International Rectifier

APPLICATION NOTE

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Power Loss Estimation in BLDC Motor Drives Using iCalc

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This note explains the power loss estimation spreadsheet prepared for brushless DC (BLDC) motor drivers. Steady state averagepower losses in the IGBT/ MOSFET switches and anti-parallel diodes can be reasonably and easily predicted, if certain operating conditions of the motor driver are known. This tool has been developed to cover the four most common drive strategies implemented for BLDC motors with trapezoidal flux distribution viz. 60° switching, 120° switching, PAM and hard switching. The switching in each of these strategies willbe briefly explained, followed by an explanation of the loss calculation method for that strategy.

INTRODUCTION

Power losses in semiconductors can be represented as functions of current and voltage based on empirical models. Physics based models, though useful from the silicon designer's point of view, may not be sufficiently accurate in practical circuits. Higher levels of accuracy can be obtained only at the cost of simplicity. On the other hand, empirical models usually do not suggest any silicon design direction. However they can be easily extracted and can be optimized for high accuracy. For quick performance estimation and loss prediction, the empirical models used in this note prove extremely useful.

Losses in semiconductors can be divided into conduction losses and switching losses. Conduction losses depend upon the on-state voltage drop V_{CEON} across the IGBT or the forward drop V_F across the diode. Both V_{CEON} and V_F increase with conducted current and are ideally independent of switching frequency and switching (bus) voltage. Switching power losses on the other hand increase with current, switching voltage and switching frequency. In the IGBT, switching losses mainly occur during turn-on and turn-off transients, while the major component of the diode switching loss is that due to its reverse recovery. These parameters can be modeled as below.

$$V_{CEON} = V_T + a.I^b$$
$$V_F = V_{TD} + ad.I^{bd}$$
$$E_{ON} = \left(h1 + h2I^x\right)I^k$$
$$E_{OFF} = \left(m1 + m2I^y\right)I^n$$
$$E_{DIODE} = d1.I^{d2}$$

In the above equations, V_T, a, b, V_{TD}, ad, bd, E_{ON}, h1, h2, x, k, E_{OFF}, m1, m2, y and n are empirically determined parameters. That means that these parameters are extracted to fit measured data for V_{CEON}, V_F, E_{ON}, E_{OFF}, and E_{DIODE}. Variation of the switching energy loss with bus voltage is assumed to be linear. Note that both conduction and switching losses increase with temperature for NPT IGBTs, but that variation is not considered in here, only the worst-case condition, i.e.

maximum junction temperature is looked at. Using equations (1) and knowing the variation of current in a particular application, total power losses can be calculated.

OVERALL SYSTEM DESCRIPTION

The operating characteristics of a BLDC motor are very similar to that of a brush DC motor. Since a permanent magnet rotor is used in a BLDC, speed control can be implemented by varying average voltage across the stator windings. This tends to change the value of the average stator current. However for a given load torque, the average stator current has to be ideally fixed. Hence the back EMF induced in the stator windings has to change such that the stator current remains constant. For a constant field, this amounts to change in speed. Thus increasing the applied stator voltage increases the motor speed and vice-versa. Variation in the motor voltage can be achieved using several techniques. Usage of semiconductor switches is preferred due to their low loss, high frequency operation and the allowance for electronic control. This is apart from the other advantages like space and cost saving.

For a three-phase BLDC application, the most common topology used is a three-phase buck derived converter or a three-phase inverter bridge. The typical system structure for a domestic application is as shown in figure 1. The figure shows an input diode rectifier bridge with either a 230 V or a 110 V single-phase AC input. Usually the DC bus voltage is adjusted in either case to be about 320 V DC, using a voltage doubler configuration for 110 V input. Output stage consists of a three-phase inverter composed of switches that could be MOSFETs or IGBTs. If IGBTs are used, anti-parallel diodes need to be connected across them for carrying reverse currents, while MOSFETs use body diodes. MOSFETs give lower turn-off switching loss and usually lower diode forward drop, but that advantage may be offset by higher on-state voltage drop and turn-on switching/diode reverse recovery losses than IGBTs. One of the purposes of the loss estimation tool is to enable users to compare such performance nuances for their particular application.

