation. Unless motor speed is extremely high, such that the motor core losses start to dominate, SRM performance improves at high speed. Fig. 3 shows the efficiency and PF of the SRM as a function of the rotor speed. It can be seen that the PF is poor at low speed. This would increase the inverter rating of the motor. However, the SRM PF improves significantly at high speed. This allows us to obtain significantly more than the rated power at high speed, without exceeding the voltage and current rating of the motor. This is illustrated in Fig. 4(a) as follows. The rated power of the motor is roughly 0.6 pu of the ideal power. The ideal power is defined as the power that is obtained if the PF is one. The output power [Fig. 4(a)] increases significantly beyond the rated power (0.6 pu) at high speed. The torque (power)–speed profiles of Figs. 2 and 4(a) are used for the simulation of the SRM performance.

In the case of the IM, the constant-power range is generally two times that of the base speed. A specially designed IM has been shown to exhibit a constant-power range of four times that of the base speed. The PF of an IM is typically 0.8 at the rated speed.

In the case of the BLDC motor, the constant-power range is short, due to its small phase inductance. The typical range of constant-power operation of a BLDC motor is 2–2.5 times that of the base speed. This range can be shorter if the motor has more magnet contents. The PF of the BLDC motor is typically 0.9 or higher at rated or beyond rated speed. Trapezoidal BLDC motors typically run at low speed, due to the containment problem of the surface-mount magnets. New designs with

TABLE I
MOTOR AND INVERTER SPECIFICATIONS

Motor	Power (kW)		Inverter (KVA)		Base speed (rpm)	Max. speed (rpm)	Max. stator frequency (Hz)	Motor gear ratio
	HEV	EV	HEV	EV				
IM	57.88	93	72.35	116.3	3000	12000	200	7.068
SRM	42.1	77.1	70.2	128.5	2000	12000	800	9.1629
BLDC	75.5	110.5	83.9	122.8	4000	9000	300	5.2359

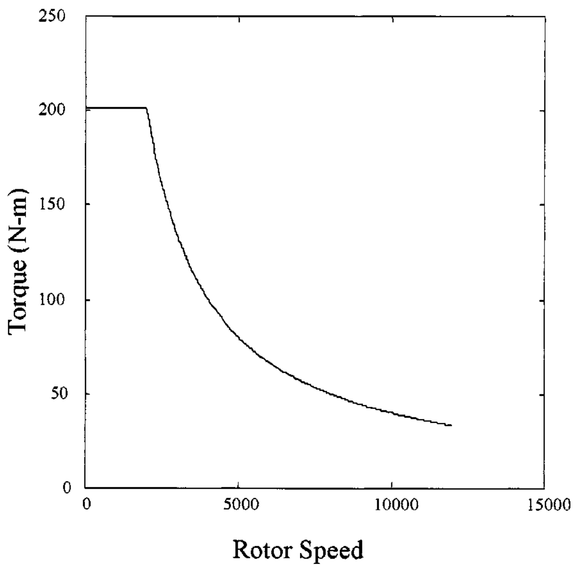


Fig. 2. Extended constant power range of SRM.

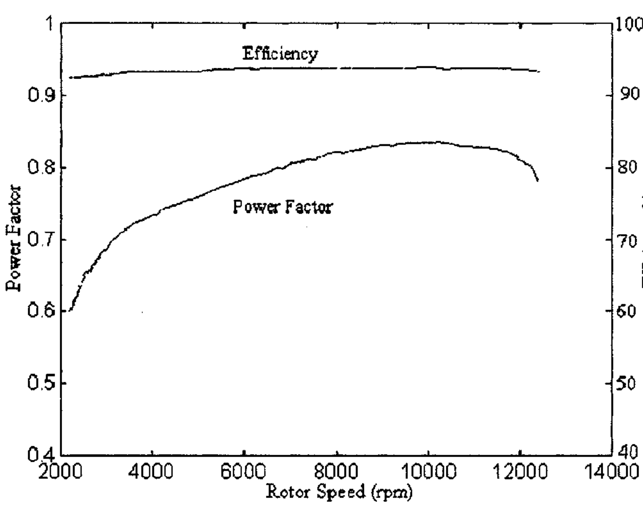


Fig. 3. Efficiency and PF of the SRM for constant power operation.

high-speed capability, however, have been reported. Nevertheless, a somewhat low-speed BLDC motor is simulated here.

