A Model to Estimate the Effect of DC Bus Voltage on HEV Powertrain Efficiency

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***Abstract*—The efficiency of the electric drive system in a Hybrid Electric Vehicle plays a significant role in overall hybrid propulsion system efficiency and influences design choices for other mechanical components in the system. Increasing the DC bus voltage is thought to improve overall powertrain efficiency. In this paper, models are developed to predict the effect of DC bus voltage on the power loss in a PWM inverter motor drive and a brushless DC electric machine. The models indicate that a higher bus voltage will improve powertrain efficiency in some, but not all, operating conditions.**

Keywords-Hybrid Electric Vehicle; efficiency; inverter; IGBT; conduction loss; switching loss; drivetrain ; iron loss; windage loss

I. INTRODUCTION

The efficiency of the electric drive system (inverter and traction motor) in a Hybrid Electric Vehicle (HEV) plays a significant role in the overall hybrid propulsion system efficiency and influences design choices for other mechanical components in the system [1]. The loss mechanisms in the semiconductor power devices, (Insulated Gate Bipolar Transistors (IGBT's) and diodes), of the power inverter and the loss mechanisms of the traction motor can be defined from a foundation of fundamental material properties, device physics and electromagnetic interactions. The balance of losses introduced into an HEV electric drive system can be calculated based on these fundamental concepts applied to the specific type of inverter circuit employed and the design of the specific traction motor utilized. Furthermore, to be useful to the system designer, the method of calculating losses must be simple and accurate enough to yield useful design information and employ readily available parameters that can be extracted from manufacturer supplied datasheets. A complete inverter / motor efficiency map is an important tool in the HEV design process in that it facilitates system level simulation of HEV propulsion systems.

The electric drive system losses not only affect the system efficiency directly, but also influence the design and selection of other components throughout the HEV system [2,3]. A notable example is the design of the cooling system for the power electronics. Understanding the influence of the electrical loss mechanisms is necessary for the development of efficient HEV propulsion systems. This paper investigates the influence of DC bus voltage level on the power losses in the inverter and traction motor and develops an efficiency map model for design of HEV propulsion systems.

II. ELECTRIC DRIVE SYSTEM LOSS MODELS

A. Loss Model for the Inverter

In this section, we discuss analytical models to predict the losses in the IGBT's and diodes of a 3-phase voltage source inverter driving an HEV traction motor [4,5,6,7,8]. For this purpose, the motor is modeled as a 3-phase wye connected inductive load. For the purposes of developing the inverter loss model and the motor loss model, the traction motor load is assumed to be a brushless DC motor (BLDC). The specific inverter circuit modeled is a pulse width modulated (PWM) inverter implemented with IGBT power switches and anti-parallel diodes. The diodes can be either the intrinsic diodes of the IGBT's or external free-wheeling diodes. A sine wave PWM control scheme is assumed for development of the analytical loss model. A simplified schematic of a PWM controlled inverter drive system is shown in Fig. 1.

The power loss in each semiconductor device will be modeled as the average power loss over one motor electrical cycle. In this way, the calculated average power loss in each IGBT and each diode will be equal. It will be assumed that the PWM switching frequency, f_s, is much higher than the motor electrical frequency, f_m.

A simple piece-wise linear conduction model for both IGBT's and diodes can be used to calculate the conduction losses in these devices. A good approximation of the current – voltage characteristics in conduction can be achieved with a series connection of a DC voltage source and a resistance, both parameters being temperature dependent. These parameters can be easily extracted from device datasheets.

Conduction Model for IGBT:

$$v_{CE} = V_{CE0} + r_{CE} i_C \quad (1)$$

Conduction Model for Diode:

$$v_F = V_{F0} + r_D i_F \quad (2)$$

Representative manufacturer datasheet graphs are shown in Fig. 2 that can be used to extract the conduction model parameters *(V_{CE0}, r_{CE}, V_{F0}, r_D)* for (1) and (2). The off-state blocking losses of both the IGBT's and diodes will be

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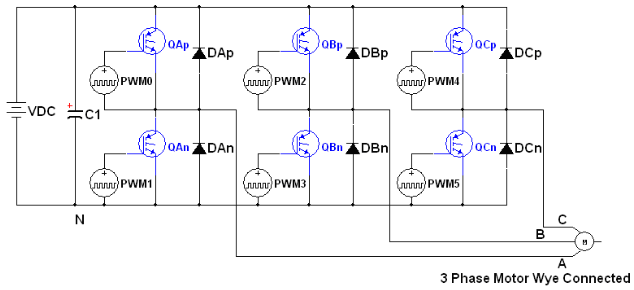

Figure 1. PWM inverter motor drive

neglected in this analytical model development based on the negligibly small value of leakage current for both of these devices.