BRUSHLESS DC DRIVE STRATEGIES

Typical waveforms for a 3-phase BLDC motor with trapezoidal flux distribution are shown in figure 2. Approximately, the back EMF induced per phase of the motor winding is constant for 120 °, before and after which it changes linearly with rotor angle.

In order to get constant output power and consequently constant output torque, current is driven through a motor winding during the flat portion of the its back EMF waveform. At a time, only two switches are turned on, one in a high side and the other in a low side. Thus for a

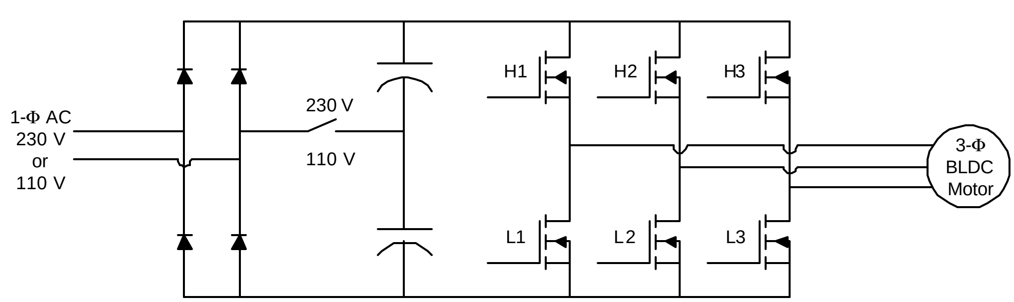

Figure 1. Typical inverter drive system for BLDC motor

star connected motor winding, two phase windings are connected in series across the DC bus, while the third winding is open. The switches in figure 1 are switched such that each phase carries current only during the 120 ° electrical degrees when the back EMF is constant. Thus there is a commutation event between phases every 60 ° electrical, as seen from figure 2. Effectively it means that there is a current transition every 60 °. Appropriate commutation therefore requires knowledge of the rotor position, which can be directly detected using position sensors or estimated in sensor-less manner by monitoring back EMF in the open-phase. In any case, the phase current is essentially constant for the 120° conduction period. Hence the switch current carries current for 1/3 of one electrical rotation and the current is constant for a constant load. This can be used to calculate switch conduction losses. Furthermore, PWM may be introduced during switch conduction giving rise to switching losses. Switching fashion depends upon the type of strategy

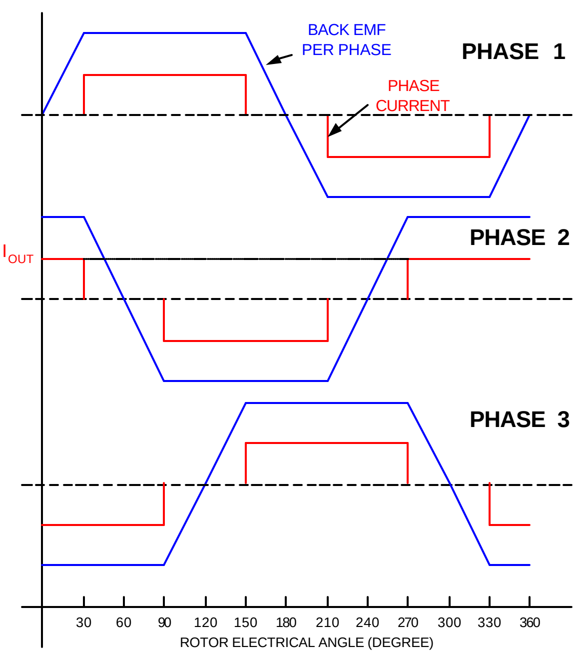

Figure 2. Back EMF and phase current variation with rotor electrical angle

employed. Various strategies are described below.

As mentioned earlier, controlling the speed amounts to changing the applied voltage across motor phases. This can be done in the following ways:

1. Pulse Amplitude Modulation (PAM)

In this strategy, the applied voltage across motor windings is changed by varying the magnitude of the bus voltage. For that usually a boost converter is added after the diode bridge rectifier for a 110 V system. Apart from DC bus voltage control, power factor correction can also be achieved. Since there is no high frequency switching involved, the strategy is quite simple and efficient. The waveforms with this strategy are shown in figure 3. As can be seen, each switch is on continuously for an angular duration of 120° electrical in one complete electrical rotation. The on times of two switches in the same leg are displaced from each other by 120 °. Also on times of high side and low side switches are sequentially displaced from other high side and low side switches respectively by 120°.

