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 performances. This evaluation process would require knowledge of the vehicle dynamics. The vehicle load requires a special torque-speed profile from the drive train 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 is 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 FTP75 city driving cycle and highway driving cycle. The analysis will be carried out for several most commonly used electric motors operating on the optimal torque-speed profile. Special attention will be given to the converter losses. Features of the soft switching will be evaluated in the context of the dynamic vehicle power flow and the system losses, as well as the power converter requirements. The relative significance of soft switching for EV and HEV systems will then be established**.

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 have lower conduction drops (MCT, BJT), hence lower conduction losses, while other devices have medium to high conduction drops (IGBT, MOSFET), 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 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). 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 followings are usually claimed with respect to the operations of the soft-switched converter topologies:

- higher efficiency,
- better device utilization,
- reduced size of filtering elements,
- higher power density,
- reduced acoustic noise,

- reduced EMI,
- fast dynamic response,
- 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 powertrain 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 out on a system level for induction motor, switched reluctance motor (SRM), and brushless dc (BLDC) motor operating on the optimal torque-speed profile. Efficiency is a major issue, especially for EV operations. Hence, special attention will be given to the converter losses, as a means to evaluate the improvement in the system efficiency that could be achieved by using soft switching. The loss estimation will be carried out for the vehicle running in both standard FTP75 city driving cycle and highway driving cycle. 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

Electric vehicles (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 (ZEVs). However, EVs suffer from range limitations. As a consequence, efficiency is a major issue for EV, since it relates directly to the range of the vehicle.

Hybrid electric vehicles (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 ICE engine 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 conversions 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 into the wheel.

In 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 they are comparatively lower for parallel hybrid. 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 powertrain 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 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 [8]. Torque control in this mode and smooth transition between current regulated PWM mode and six-step mode becomes an important issue.

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 [9]. Due to the high back emf, 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 SRM. Due to the presence of the permanent magnet field which can only be weakened through a production of a stator field component which opposes the rotor magnetic field, field weakening is difficult in BLDC motor. Extended constant power operation is possible through the advancing of the commutation angle [10-12].

In summary we conclude that the switching of the DC bus by the converter is dictated by the torque control method. That is, the torque at low speed will be controlled by the PWM control of the current. However, to maximize the torque capability of electric motor drives for EV and HEV applications, torque at high speed will be controlled by controlling the phase of the input voltage (phase-shift control). Since the control operation influences the number of switchings performed by the converter, it will influence the switching losses. Hence, torque control scheme of each motor will be studied in detail 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. Also, the use of induction motor (IM), brushless dc (BLDC) motor and switched reluctance motor (SRM) is considered in the study of the two systems.

The vehicle characteristics of a typical 4-seat passenger car are given below:

- 0-26.82 m/s (0-60 mph) in 10 seconds.

- vehicle mass of 1700 kg.
- rolling resistance coefficient of 0.013.
- aerodynamic drag coefficient of 0.29.
- wheel radius of 0.2794 m (11 inch).
- level ground.
- zero head wind velocity.

In the series hybrid system, the electric motor behaves exactly in the same manner as in an electric vehicle. In both cases, the electric motor provides the necessary power to the drive shaft. Whereas, in the case of the parallel hybrid vehicle, the necessary wheel power is provided by the ICE and the electric motor. Therefore, the torque and power requirements of the electric motor are roughly equal for EV and series hybrid, while due to power sharing they are comparatively lower for parallel hybrid. The amount of power sharing in parallel hybrid, however, depends on the relative size of the ICE and the electric motor, and on the control strategy. In this study, the system mode of control assumes the ICE is providing the base power for cruising the vehicle, and the electric motor is used to provide the peak power during acceleration and hill climbing [13]. 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].

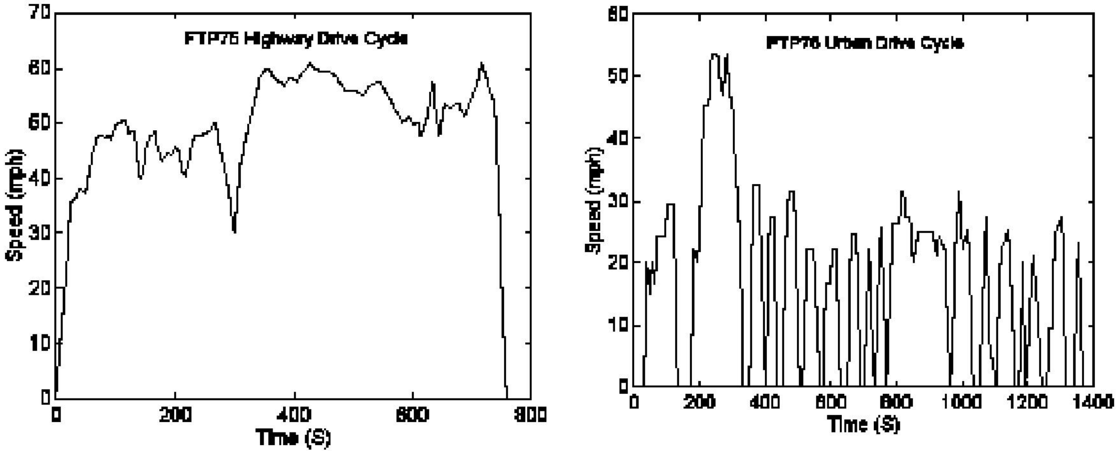
In the calculation of the conduction and switching losses of the converter, PWM operation with hard switching is considered. The maximum switching frequency is assumed to be 10 kHz. The voltage and current rating of each switch of the inverter module used in the simulation are 600V and 400A respectively. For the calculation of the switching loss, the manufacturer's data on the switch turn on and turn off profiles, including reverse recovery effects of anti-parallel diodes, are used. 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. This simplified model is used for the calculation of the conduction loss. The control strategy, the pf of operation, and the high speed-constant power capability are different for each type of motor. Consequently, the converter losses will be different for each case. In the simulations, IM, BLDC motor, and SRM are considered. Torque control below the base speed is achieved through the PWM chopping of current. As mentioned earlier, to maximize the available torque at high speed, phase control of the input voltage is used to control the torque. This control technique has the advantage of requiring only few switchings per electrical cycle. On the other hand, it has the disadvantages of being sluggish in response and having higher torque ripple. These drawbacks, however, are expected to have minimal effect on the vehicle operation due to the high vehicle inertia. Simulation results of the converter losses are presented in the next section.

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 urban drive cycle (Fig. 1(a)) and on the highway drive cycle (Fig. 1(b)) are studied.