C. Control Considerations

The SRM is controlled with the optimal control parameters obtained using an average model of the SRM. The nonlinearity is included in the model by using the static flux linkage and torque data as functions of rotor position and stator current, obtained using the FE analysis. This control strategy aims to maximize the constant-power operation range with maximized efficiency. The optimal control parameters at low speed are the phase turn-on and turn-off angles and the reference current [Fig. 4(b)]. The high-speed control parameters are the phase turn-on and turn-off angles. A detailed description of this optimal control scheme of the SRM is presented in [15] and [16].

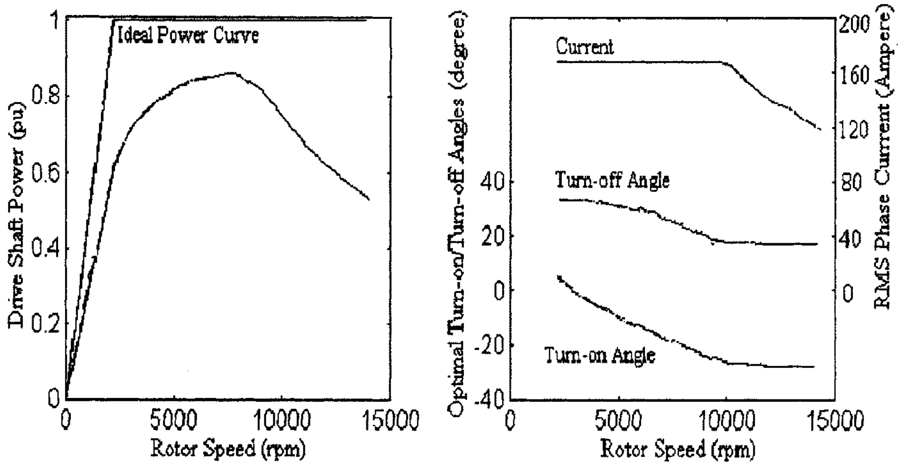
The control of the BLDC motor is very similar to the SRM control. The BLDC motor is also controlled to maximize the constant power range with optimum efficiency. At low speeds, the phase current in the BLDC motor, as well as in the SRM, are regulated using fixed-frequency PWM, at 10 kHz, and a proportional plus integral (PI) regulator. In the case of the IM, space-vector PWM, at 10 kHz, and an indirect-rotor-field-oriented control, with synchronous current regulator, are implemented. At high speeds, e.g., above rated speed, SRM and BLDC motors are driven by single-pulse phase-advance operation mode. In this case, the corresponding converter losses are predominantly due to conduction losses. When the IM is operating above rated speed, a six-step mode of operation is used. This mode of operation provides better utilization of the dc-bus voltage. However, this mode of operation will produce more ripple in the current. Moreover, the motor operation may become unstable if not controlled properly.

D. Power Converter Considerations

It is considered that the dc-bus voltage is equal to 228 V. IGBTs are considered in the three-phase six-switch inverter model for each motor. Manufacturers' data are used for the calculation of the switching and the conduction losses. The switch turn-on and turn-off profiles, including reverse-recovery effects of antiparallel diodes, are considered. The IGBTs used in the inverters of each motor are rated 600 V/600 A. Losses at different operating points (voltage and current) of each IGBT are obtained by linear interpolation. The on-state characteristic of each switch module is simulated by a dc source, representing the saturation voltage, in series with an on-state resistance. The operating point of each IGBT, for a certain speed and torque demand, is obtained by using the time-average model of the motor.