Looking at the overall picture, it is seen that if all the switches are identical, total power loss can be said to be equivalent to that when two switches conduct current continuously.

Switch power loss is only due to conduction and diodes conduct only during commutation. The power loss per switch is one sixth of the total power loss

$$P_{SW} = \frac{I_{OUT}.V_{CEON}}{3} \quad (2)$$

where I_{OUT} is the as defined in figure 2.

2. PULSE WIDTH MODULATION

The average applied voltage across the motor stator windings can also be changed by modulating switch duty cycle within the conduction interval. In this case the DC bus voltage is kept constant while the winding current is determined by low frequency component of the inverter output voltage. Hence the output current is more or less similar to that shown in figures 2 and 3, with a switching frequency ripple. Switching output voltage can be realized either by switching only one of the two switches per leg or switching both the switches. Accordingly, the following types of PWM strategies can be obtained.

A. 120 ° SWITCHING

In this case, only one switch switches per leg while the other one conducts as in figure 3. Usually the high side switch is the one which modulates the duty cycle while the low side switch "steers" the current continuously for a 120 ° duration as shown in figure 4.

The low frequency envelope in figure 4 is similar to that in figure 3.

With this switching strategy, two aspects can be immediately noted concerning power losses, as compared to the PAM strategy. Firstly, switching losses are introduced due to high frequency switching besides conduction losses. Secondly, loss distribution between switches is not uniform: while the low side switches have only conduction losses, the high side switches have both switching and conduction losses. Whether it is the high side switch or low side switch that has higher losses depends upon the particular switch selected, switching frequency and operating conditions. In any case, the total low and high side power losses are given by

$$P_L = I_{OUT}.V_{CEON}$$
$$P_H = D.I_{OUT}.V_{CEON} + f_{SW}.(E_{ON} + E_{OFF}) \quad (3)$$

In the above equations, D is the high side switch duty cycle and fsw is the switching frequency. Also in this strategy, the low side anti-parallel diodes (for IGBT) or body diodes (for MOSFET), conduct during off time of the high side switch. Consequently, diode conduction and reverse recovery losses