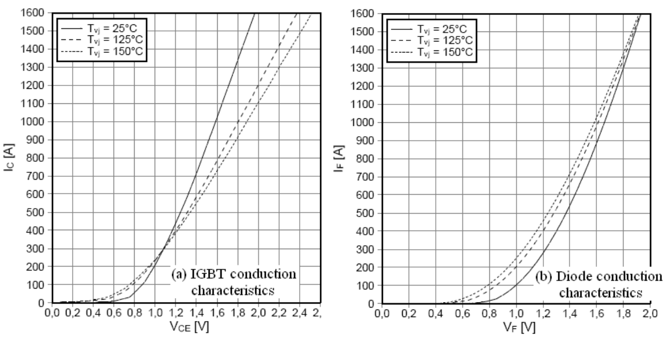

Figure 2. (a) IGBT and (b) Diode conduction current-voltage characteristics

1) IGBT conduction loss: The IGBT conduction losses are calculated by averaging over one motor electrical cycle the average IGBT losses in each switching cycle.

$$P_{QCav} = \frac{1}{N}\sum_{n}\frac{1}{T_s}\int_{(n-1)T_s}^{nT_s} v_{CE}(t)\cdot i_C(t)dt \tag{3}$$

Here N is the number of switching cycles in a motor electrical cycle and T_s is the switching period. Using models of the IGBT conduction voltage – current characteristics from (1) it can be shown that for $f_s >> f_m$ and assuming a sine wave PWM control scheme, the IGBT conduction loss model for a sine wave PWM inverter driving a 3-phase motor is

$$P_{QCav} = I_P\left(\frac{V_{CE0}}{2\pi}+\frac{I_P r_C}{8}\right)+I_P D_m\left(\frac{V_{CE0}}{4}+\frac{I_P r_C}{3\pi/2}\right)PF \tag{4}$$

where I_P is the peak value of the motor phase current, D_m is a duty cycle modulation parameter ($0 < D_m < ½$), and PF is the power factor of the motor inductive load.

2) IGBT switching loss: Assuming IGBT switching times are independent of device current and DC voltage then IGBT switching energies may be assumed to be proportional to these expressed as

$$E_{on} = E_{on-test}\frac{V_{DC}}{V_{DC-test}}\frac{I_P}{I_{C-test}} \tag{5}$$

$$E_{off} = E_{off-test}\frac{V_{DC}}{V_{DC-test}}\frac{I_P}{I_{C-test}} \tag{6}$$

where E_{on} and E_{off} are the IGBT on and off switching energies and $E_{on-test}$ and $E_{off-test}$ are values supplied on manufacturer datasheet under test conditions $V_{DC-test}$ and I_{C-test}. Averaging the switching losses over a switching cycle yields the IGBT switching loss model

$$P_{QSav} = \frac{f_s}{\pi}\left(E_{on}+E_{off}\right) \ . \tag{7}$$

3) Diode conduction loss: Diode conduction losses are calculated in an analogous fashion to the IGBT conduction losses yielding the diode conduction loss model for a sine wave PWM inverter driving a 3-phase motor

$$P_{DCav} = I_P\left(\frac{V_{F0}}{2\pi}+\frac{I_P r_D}{8}\right)-I_P D_m\left(\frac{V_{F0}}{4}+\frac{I_P r_D}{3\pi/2}\right)PF. \tag{8}$$

4) Application of inverter loss model: In this section, we apply the loss models to a representative commercially available IGBT "six-pack" power module to study the loss mechanisms and efficiency of a sine wave PWM inverter driving a 3-phase BLDC motor. Assume the inverter load is operating at a constant *26 kW, PF = 1* at a DC bus voltage of $V_{DC} = 300\ V$ and $I_P = 100\ A$ and $D_m = ½$.