A. Losses in an HEV

The converter losses in an HEV depend on the energy sharing between the ICE and the electric motor. Figures 2(a) and 2(b) show the total energy through put 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 analysis, it is assumed that all the kinetic energy released during the vehicle deceleration is recovered through regeneration, except for the amount lost in the process of regeneration. However, this is not practical for a very rapid braking of the vehicle. The electric motor and the battery pack are not capable of handling the huge amount of power released in a short burst during the harsh braking. In that case the mechanical brake needs to be engaged in addition to the regenerative braking. However, for the drive cycles considered in this study (Figs. 1(a) and 1(b)), the above assumption is valid. It is obvious, from the simulation results of Fig. 2(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. 1(b)), however, requires the electric motor more frequently, to supply the acceleration power of the hybrid vehicle. Moreover, the energy released during vehicle deceleration in the urban drive cycle is also recovered by the electric motor (generator), converter set.

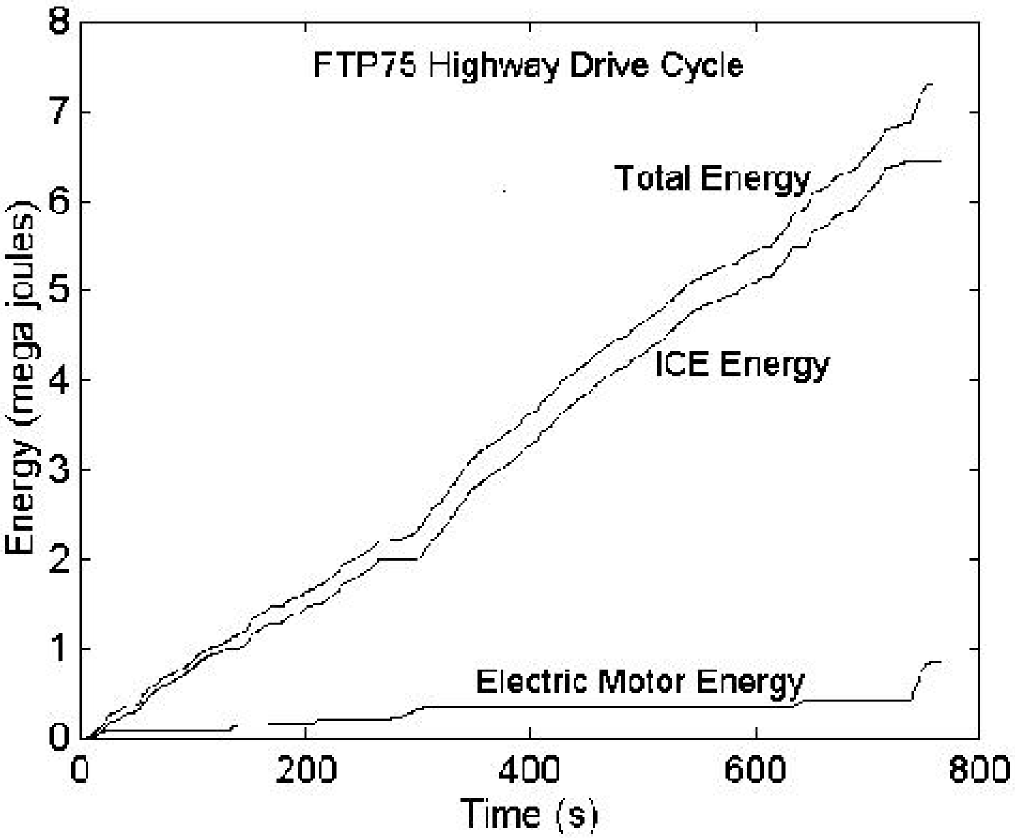


(a) (b)

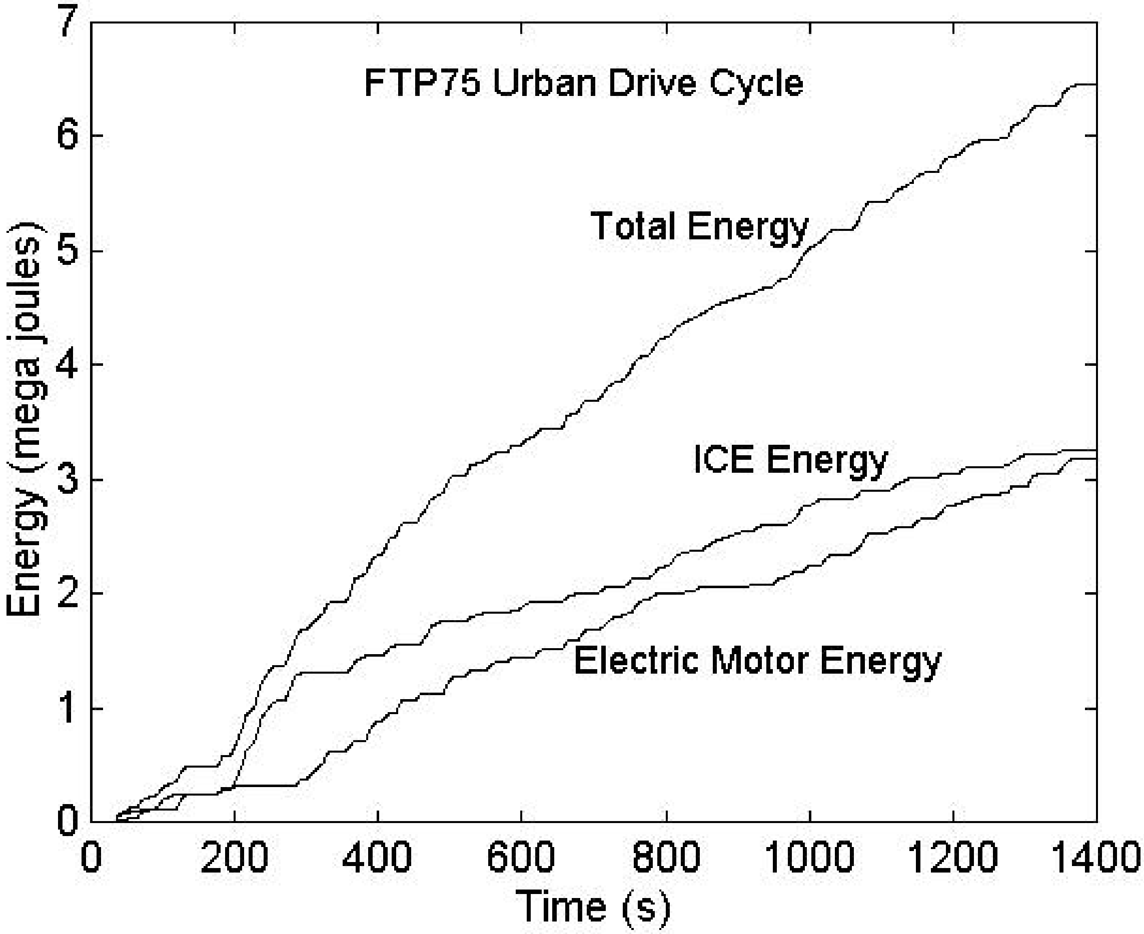
Fig 1. FTP75 highway (a) and urban (b) drive cycles.