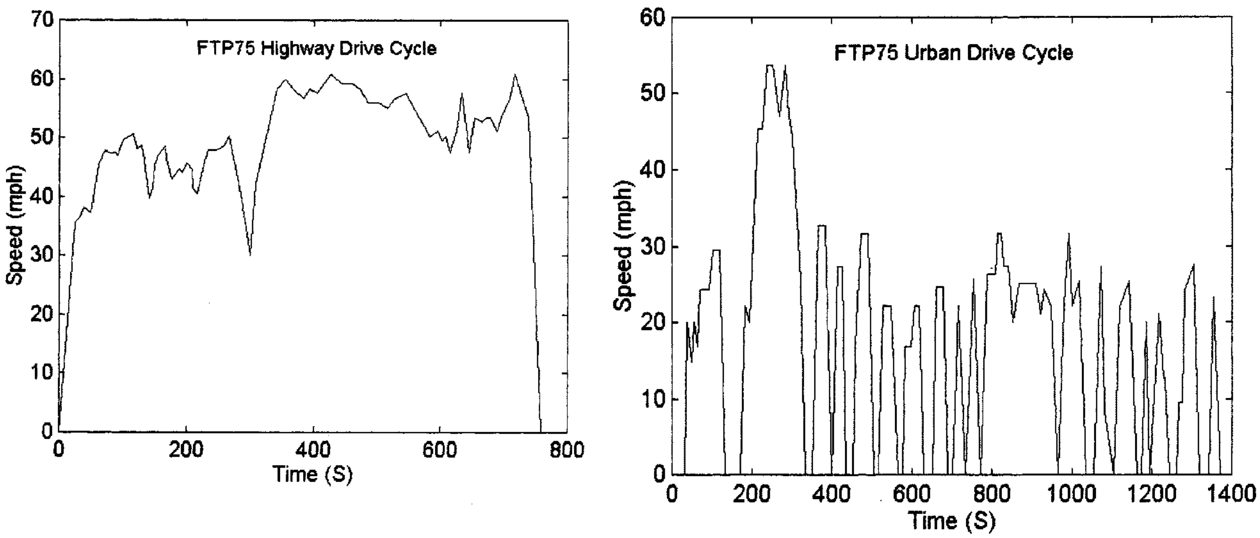
IV. SIMULATION RESULTS

In this section, the converter switching and conduction losses of a simulated electric and hybrid electric vehicle are calculated. For both systems, the cases when the vehicle runs on the FTP75 highway drive cycle [Fig. 5(a)] and on the urban drive cycle [Fig. 5(b)] are studied. The converter losses in an HEV depend on the energy sharing between the ICE and the electric motor. Fig. 6(a) and (b) shows the total energy throughput



(a) (b)

Fig. 4. (a) Maximum output power and (b) optimal control angles and rms phase current for the SRM design.



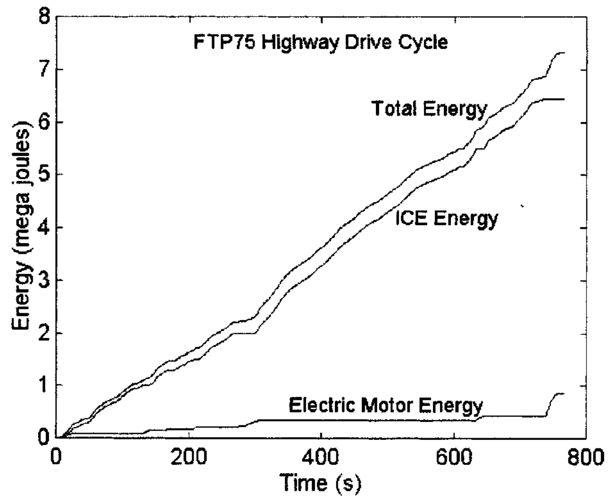
(a) (b)

Fig. 5. FTP75 (a) highway and (b) urban drive cycles.