From the IGBT module datasheet at $T = 150°\ C$, the conduction parameters can be extracted by a linear curve fit to Fig. 2 (a) and (b) for the IGBT and the internal IGBT diode in the region $I_C \leq 100\ A$ and $I_F \leq 100\ A$. The conduction parameters are determined to be $V_{CE0} = 0.5\ V$, $r_C = 3\ m\Omega$, $V_{F0} = 0.55\ V$, $r_D = 2.5\ m\Omega$, yielding conduction loss models

$$P_{QCav} = 0.142 I_P + 6.93\times10^{-4} I_P^2 \tag{9}$$

and

$$P_{DCav} = 1.87\times10^{-2} I_P + 4.74\times10^{-5} I_P^2 . \tag{10}$$

At $T=150°\ C$, datasheet values for the switching energies are $E_{on-test} = 76\ mJ$ and $E_{off-test} = 58\ mJ$ for $V_{DC-test} = 300\ V$ and $I_{C-test} = 550\ A$ and $R_G = 10\ \Omega$, yielding a switching loss model

$$P_{QSav} = 2.58\times10^{-7} V_{DC} I_P f_s \ . \tag{11}$$

Total conduction loss in the inverter at DC bus voltage $V_{DC} = 300\ V$ is *140.9 W* compared to *59.3 W* at $V_{DC} = 600\ V$. This is a reduction of *57.9%* with the increase in DC bus voltage. Switching loss at constant load power is independent on DC bus voltage and depends only on switching frequency as shown in Table I along with total power loss in the inverter IGBT's and diodes. For switching frequencies $f_s > 3\ kHz$ at $V_{DC} = 300\ V$ and $f_s > 1.3\ kHz$ at $V_{DC} = 600\ V$, switching losses begin to dominate over conduction losses. Thus, for PWM switching frequencies in these regions, improvement in inverter efficiency with increased DC bus voltage is small and can be neglected when integrating it with the motor efficiency model.

Based on the results of this study, the inverter losses may be assumed to be nearly constant as the DC bus voltage is changed. This conclusion is based on data for the particular IGBT's in this example while neglecting diode reverse recovery energy. In the future we plan to expand the number of example IGBT's, include reverse recovery energy, and consider the effects of transient snubber circuits.

TABLE I. Inverter Power Loss

f_s (kHz)	P_{QSav} (W)	P_{total} (W) $V_{DC} = 300$ V	P_{total} (W) $V_{DC} = 600$ V
0.5	23.3	164.2	82.6
1	46.5	187.4	105.7
5	232.7	373.6	292.0
10	465.3	606.2	563.8
15	698.0	838.9	786.4
20	930.6	1071.5	1009.0

B. Loss Model for the Motor

This section explains the common losses in the motor, and will examine how DC supply voltage affects a vehicle's energy efficiency. A goal in this analysis will be to develop an equation for motor efficiency that can be used for further study. Ideally, this model will be based on constants that can be derived from information normally supplied with motor specification sheets.

The efficiency for an electric motor may be calculated from an equation of the form:

$$\eta_{motor} = \frac{P_{out}}{P_{in}} = \frac{T\omega}{T\omega + P_{loss}} \tag{12}$$

The output power is calculated from the output torque *(T)* and angular speed *(ω)* of the motor. The power losses include copper losses, iron losses, friction losses, windage losses, and power losses in the inverter.

$$P_{loss} = P_{loss,copper} + P_{loss,iron} + P_{loss,friction} + P_{loss,windage} + P_{loss,inverter} \tag{13}$$

The loss terms depend on the construction of the motor. For the purpose of the following discussion, the motor will be assumed to be a BLDC motor.

The copper losses are caused by the electrical resistance of the motor windings and can be expressed as:

$$P_{loss,copper} = I^2 R_s = \left(\frac{T}{k_t}\right)^2 R_s = k_c T^2 \tag{14}$$

Because the motor current and torque are directly related *($T = k_t I$)* the copper loss becomes a function of the square of the torque. The constant for the motor loss is easily calculated from the motor constant *(k_t)* and stator resistance *(R_s)*. Both of these values are commonly given on motor specification sheets.

The iron losses are a result of magnetic hysteresis. They are dependent on the rate at which the magnetic field in the rotor changes and can expressed as:

$$P_{loss,iron} = k_i \omega \tag{15}$$

Data on the iron loss coefficient *(k_i)* is not commonly available in manufacturer's specifications, so in the example which follows this coefficient is estimated based on known values for similar motors.

Friction and windage are mechanical losses due to friction in the motor bearings and aerodynamic drag, respectively. The friction power loss is dependent on the magnitude of the bearing friction and the rate of rotation. With well designed bearings, this loss should be low. It can be expressed as:

$$P_{loss,friction} = k_f \omega \tag{16}$$

The friction loss coefficient *(k_f)* often can be found in manufacture's specifications. The aerodynamics losses can be expressed as:

$$P_{loss,windage} = k_w \omega^3 \tag{17}$$

The aerodynamic loss coefficient *(k_w)* is not commonly found in manufacturer's specifications and must be estimated. At high rotational speeds the aerodynamic losses tend to dominate the mechanical power losses, because of the third-power relationship.