In the case of 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.

The calculated values of the conduction (the solid line curve) and switching (the dashed curve) losses of HEV drivetrain systems using IM, BLDC, and SRM are presented in Figs. 3(a) and 3(b) for the urban drive cycle. Fig. 3(a) considers the case when the vehicle deceleration energy is recovered through regenerative braking, and Fig. 3(b) is for the case when the regeneration is not considered. The losses of Figs 3(a) and 3(b) 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 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 figures 3(a) and 3(b) 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.


FTP75 Highway Drive Cycle
Total Energy
ICE Energy
Electric Motor Energy
Energy (mega joules)
0
1
2
3
4
5
6
7
8
Time (s)
0
200
400
600
800

(a)


FTP75 Urban Drive Cycle
Total Energy
ICE Energy
Electric Motor Energy
Energy (mega joules)
0
1
2
3
4
5
6
7
Time (s)
0
200
400
600
800
1000
1200
1400

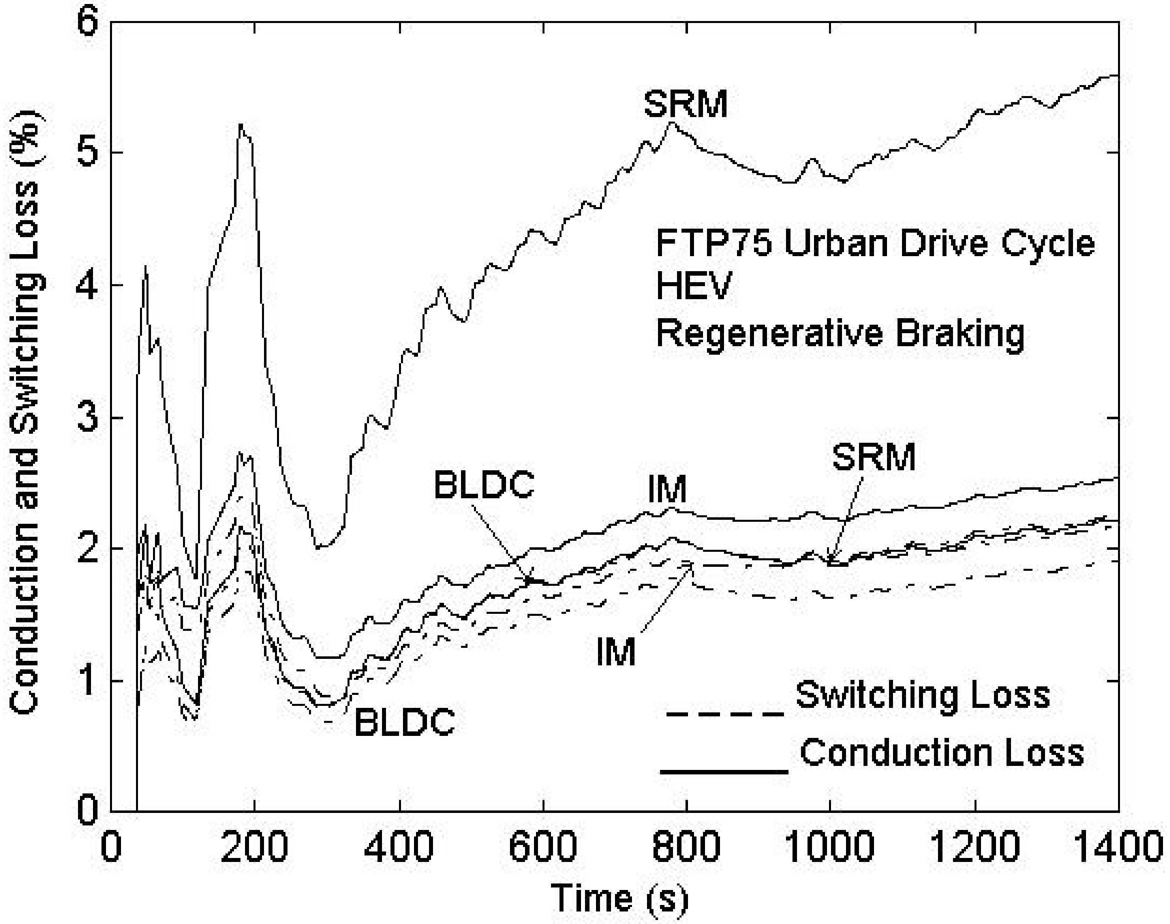
(b)

Fig 2. Energy consumption in HEV for highway (a) and urban (b) drive cycles.