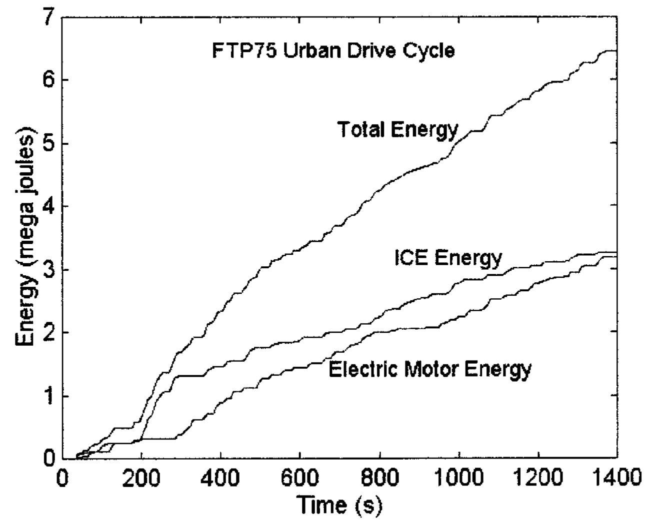
and the energy distribution between the ICE and the electric motor, when the vehicle is running in the two drive cycles. In these figures, the energies are calculated cumulatively by integrating each power component over the drive cycle time. It is possible to recover, at least partially, the kinetic energy released by the vehicle when it decelerates. This is achieved by running the electric motor as a generator and charging the battery pack. This mode of control is referred to as regenerative braking in the literature. For obvious reason, the regenerative braking energy, which has its associated converter losses, is considered positive. This energy is added to the electric motor energy. In this study, however, only simulation results without regenerative braking are presented. In this case, the losses of the inverter and of the motor are smaller than those for the case with regenerative breaking. It can be seen in the simulation results of Fig. 6(a) that the energy flow through the electric motor of the hybrid vehicle, running in highway drive cycle, is extremely small when compared to the total energy. Any amount of energy savings, by soft switching, in this case will not have much impact on the total energy savings. The urban drive cycle [Fig. 5(b)], however, requires the electric motor more frequently to supply the acceleration power of the hybrid vehicle. In the case of the EV, since the battery is the only source of energy, the total energy required to run the vehicle is handled by the electric motor. Special assessment of energy savings due to soft switching is, therefore, necessary for the EV operation in both drive cycles. For the HEV operation, it might be important only in the urban drive cycle.

A. Losses in an HEV

The calculated values of the conduction (the solid line curve) and switching (the dashed curve) losses of HEV drivetrain systems using an IM, BLDC, and SRM are presented in Fig. 7 for the urban drive cycle. In this figure, the losses are shown as a percentage of the total expended energy of the propulsion system. The converter energy losses and the total energy are calculated cumulatively, integrating the losses and the system power over the drive cycle time. Hence, loss percentage shown



(a)



(b)

Fig. 6. Energy consumption in HEV for (a) highway and (b) urban drive cycles.

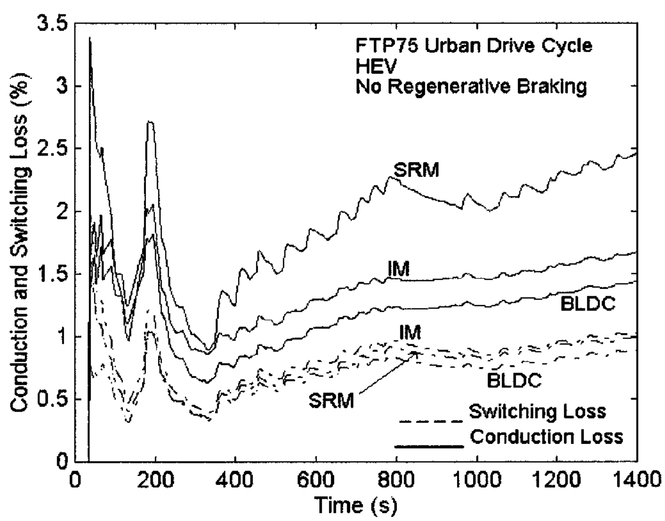


Fig. 7. Converter losses for HEV in urban drive cycle.