The inverter losses ($P_{loss,inverter}$) may be evaluated using the methods developed in Section A.

III. DC BUS VOLTAGE AND EFFICIENCY OF HEV DRIVETRAIN

To determine the effect of DC bus voltage on the efficiency of a HEV drivetrain, a 4 kW (5 hp) commercially available BLDC motor was considered. The constants for the model were determined from data available on the motor specification sheet, or estimated based on data for a similarly sized motor, when necessary. The inverter power loss was determined from the model developed here. Fig. 3 shows the calculated efficiency map for this motor.

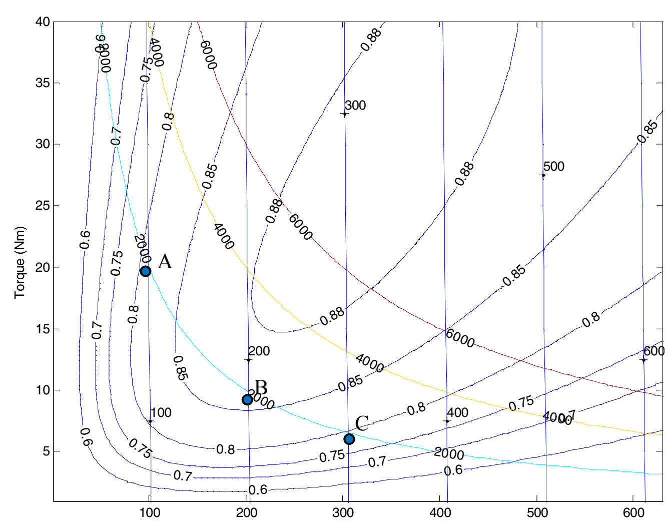

Figure 3. Calculated efficiency map for a 4kW BLDC motor.

Parameters for this motor include a motor torque constant (k_t) of 0.98 Nm/A, a stator resistance (R_s) of 0.76 Ω, a back EMF constant (k_b) of 63.3 V/rpm, a continuous stall torque of 17 Nm, and a peak torque of 43 Nm. With an assumption of a 10 kHz switching frequency, the inverter losses were estimated to be 93 W at 300 V_{DC} and 86 W at 600 V_{DC}.

Also included on Fig. 3 are lines of constant power and lines of constant voltage. Lines of constant power are hyperbolas in the torque-speed plane. Lines for 2000, 4000, and 6000 W are shown. Lines of constant voltage are straight-lines in the torque-speed plane. Lines of constant voltage are shown for 100 V increments up to 600 V.

In examining Fig. 3 one clear effect of increasing the voltage is to allow the motor to achieve higher speeds. For example increasing the supply voltage from 300 V to 600 V, allows the motor to double the no-load speed from 310 rad/s (3000 rpm) to 620 rad/s (6000 rpm).

Whether or not an increase in voltage will improve the efficiency of the motor depends on where the motor is operating on the torque-speed plane. Consider the case that the motor is asked to provide 2000 W. The motor can achieve this power output by operating at point A, with a supply voltage of about 100 V, a torque output of about 20 Nm, (which corresponds to a supply current of nominally 20.4 A), and a rotational speed of about 100 rad/s. At this operating point the motor efficiency is 81%.

Increasing the voltage to 200 V (point B) while maintaining the same power delivered improves the motor efficiency to 85.5%. This occurs because the increased voltage allows the motor to spin at higher rotational speed (200 rad/s), lower torque (10 Nm) and correspondingly lower current draw (10.2 A). In this operating region the power loss is dominated by the copper losses, so that reducing the current draw improves efficiency.

Increasing the voltage to 300 V (point C) results in a decrease in the motor efficiency (to 80%). As before, increasing the voltage allows the motor to spin at a higher rotational speed (300 rad/s), lower torque (6.7 Nm), and hence lower current (6.8 A). The difference is that at this operating point the windage losses are beginning to dominate, so that the increase in windage losses offsets the reduction in the copper losses, and efficiency is reduced.

As a result of this analysis it is clear that whether or not an increase in supply voltage will improve the efficiency of the motor is strongly dependent on (a) the loss characteristics of the motor and (b) where the motor is operating on the torque-speed plane. These factors are strongly dependent on the motor design and the operational requirements for the motor.