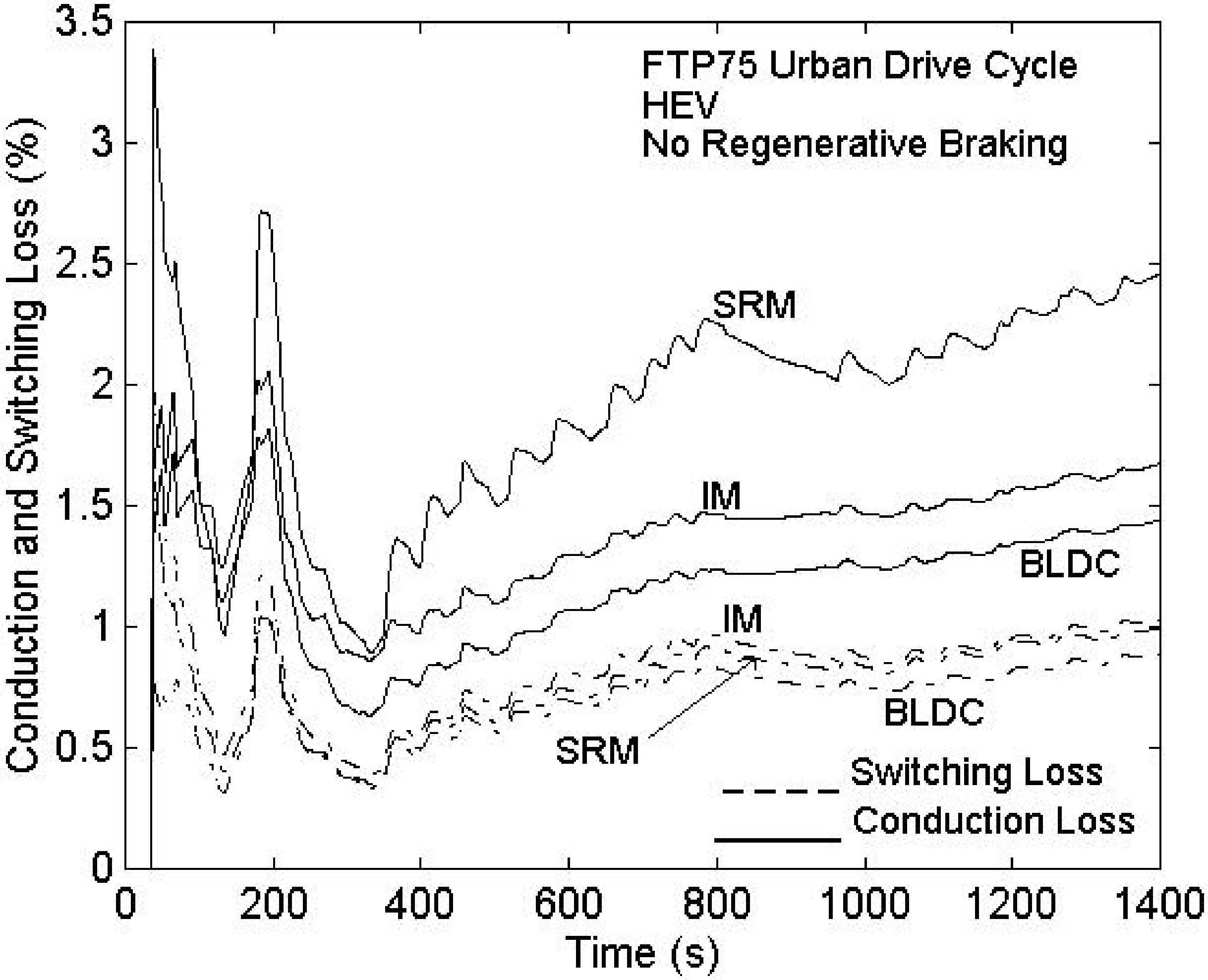
Due to the lower pf of operation of SRM, its conduction loss is higher in both cases. However, the switching loss of SRM converter is comparable to those of IM and BLDC inverters. High speed capability of SRM, besides the fact that the torque control at high speed is attained by the phase control of the input voltage, have helped to lower the switching losses in SRM converter, despite its lower pf of operation. For the HEV urban drive cycle the average switching losses (Fig. 3(a) and Fig. 3(b)), for all motors considered here, are less than 2% of the total energy for the case with regenerative braking and less than 1% for the case without regenerative braking. In some soft switched topologies the conduction loss can be higher than in a hard-switched converter [14]. Although the switching loss can be reduced considerably, it is not totally eliminated. Hence, if one assumes zero switching losses by using a soft switching

technique, for this drive cycle, the maximum gain in energy would, therefore, be less than 2%.

Now, let us examine the impact of soft switching on the operation of HEV in terms of the gasoline saved per 100 miles of travel.



(a)



(b)

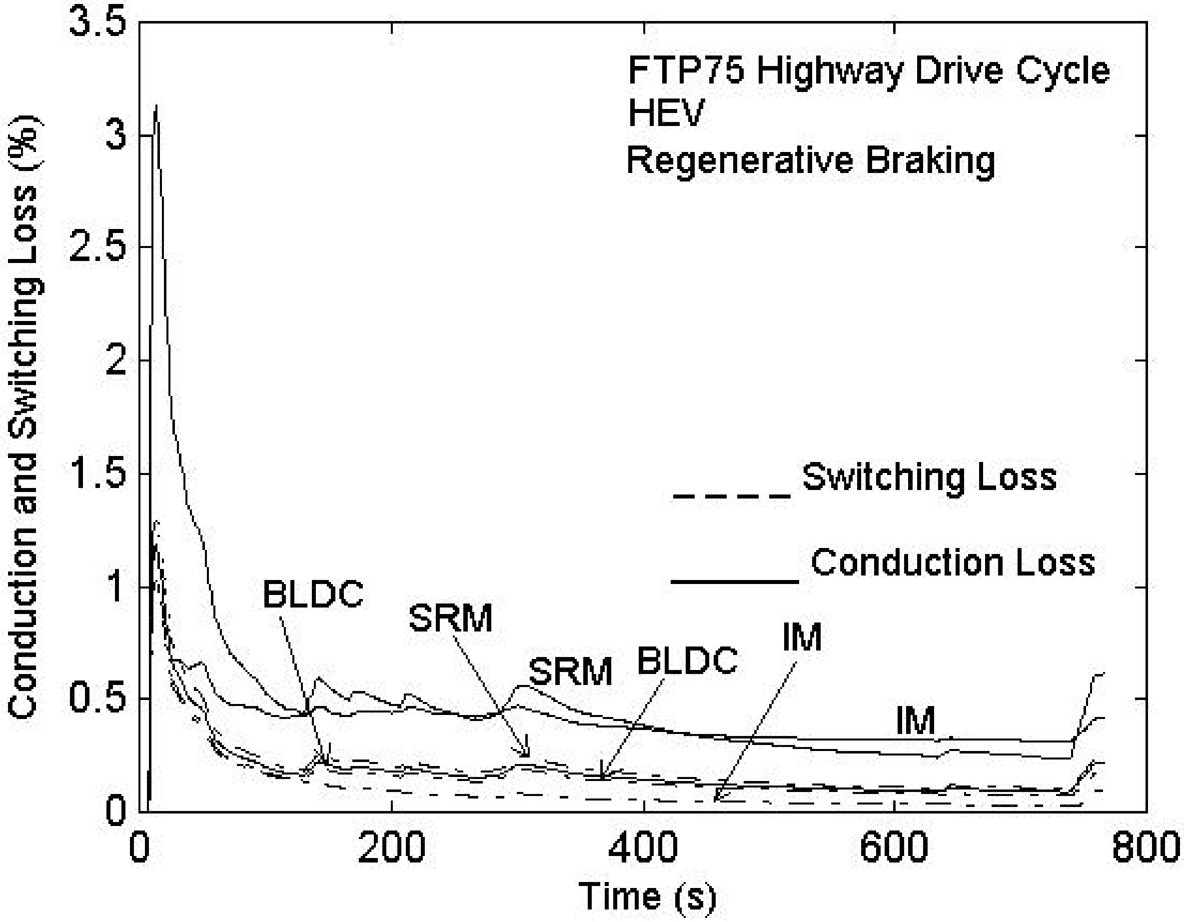
Fig 3. Converter losses for HEV in urban drive cycle with (a) and without (b) regenerative brakings.

The total energy spent for the operation of the vehicle in the urban drive cycle is 6.45 mega joules. Total distance traveled by the vehicle in this drive cycle is 6.6 miles. Energy density per gallon of gasoline is 121 mega joules. Assuming an efficiency of 20% in the operation of the ICE, the total savings in the gasoline is only 0.0808 gallons per hundred miles traveled in the urban drive cycle. Total savings for an average urban driving of 10,000 miles in a year is only 8.08 gallons of gasoline. Since HEV is not energy limited, we conclude, the extra cost and complexity associated with the operation of a soft switched converter do not justify soft switching for HEV.