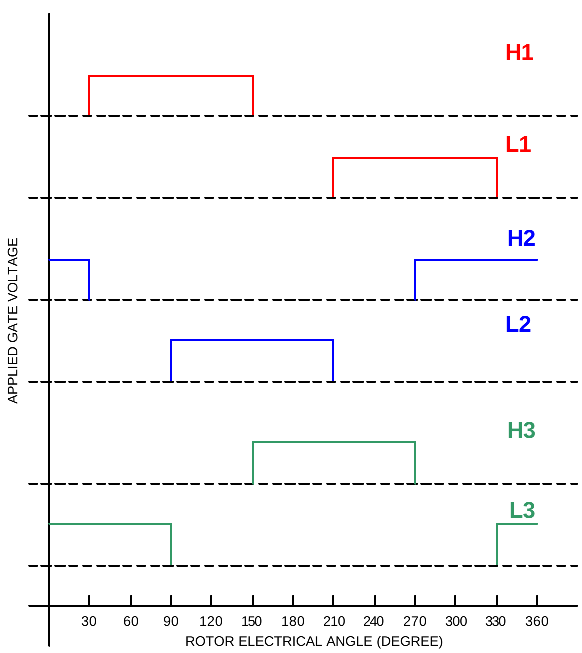

Figure 3. Gate waveforms (conducted current) for PAM

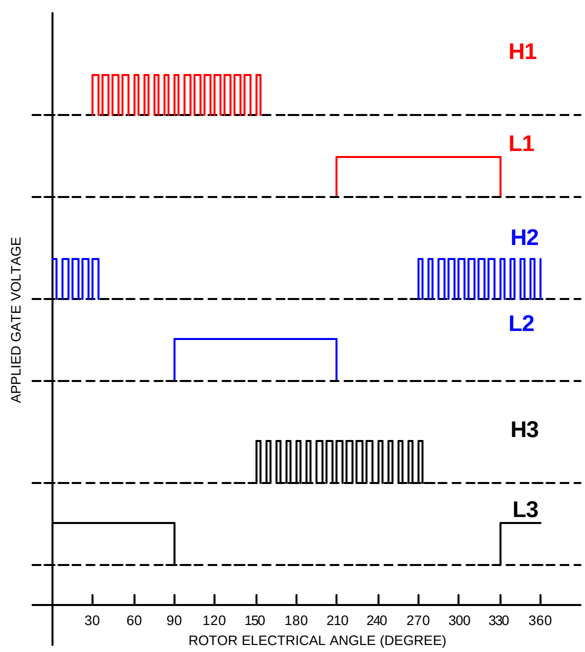

Figure 4. Switch gate waveforms for 120 ° PWM switching

are also non-trivial. These losses are given by

$$P_D = (1-D).I_{OUT}.V_F + f_{SW}.(E_{DIODE}) \quad (4)$$

From the above equations (3) and (4), individual switch and diode losses are given by

$$P_{LI} = \frac{I_{OUT}.V_{CEON}}{3}$$
$$P_{HI} = \frac{[D.I_{OUT}.V_{CEON} + f_{SW}.(E_{ON} + E_{OFF})]}{3} \quad (5)$$
$$P_{DI} = \frac{(1-D).I_{OUT}.V_F + f_{SW}.(E_{DIODE})}{3}$$

where P_{LI}, P_{HI} and P_{DI} are individual high side switch, low side switch and low side diode losses.

B. 60 ° SWITCHING

This strategy realizes a symmetrical version of the previous method. Both the high and low side switches are switched for 60 ° electrical and operate in continuous conduction for 60 ° electrical. Again the low frequency envelope is of basically the same form as in figure 3. Gate waveforms for the high and low side switches are shown in figure 5. At any time, only one switch is switching while the other one is in conduction. Whether the high side switch is switching or the low side switch is conduction depends upon the polarity of the voltage at the third (unfed) phase. When this voltage is positive, the high side switch is switched while the low side switch is switched when the voltage is negative. Since all the switches switch symmetrically, power losses are distributed symmetrically as well between high and low side switches. Similarly, both the high and low side diodes have non-trivial power losses.

It can be easily seen comparing figure 4 and figure 5 that the total power losses are the same in both cases. Then the individual switch and diode power losses are

$$P_{SWITCH} = \frac{I_{OUT}.V_{CEON} + [D.I_{OUT}.V_{CEON} + f_{SW}.(E_{ON} + E_{OFF})]}{6}$$
$$P_{DIODE} = \frac{(1-D).I_{OUT}.V_F + f_{SW}.(E_{DIODE})}{6} \quad (6)$$

C. HARD SWITCHING

In this strategy, both the high and low side switches are switched simultaneously, keeping the same low frequency envelope as the earlier strategies. Both high and low side diodes conduct. Since switching is symmetrical, power losses are equally distributed between switches. Unlike 60 ° and 120 ° switching, here is no switch that conducts continuously hence losses are strongly affected by duty cycle and switching frequency.

Individual switch and diode losses are given by the following expressions

$$P_{SWITCH} = \frac{[D.I_{OUT}.V_{CEON} + f_{SW}.(E_{ON} + E_{OFF})]}{6}$$
$$P_{DIODE} = \frac{(1-D).I_{OUT}.V_F + f_{SW}.(E_{DIODE})}{6} \quad (7)$$

SYSTEM EFFICIENCY AND THERMAL PERFORMANCE

Total losses in the inverter can be calculated from the expressions given above depending upon the type of strategy adopted for driving the BLDC motor. Knowing