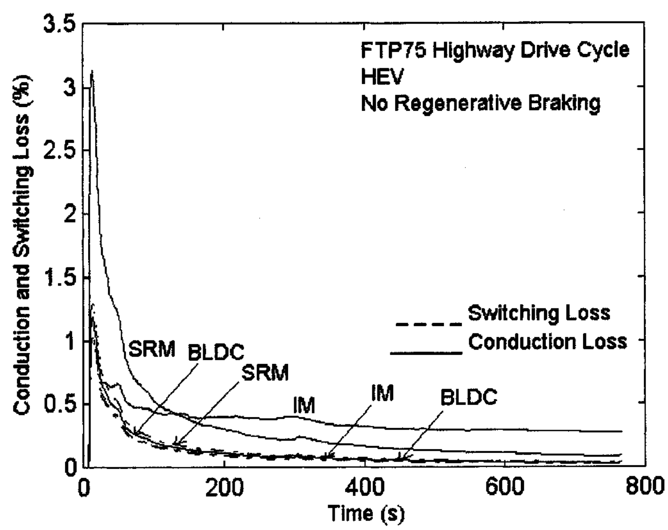


Fig. 8. Converter losses for HEV in highway drive cycle.

at any point in these figures indicates the average loss (in percent) up to that time of the drive cycle. The losses shown at the end of the drive cycle are, therefore, the average losses for the whole drive cycle. In Fig. 7, we can see two spikes at the beginning of the drive cycle. These spikes are due to the two initial accelerations of the vehicle. As time progresses, the cumulative energy builds up and any local fluctuation, due to subsequent car accelerations, does not show up in the global picture. Due to the lower PF of operation of the SRM, its conduction losses are higher in both cases. However, the switching loss of the SRM converter is comparable to those of IM and BLDC inverters. High-speed capability of the SRM, besides the fact that the torque control at high speed is attained by the phase control of the input voltage, has helped to lower the switching losses in the SRM converter, despite its lower PF of operation. For the HEV urban drive cycle, the average switching losses, for all motors considered here, are less than 1%. In some soft-switched topologies the conduction loss can be higher than in a hard-switched converter [17]. Although the switching loss can be reduced considerably, in practice, it is not totally eliminated. Hence, if one assumes zero switching losses by using an ideal soft-switching technique, for this drive cycle, the maximum gain in system energy would, therefore, be less than 1%. Now, let us examine the impact of soft switching on the operation of HEV in terms of the gasoline saved per 100 mi of travel. The total energy spent for the operation of the vehicle in the urban drive cycle is 6.45 MJ. Total distance traveled by the vehicle in this drive cycle is 6.6 mi. Energy density per gallon of gasoline is 121 MJ. Assuming an efficiency of 20% in the operation of the ICE, the total savings in the gasoline is only 0.0808 gal per 100 mi traveled in the urban drive cycle. Total savings for an average urban driving of 10 000 miles in a year is only 8.08 gal of gasoline. Since the HEV is not energy limited, we conclude, that the extra cost and complexity associated with the operation of a soft switched converter do not justify soft switching for the HEV, if the target is to improve the system efficiency. In the highway driving cycle, except for a few accelerations and a few cases of regenerative braking, the electric motor is seldomly used. Calculated values of the switching