One point that should not be lost in this discussion is that increasing the supply voltage for the motor also necessitates the changing of the gear ratios used in the vehicle. A larger numerical gear ratio will be required when the voltage is increased to step down shaft speeds to match wheel speeds. This change in gear ratio will also affect vehicle performance.

To illustrate the last two points, the efficiency of the 4 kW motor was compared at two operating voltages (450 V and 600 V). To enable the comparison, the gear ratio selected for the 600 V motor needed to be 33% larger numerically than the gear ratio used with the motor at 450 V. This design decision allows the vehicles equipped with two options to have the same top-end speed. (It should be noted that other powertrain design options could have been considered.) The relative efficiencies for the two voltage options at various vehicle speeds and torque demands are shown in Fig. 4.

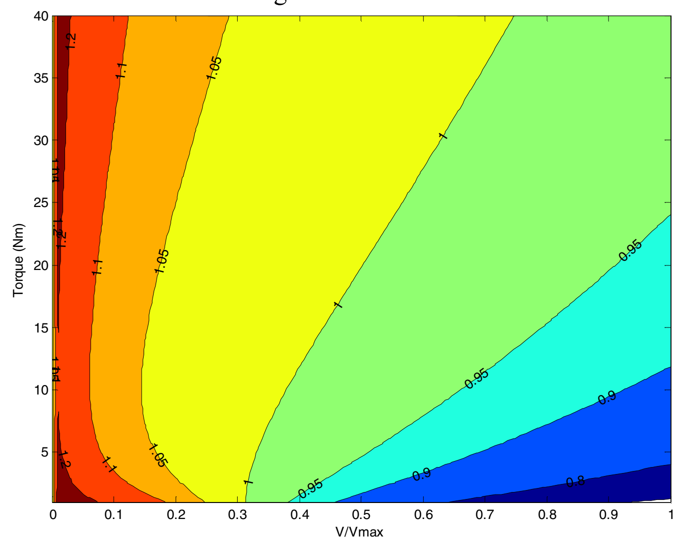

Figure 4. Relative efficiency map for a 4kW BLDC motor comparing the efficiency at 600 VDC to the efficiency at 450 VDC.

The figure shows that for low vehicle speeds increasing the supply voltage from 450 V to 600 V results in a relative efficiency greater than one, which indicates that the higher voltage motor will improve the drivetrain efficiency. The improvement is greatest at the lowest vehicle speeds. In this region where the efficiency is being improved by the increase in voltage, it is the copper losses that are dominating the power loss term. At higher speeds increasing the voltage tends to reduce the relative efficiency to less than one, which indicates that the higher bus voltage is resulting in lower drivetrain efficiency. In this operating region the windage losses are tending to dominate.

These results suggest that driving cycles that tend to have a significant amount of low speed driving (e.g. a city driving cycle) the higher supply voltages will be desirable. In high speed driving cycles (e.g. a highway cycle) the higher voltages may not be desirable.

One must be careful of extrapolating the results of the example presented here, since the results are highly dependent on the shape of the efficiency map, which in turn is dependent on the type and characteristics of the motor.

IV. CONCLUSIONS

A model has been presented which allows the power loss for a typical PWM inverter motor drive to be determined from data sheet parameters. The inverter losses can be expressed as the sum of conduction losses and switching losses. For the example inverter presented, it was found that at the relatively high switching frequencies of interest, switching losses tend to dominate conduction losses. Consequently, at high switching frequency the inverter losses are relatively insensitive to increases in the DC voltage bus. In the future we plan to expand the number of example IGBT's to cover a wide region of operating conditions, include reverse recovery energy in the loss model, and consider the effects of transient snubber circuits.

A model has also been presented that allows the efficiency for a BLDC electric motor to be determined from data sheet parameters. This model was used to determine the effect of increasing the bus voltage on the efficiency map for the motor. It was found that the higher bus voltage may or may not improve the efficiency of the motor when operated in the vehicle. At lower vehicle speeds, the increase in bus voltage improves the drivetrain efficiency. This occurs because in this operating range the copper losses tend to dominate and increasing the bus voltage decreases current demand. At higher vehicle speeds, the increase in bus voltage decreases the drivetrain efficiency. This occurs because in this operating rage the windage losses tend to dominate and increasing the bus voltage for a BLDC voltage increases motor speed.

To more fully understand the effect of the bus voltage increase, the actual operating points for the motor in the vehicle powertrain need to be determined. This can be accomplished by inserting the motor efficiency maps into a powertrain simulation program such as PSAT. This will be a goal for the next phase of this study. In addition, the study will be broadened to apply the model to motors of other sizes and types.

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