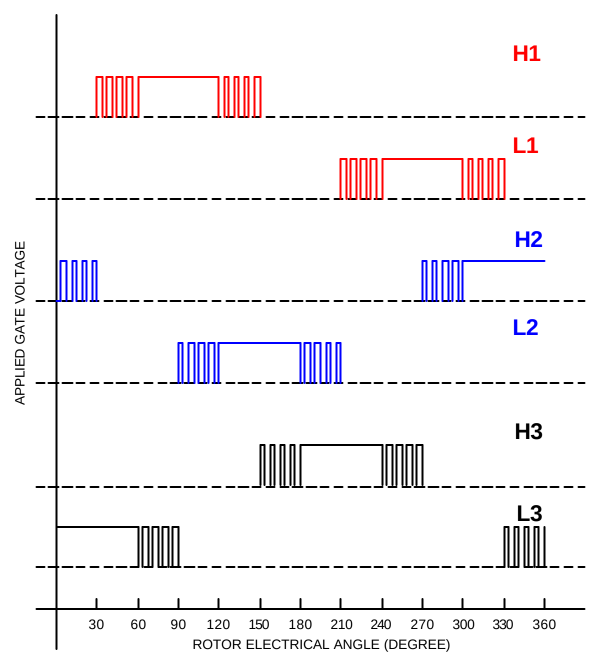

Figure 5. Switch gate waveforms for 60 ° PWM switching

thermal resistance R_{THJ-C} and R_{THC-S} for the semiconductor part being evaluated, maximum junction temperature can be estimated using the following expression

$$T_J = T_C + (R_{THJ-C} + R_{THC-S}).P_{SWITCH} \quad (8)$$

where T_C is the case temperature. Similarly diode junction temperature can also be calculated. Note that for the temperature calculations, power losses used are calculated at maximum junction temperature. Hence actual and estimated temperatures converge as operating junction temperature increases, finally becoming equal at T_{JMAX}. From the above expression, a maximum value of T_C can be determined, in order that maximum T_J is within limit. Then, knowing the maximum permissible T_C and maximum ambient temperature, the heat sink thermal resistance can be estimated from the following expression

$$T_C = T_A + R_{THC-A}.[N.(P_{SWITCH} + P_{DIODE})] \quad (9)$$

where R_{THC-A} is the heat sink thermal resistance, T_A is the maximum estimated ambient temperature and N is the number of switches mounted on the heat sink.

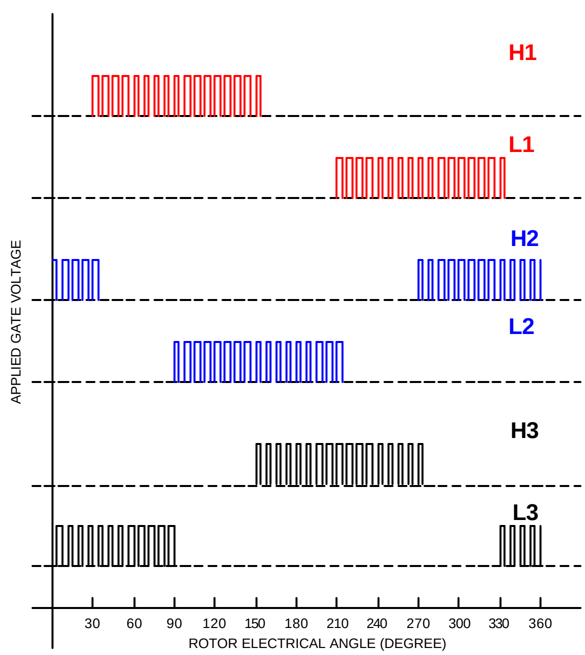

Figure 6. Switch gate waveforms for hard switching

Output power to the motor can be approximated to be

$$P_{OUT} = D.V_{BUS}.I_{OUT} \quad (10)$$

Then, knowing the desired output power and obtainable bus voltage, output current and operating duty cycle could be calculated. Inverter efficiency is given by

$$h = \frac{D.V_{BUS}.I_{OUT}}{D.V_{BUS}.I_{OUT} + 6(P_{SWITCH} + P_{DIODE})} \quad (11)$$

where the denominator gives input power as the sum of output power and total inverter losses. Furthermore, the average input current is given by

$$I_{IN} = \frac{D.V_{BUS}.I_{OUT} + 6(P_{SWITCH} + P_{DIODE})}{V_{BUS}} \quad (12)$$

LOSS ESTIMATION SPREADSHEET

All the above calculations can be conveniently performed using a spreadsheet-based tool. This is explained in the following section.