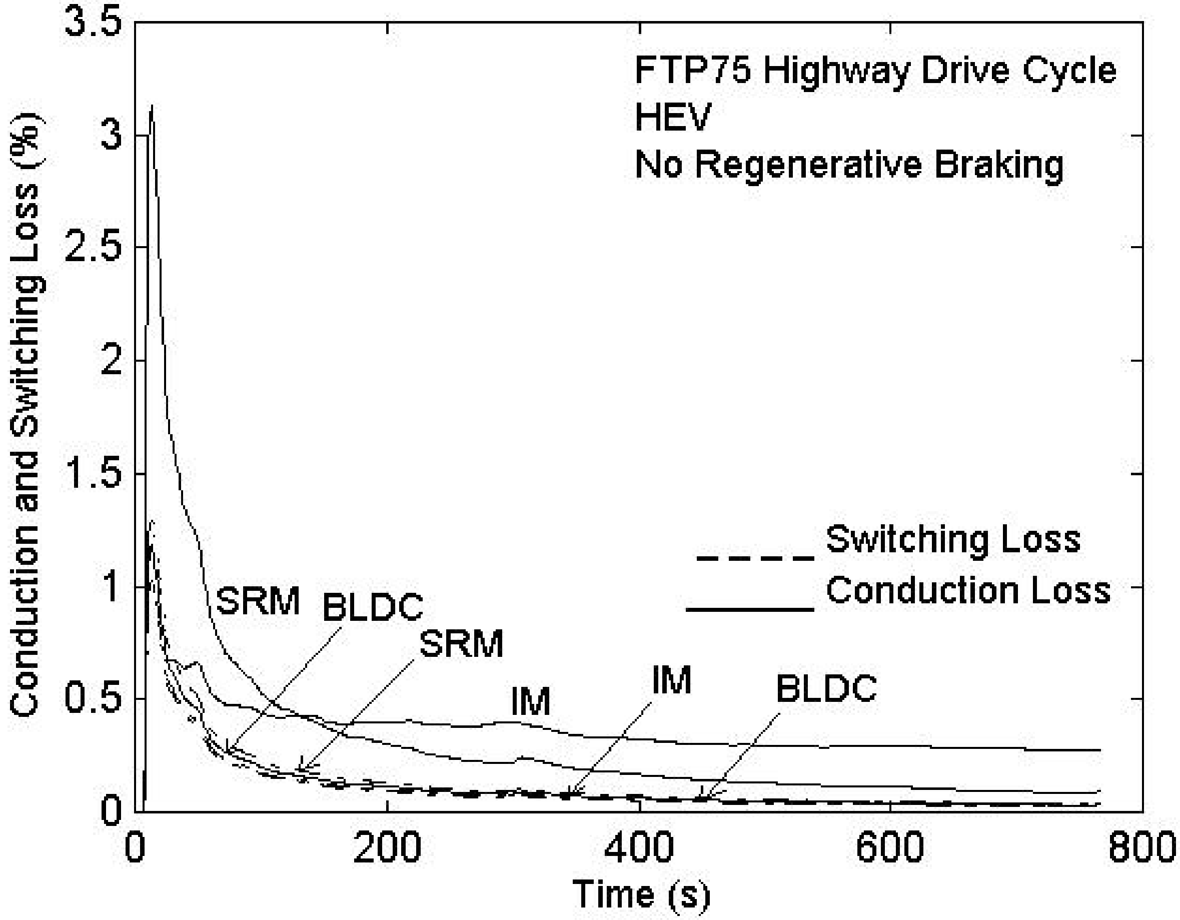
In highway driving cycle, except for few accelerations and few cases of regenerative braking, the electric motor is seldomly used . Calculated values of the switching losses for the operation of HEV in the highway drive cycle are shown in Figs. 4(a) and 4(b) with and without the consideration of regenerative braking, respectively. These losses are not significant and do not warrant any special effort in converter efficiency improvement.

B. Losses in EV

The energy recovered through regenerative braking is the same in EV as in HEV. However, since the battery is the only source of energy, the energy flow out of the battery pack is higher in case of 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 is higher in case of EV. This is shown in Fig. 5(a) and 5(b) for urban driving cycle with and without the consideration


FTP75 Highway Drive Cycle
HEV
Regenerative Braking
Switching Loss
Conduction Loss
BLDC
SRM
SRM
BLDC
IM
IM
Conduction and Switching Loss (%)
Time (s)
0
0.5
1
1.5
2
2.5
3
3.5
0
200
400
600
800

(a)