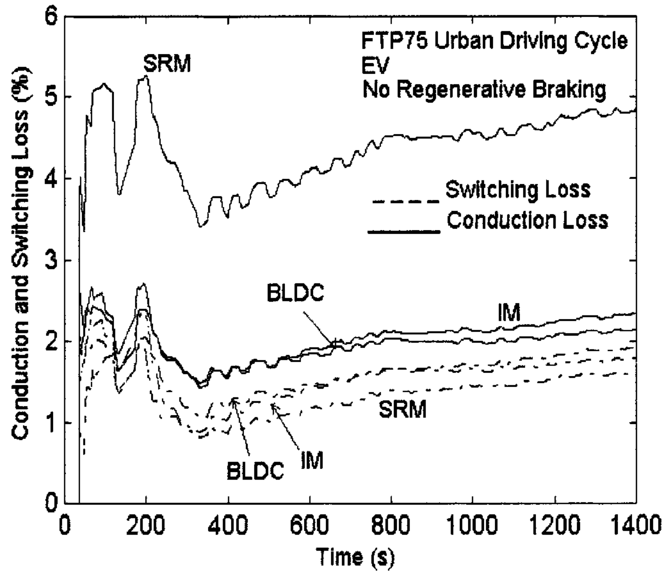


Fig. 9. Converter losses for EV in urban drive cycle.

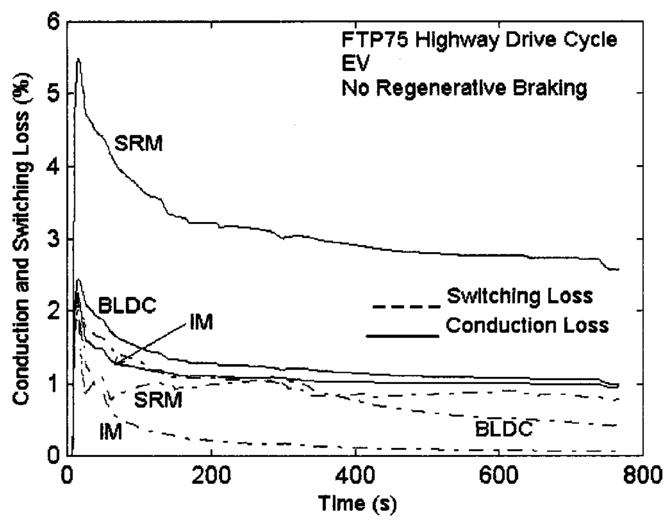


Fig. 10. Converter losses for EV in highway drive cycle.

losses for the operation of the HEV in the highway drive cycle are shown in Fig. 8, without the consideration of regenerative braking. These losses are not significant.

B. Losses in EV

Since, in an EV, the battery is the only source of energy, the energy flow out of the battery pack is higher in the case of an EV. Due to this increased energy flow through the electric motor, the converter incurs more losses in both conduction and switching. Hence, losses as a percent of total energy are higher in the case of an EV, as shown in Fig. 9. Hence, losses as a percent of total energy are higher in the case of an EV, as shown in Fig. 8. In this figure, the switching and the conduction losses are increased for the operation of EVs when compared to those of HEVs. The switching loss is close to 2%. Although the losses in an EV are not greatly increased compared to the losses of an HEV, EV losses have severe consequences since they are related directly to the range of the vehicle. Therefore, the energy savings through soft switching may justify the additional cost, complexity, and lower reliability usually associated with its operation. Finally, we consider the highway driving for an EV. Although EVs are not best suited for highway driving, the losses can be calculated for completeness. Fig. 10 shows the converter losses for the operation of the EV in the highway drive cycle. Since the electric motor (battery) supplies all the energy in the operation of the EV, the losses are higher than in the case of HEV operation in the same drive cycle. However, the switching loss percentage is lower in highway driving as compared to the city driving of the EV (Fig. 9) . It can be seen in Fig. 10 that the switching losses are actually less than 1% . The energy savings in the hypothetical highway driving of the EV, therefore, may not justify the use of soft switching for its driving in the highway cycle.