Switching energies and on-state voltage drop values can be calculated for a given part if the empirical loss parameters specified in equation (1) are known for that part. Then, using the other equations above pertinent to the switching strategy, power losses can be calculated. In the spreadsheet loss tool, the user can make desired selection of switching strategy and part number using a drop-down menu. Appropriate loss parameters are then automatically used for loss calculations. To the right of the selection menu, the part selected is displayed along with some information about that part like rated voltage & current levels, package, on-state voltage drop and thermal parameters. Thus the user can determine if the part specifications look relevant to the application. To further aid the user, a link above the part number selection drop down menu leads to an IGBT selection guide that gives a comprehensive parameter list for all the available IGBTs.

A separate section is provided on the front page for all the parameters that the user needs to input. From equation (10), output power is determined by the product of bus voltage, output current I_{OUT} and duty cycle. Knowing the bus voltage, the user can specify any two of the remaining three parameters viz. P_{OUT}, I_{OUT} and D. The third one is calculated based on the specified parameters. If all the three parameters are specified, output current I_{OUT} is calculated from specified duty cycle and output power values overriding the specified I_{OUT} value. No default parameters are used for these three quantities, so two of them have to be specified. Parameter values used for following calculations are displayed in a separate column titled "Calculated." Note that for hard switching, assuming a constant current, the net output power is the algebraic sum of positive power (supplied to load during IGBT on time) and negative power (supplied back to input during IGBT off time). Thus for a duty cycle of 0.5, the net output power is zero and for lower duty cycle values, the net output power goes negative. Physically this would correspond to braking and this state would exist for a short time. Power losses however are dependent only on the device current (which is a user specification) and hence are always positive.

Bus voltage and thermal parameters (ambient and case temperatures) can be specified at a separate location. Note that thermal resistance of the part from junction to case is specific to the part number selected and is automatically determined when a particular part number is selected. IGBT switching losses vary with gate resistance. This effect is accounted for by turn-on and turn-off gate drive correction factors. Part datasheets specify the variation of switching losses with gate resistance. Gate resistances used in the spreadsheet by default are given in the relevant datasheets. Then if the user uses a different gate resistance, the gate drive correction factor either for turn-on or turn-off is given by

Input Fields

Choose Switching Strategy and IGBT Part #

View Switching Strategy Guide — View IGBT Selection Guide

Switching Strategy: 120 Degree Switching — IGBT P/N: IRGSL10B60KD

Enter 2 of the 3 parameters listed below		Calculated	
Duty cycle	0.65	0.65	
Power out	500	500.0	
Iout	20	2.608	**Calculating Iout from known duty cycle and power out**

Enter the following parameters or accept the default values	
Bus Voltage	295
Ambient temp [°C]	25
Case temp [°C]	100
Gate drive correction Factor	
Turn-on	1.00
Turn-off	1.00

Figure 7. Sample display from spreadsheet tool showing input fields

$$CF = \frac{switch\_loss\_at\_user\_R_G}{switch\_loss\_at\_default\_R_G} \qquad (13)$$

The figure 7 above shows a sample of the input selection fields. Here the user has selected the 120 deg switching strategy for IGBT part number IRGSL10B60KD. The switch duty cycle (0.65), output current (20 A) and output power are specified. As explained earlier, the software has calculated the output current of 2.6 A for a bus voltage of 295 V, overriding the specified I_{OUT} value. This is stated beside the calculated current value. The ambient temperature is 25 C and case temperature is 100 °C. The user has entered both the turn-on and turn-off gate drive correction factors as one, thus accepting default R_G values.

Based on these inputs, the software calculates the IGBT and diode power losses, junction temperatures and total inverter power loss as a function of the switching frequency. These results are displayed in separate charts in the sheet. If the junction temperature exceeds 150 C, a warning is generated indicating that usage of the particular part for switching frequencies above a limiting value leads to junction temperatures greater than 150 C. Calculated data can be also viewed in the form of tables. A different sheet titled “Max Current” gives a chart of maximum current I_{OUT} (corresponding to Tjmax) Vs switching frequency. This chart effectively gives the maximum current rating of the particular part when driven using the selected strategy under the specified thermal conditions and bus voltage and is believed to greatly help the user in selecting an appropriate part.