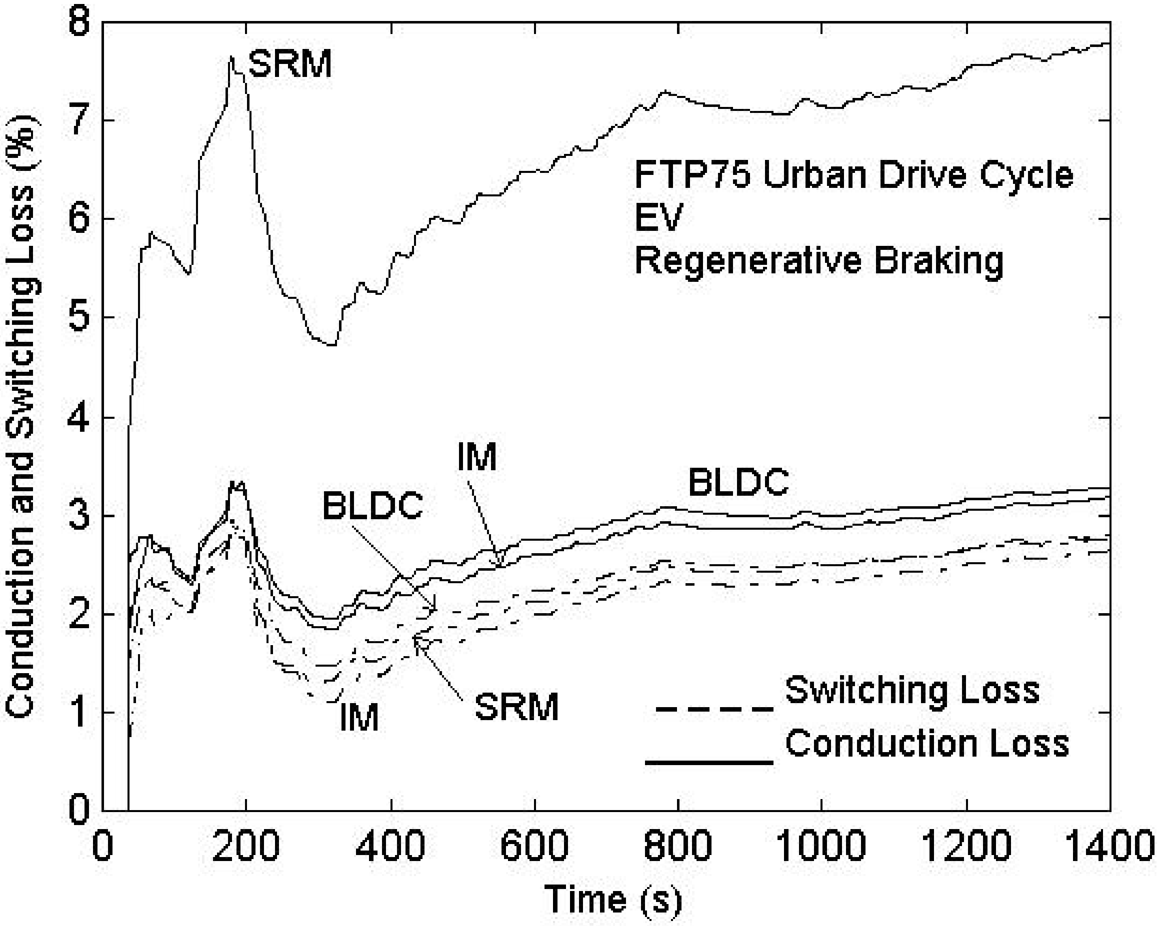

FTP75 Highway Drive Cycle
HEV
No Regenerative Braking
Switching Loss
Conduction Loss
SRM
BLDC
SRM
IM
IM
BLDC
Conduction and Switching Loss (%)
Time (s)
0
0.5
1
1.5
2
2.5
3
3.5
0
200
400
600
800

(b)

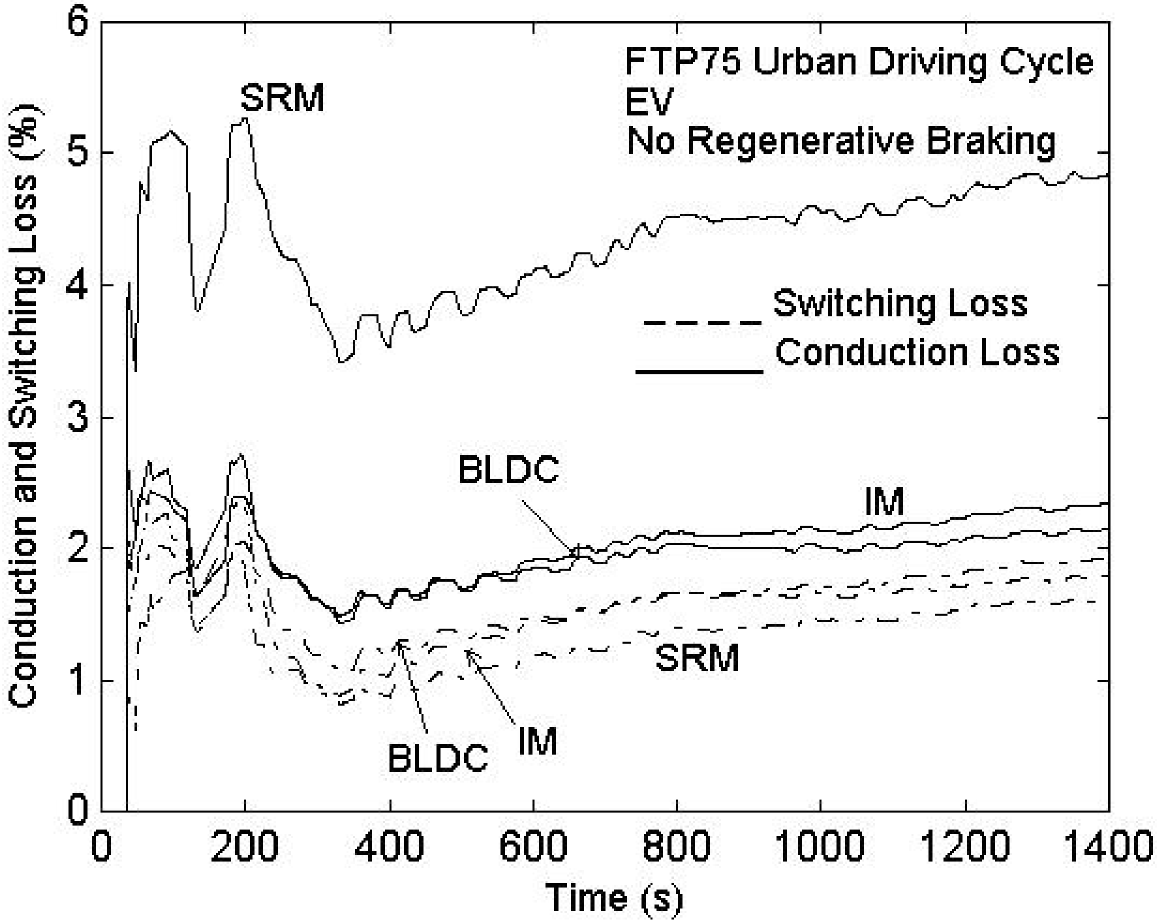
Fig.5. Converter losses for HEV in highway drive cycle with (a) and without (b) regenerative brakings.

of regenerative braking respectively. In both cases 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 3% with regenerative braking and close to 2% without regenerative braking. Although, the losses in EV are not greatly increased compared to the losses of 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 associated with its operation.

Finally, we consider the highway driving for EV. Although, EVs are not best suited for highway driving, the losses can be calculated for completeness. Figs. 6(a) and 6(b)



(a)