V. Discussion

It is important to note that this paper evaluates the impact of the converter losses on the overall efficiency of the car, expressed in gallons per mile. The efficiency of the converter is not the focus of this work. In other papers, e.g., [18], the soft-switching operation is shown to provide more gain in the efficiency than it is shown here. In those results, however, the vehicle efficiency is not taken into account. Typically, in a vehicle, HEV or EV, the efficiencies of the motor, engine, battery, and motor inverter are approximately 75%, 30%, 80%, and 90%, respectively [19]. One can see that these components are some of the dominant sources of losses in a vehicle. There are other sources of losses, such as the regenerative braking and the transmission. The study presented here shows that, in the HEV and EV, the switching losses correspond to around 2% of the overall vehicle energy. Therefore, in vehicles with no energy limitations, soft-switching techniques do not provide a significant efficiency improvement. However, there are other issues of importance in converter design for vehicles, such as EMI and power density. In this case, studies such as in [18] show that soft-switching technology can offer a favorable impact for improvements. Another issue of concern is the system control stability. With a higher switching frequency, the closed-loop bandwidth of the converter control system can be larger, in order to increase the system response. Soft switching may favor this aspect, provided the switching strategy does not generate subharmonics [20]. Nevertheless, a faster dynamic response may not be necessary from the electrical propulsion system point of view [21]. A different approach to reduce the EMI and switch stresses is to use slower switching [8], since that would not be of much impact on the system efficiency. However, slower switching would increase torque and current ripples, as well as reduce the power density. The audible noise for switching at frequencies lower than 20 kHz is another issue. Switching over 20 kHz with hard switching may not be practical for high-power drives. The audible noise, however, may not be unacceptable to the users who are already accustomed to the noisy operation of conventional automobiles. It may also be particularly tuned to be pleasant to the ear.

VI. CONCLUSION

An evaluation of the soft-switching inverters for EV and HEV motor drives was presented. Simulation results of the converter losses were presented for the operation of the EV and the HEV in the FTP75 city and highway drive cycles. Operation of an induction motor, BLDC motor, and SRM was considered for the electrical propulsion system of the EV and the HEV. The simulation results show that the energy savings by using soft switching is less than 2% of the total energy for the operation of the HEV in the standard highway as well as in the urban driving cycles. Since the HEV does not have any energy limitation, this small saving in energy does not justify the extra cost and complexity associated with the soft-switched converter. The simulation results for the operation of the EV in the urban driving cycle reveal that the maximum savings in energy would be up to 3% with soft switching. These savings, although marginal, may justify soft switching for EV applications until high-energy-density batteries with extremely quick charging characteristics are developed in the future. The energy savings for the EV with soft switching in highway driving are less than 1% of the total energy. Since, EVs are not designed for primary highway driving, the small energy savings may not justify soft switching for this case. If the design is aimed to improve the system efficiency, we can summarize our findings as follows.

- Soft switching is not recommended for the design of an HEV. Soft switching is not recommended for the design of an EV in highway driving.
- Soft switching may be recommended for EV operation in urban driving. However, a specialized soft-switched topology would be needed for the particular vehicle load.

If the major design considerations are power density and/or EMI, soft-switching technology can offer a favorable impact for EV or HEV applications. Other characteristics of soft switching, such as faster dynamic response and audible noise, do not have appreciable effect on the design and operation of the EVs and the HEVs.

Based on the simulation results, the authors believe the conclusions presented here can be extended for vehicles with different dimensions and weight in a per-unit sense.

ACKNOWLEDGMENT

The authors are very grateful to Z. Rahman for his valuable assistance in the completion of the final version of this paper.

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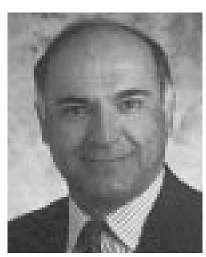

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