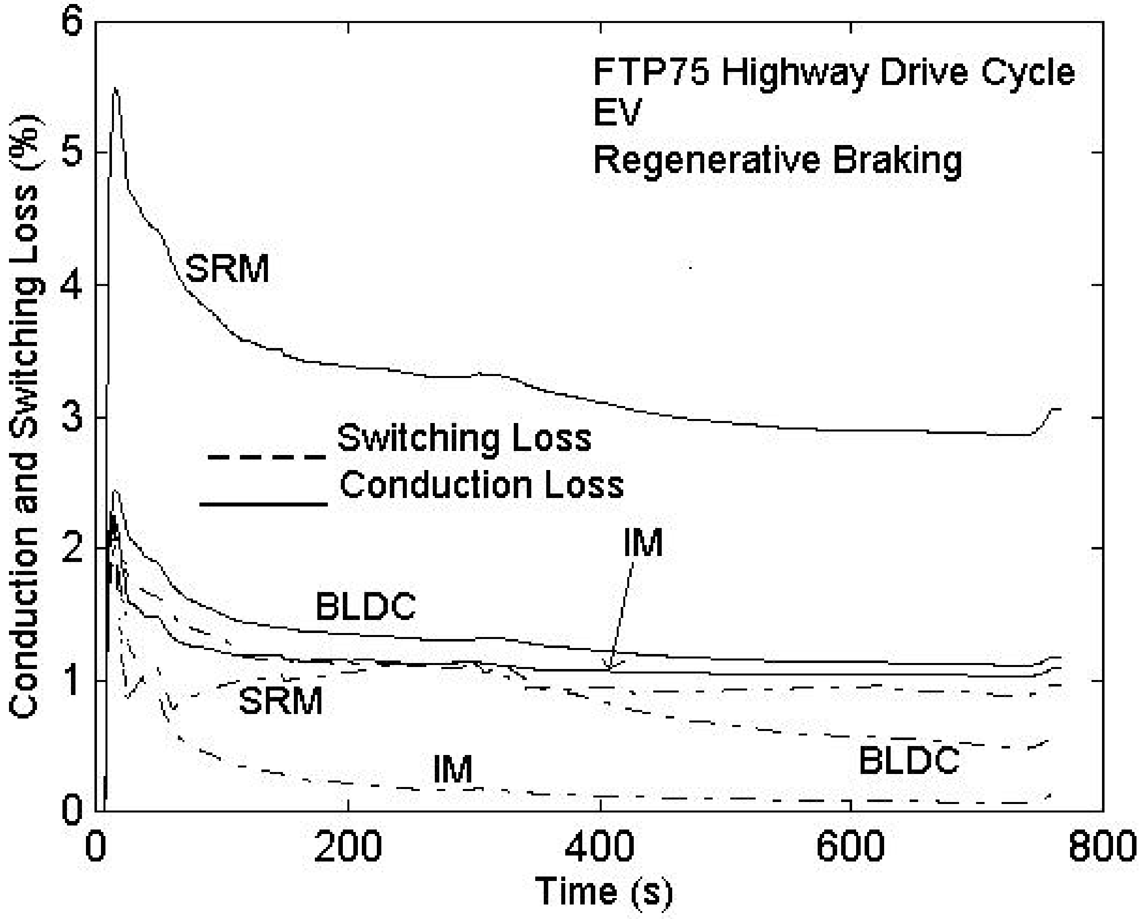
(b)

Fig 5. Converter losses for EV in urban cycle with (a) and without (b) regenerative brakings.

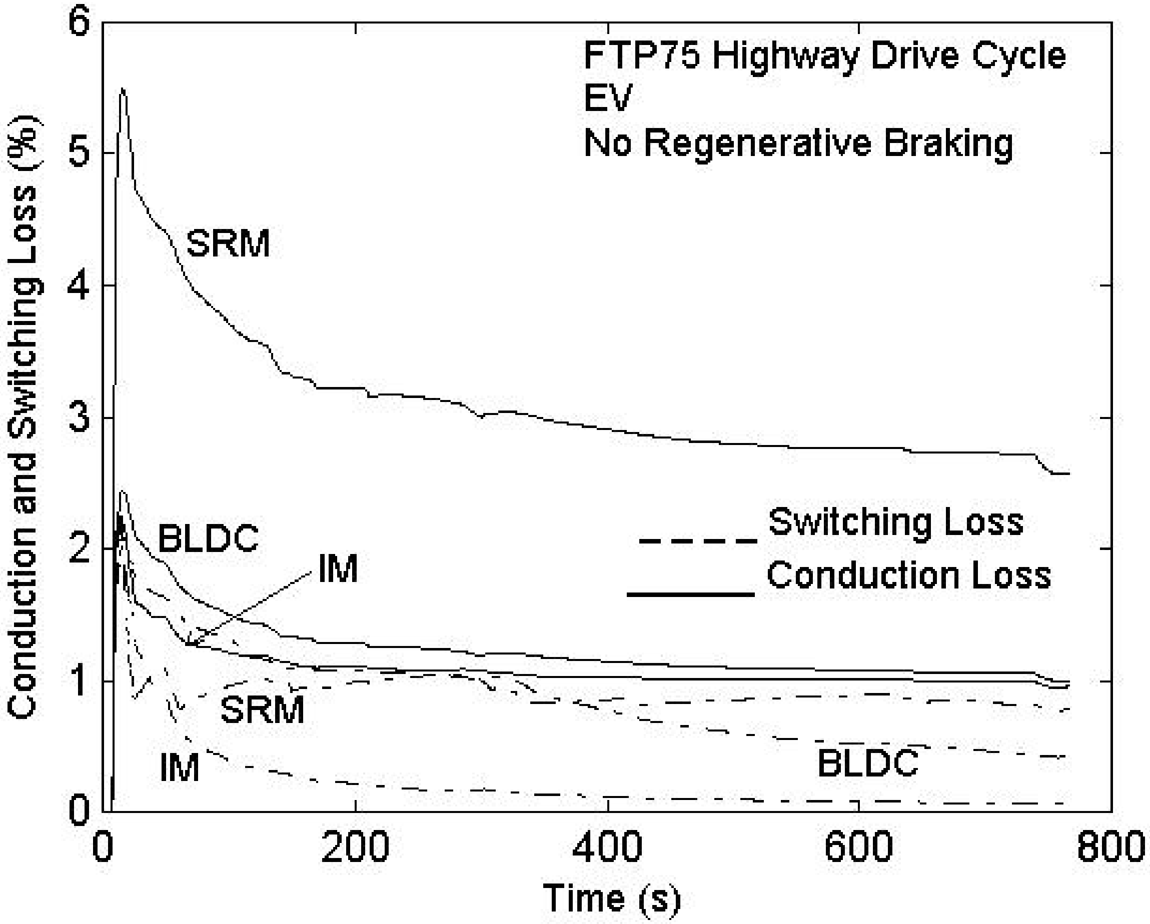
show the converter losses for the operation of the EV in the highway drive cycle with and without the consideration of the regenerative braking. Since the electric motor (battery) supplies all the energy in the operation of the EV, the losses are higher than in the case of HEV operation in the same drive cycle. However, the switching loss percentage is lower in highway driving as compared to the city driving of the EV (Figs. 5(a) and 5(b)) . It can be seen in Figs. 6(a) and 6(b), that the switching losses are actually less than 1% in both cases. The energy savings in the hypothetical highway driving of EV, therefore, may not justify the adoption of soft switching for its driving in the highway cycle.

V. Discussion

The simulation results of section IV give little incentive for soft switching in HEV, as far as the efficiency of the drivetrain is concerned. However, EV is a different issue.


FTP75 Highway Drive Cycle
EV
Regenerative Braking
Conduction and Switching Loss (%)
Time (s)
Switching Loss
Conduction Loss
SRM
BLDC
IM
SRM
IM
BLDC
0
1
2
3
4
5
6
0
200
400
600
800

(a)


FTP75 Highway Drive Cycle
EV
No Regenerative Braking
Conduction and Switching Loss (%)
Time (s)
Switching Loss
Conduction Loss
SRM
BLDC
IM
SRM
IM
BLDC
0
1
2
3
4
5
6
0
200
400
600
800

(b)

Fig 6. Converter losses for EV in highway drive cycle with (a) and without (b) regenerative brakings.

Since EV is energy limited, any gain in efficiency, by adopting soft switching, is directly related to the range of the vehicle. Hence, the marginal 3% gain in efficiency shown in the previous section for the urban driving cycle still may justify soft switching for EV electrical drive train. In other papers, e.g., [6] , the soft switching operation is shown to provide more gain in the efficiency of the converter than it is shown here. Those results should not be confused with the concepts presented in this study. Here we have evaluated the converter efficiency from the system prospectives. The gain in efficiency shown in this paper is based on the specific application to EV and HEV drivetrains with a special (optimal) mode of control, especially at the high speed operation of the vehicle (motor), as opposed to the fixed frequency PWM switching operation for a fan or resistive load used in the other works.

Faster switches are developed to reduce the switching power losses. However, the high di/dt and dv/dt associated with the faster switching cause voltage and current spikes due to stray inductance and capacitance in the circuit. This phenomenon causes high current and voltage stresses in the switch, and can also produce severe EMI problems. The use of snubbers can reduce the switching stresses in the switches, but they are lossy and add parts count. Another approach, as suggested in [8], is to use slower switches for vehicle applications. This would reduce both the EMI problem and switch stresses. But it will increase the switching losses. The additional switching losses caused by the slower switches should not have much impact on the operation of the HEV, however, it may favor soft switching for EV applications.

Soft switching with high switching frequency can produce a fast converter dynamic response. This may be difficult to achieve with hard switching without sacrificing efficiency. However, vehicle has a slow dynamics. Faster dynamic response, therefore, is not necessary from the electrical propulsion system of the EV and HEV. On the contrary, a deliberate damping may be required to suppress the possible excitation of any mechanical resonances [15].

Slower switching, in an attempt to reduce the switching losses, will introduce higher torque and current ripples. Nevertheless, the vehicle inertia is expected to smoothen the effect of torque ripple on the speed ripple.

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 the conventional automobiles. It may also be particularly tuned to be pleasant to the ear.

VI. Conclusions

An evaluation of the soft switching inverters for EV and HEV motor drives is presented. Simulation results of the converter losses are presented for the operation of the EV and the HEV in the FTP75 city and highway drive cycles. Operation of induction, brushless dc, and switched reluctance motors are 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, 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 EV with soft switching in highway driving is 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. We can summarize our findings as follows:

1. Soft switching is not recommended for the design of HEV.
2. Soft switching is not recommended for the design of EV in highway driving.
3. 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.

To reduce the EMI problem and the switch stresses due to fast switch turn-ons and turn-offs, slower switches may be used. The additional losses incurred by these slow switches are not expected to have any major impact on the operation of the electrical propulsion system of the HEV. The other characteristics of soft switching with high switching frequency such as, faster dynamic response, torque and current ripple, audible noise etc., do not have any appreciable effect on the design and operation of the EVs and the HEVs.

VII. REFERENCES

1. **Y. Murai and T. A. Lipo, "High Frequency Series Resonant DC Link Power Conversion",** ***IEEE IAS Annual Meeting Conference Record*****, 1988, pp. 772-779.**
2. **D. M. Divan, "The Resonant DC Link Converter - A New Concept in Static Power Conversion",** ***IEEE Transactions on Industrial Applications*****, Vol.25, No.2, pp. 317-325, 1989.**
3. **William McMurray, "Resonant Snubbers with Auxiliary Switches",** ***IEEE Transactions on Industry Applications,*** **Vol.29, No.2, March/April 1993.**
4. **M. Ehsani and T. S. Wu, "Zero Current Soft Switched Capacitively Coupled DC-AC Converter for High Power",** ***IEEE Industry Application Society Annual Meeting Records*****, Toronto, pp. 800-805, 1993.**
5. **T. S. Wu, M. D. Bellar, A. Tchamdjou, J. Mahdavi and M. Ehsani, "A Review of Soft-Switched DC-AC Converters",** ***IEEE IAS Annual Meeting Conference Record,*****1996, Vol.2, pp.1133-1144.**
6. **J. S. Lai, "Resonant Snubber-Based Soft-Switching Inverters for Electric Propulsion Drives",** ***IEEE Transactions on Industrial Electronics*****, Vol. 44, No.1, pp. 71-80, February 1997.**
7. **M. Ehsani, K. M. Rahman, and H. Toliyat, "Propulsion System Design of Electric and Hybrid Vehicle,"** ***IEEE Trans. on Industrial Electronics,*** **vol. 44, no. 1, pp.19-27, February 1997.**
8. **X. Xu, V. A. Sankaran, "Power Electronics in Electric Vehicles: Challenges and Opportunities,"** ***IEEE IAS Annual Meeting Conference Record,*** **1993, pp. 463-469.**
9. **T. J. E. Miller, "Switched Reluctance Drive," Short Course,** ***IEEE-IAS*** **Conference, Seattle, 1990.**
10. **T. M. Jahns, "Torque Production in Permanent Magnet Synchronous Motor Drives with Rectangular Current Excitation,"** ***IEEE Trans. Industry Application,*** **vol. 20, no. 4, pp. 803-813. July/Aug., 1984.**
11. **R. C. Becerra and M. Ehsani, "High Speed Torque Control of Permanent Brushless DC Motors,"** ***IEEE Trans. Industrial Electronics,"*** **vol. IE-35, no. 3, pp. 402-406, August, 1988.**
12. **C. C. Chan, J. Z. Jiang, G. H. Chen, X. Y. Wang, and K. T. Chau, "A Novel High Power Density Permanent Magnet Motor Drive for Electric Vehicles," in** ***Proc. EVS11,*** **paper 8.06, 1992, pp.1-12.**
13. **Y. Gao, K. M. Rahman, and M. Ehsani, "Parametric Design Of The Drive Train Of Electrically Peaking Hybrid (ELPH) Vehicle,"** ***SAE Journal Publication SP-1243, paper no. 970294,*** **1997.**
14. **J. S. Lai, R. W. Young, and J. W. McKeever, "Efficiency Consideration of DC Link Soft-Switching Inverters for Motor Drive Applications,"** ***IEEE PESC Annual Meeting,*** **1994**
15. **H. A. Toliyat, K. M. Rahman, and M. Ehsani, "Electric Machines in Electric and Hybrid Vehicle Applications,"** ***ICPE,*** **Seoul, Korea, 1995.**