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AN-980

IGBTs vs HEXFET® Power MOSFETs For Variable Frequency Motor Drives

(HEXFET is a trademark of International Rectifier)

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Summary

This application note compares International Rectifier IGBTs and HEXFET power MOSFETs for efficiencies as well as system costs for a range of 3-phase sinusoidal PWM motor drives. Losses are calculated for two different carrier frequencies and the system costs include heatsink costs. Aluminum vs. silicon tradeoff is discussed along with relevant examples. Results are presented in a graphical format, allowing designers to choose an optimum device for their motor drive application.

Introduction

Insulated Gate Bipolar Transistors (IGBTs) have recently entered the field of power electronics as serious contenders for power processing sockets. The IGBT has shed its image as an unreliable lab curiosity and is now beginning to compete seriously with established devices such as the power MOSFET. Designers are concerned with the choices available based on complexity, efficiency, and overall system cost. The aim of this application note is to compare MOSFETs and IGBTs in terms of system costs and efficiencies in typical 3-phase 220V motor control applications ranging from one-quarter horsepower to 5 hp.

The first section compares the characteristics and the structures of International Rectifier devices. The next section deals with the assumptions made and the methods used in the comparison. The results of the comparison are then provided graphically. This is followed by a closer look at a couple of specific power ratings. This application note concludes with a chart showing the tradeoffs between cost and efficiency across the board, indicating the "optimum" devices for each horsepower range, and a set of general conclusions.

Background

The field of 3-phase 220V PWM motor drives has had mainly bipolars and power MOSFETs competing with one another. Power MOSFETs have been the choice of power electronic designers, especially at power levels below 5 hp because of the ease of drive and their rugged operation. Since FETs are voltage-controlled devices, they require only very small gate current pulses to turn them off and on. The average currents necessary for controlling the device state are often magnitudes lower than those required by bipolar devices of similar ratings. What's more, the FET's wide switching safe operating area (SOA), avalanche and dv/dt capabilities allow for snubberless operation, often a great advantage over bipolars. The $R_{DS(on)}$ of the FET does, however, rise exponentially with voltage rating.

The IGBT combines the best of both worlds. It is a voltage-controlled device (like the MOSFET) allowing designers to greatly simplify their drive circuits. It is a rugged device with a square switching SOA and high peak current capability. In addition, it exhibits low forward voltage characteristics similar to bipolars, reducing the conduction loss. Also, as it does not have an internal reverse diode, designers can choose an external fast recovery diode to suit a specific application. All this indicates that the IGBT will be the device of choice for applications requiring high current densities at high voltages coupled with switching frequencies up to 20 to 50 kHz.

Comparison of the Device Structures

The IGBT is a spinoff from power MOSFET technology. Both devices have similar cross sections as can be seen from Figures 1a and 1b. Each shares a similar gate structure with polysilicon gate buses and P wells with N tubs. The N type material under the P wells form the drain region for the HEXFET power MOSFET and its resistivity is responsible for its BV_{dss} rating. Consequently, as the required breakdown voltage for HEXFETs goes up, so does the resistivity of this region, leading to an exponential increase in the on-resistance of the device. The manner in which the IGBT differs from the HEXFET power MOSFET is that it has two additional layers under the high resistivity N region. The first is a thin N+ region for decreasing the lifetime

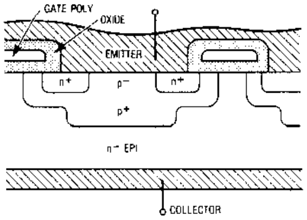


Figure 1a. HEXFET cross section

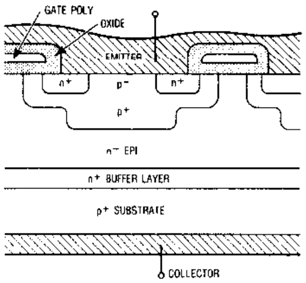


Figure 1b. IGBT cross section

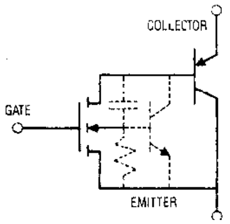


Figure 2. Equivalent circuit

of stored charges. The second is a P region which is responsible for the low on-state voltage drop. This P region floods the N region with carriers whenever the device is turned on and this process of conductivity modulation lowers the normally high resistivity of the N region. Figure 2 shows the approximate equivalent circuit which can be used to describe the operation of the device. The structure is similar to a FET input Darlington with a PNP output device.

As is evident from the device structure, the base region of the PNP is not brought out of the device and, consequently one cannot actively get rid of the carriers in the base region to effect a fast turn-off. This is why the N + layer is required to reduce the lifetime of carriers. It also serves to reduce the gain of the output PNP structure which is important to prevent device latch-up.

Figure 3 shows a comparison of forward voltage characteristics of 600V-rated devices. An IGBT of the same size as that of a MOSFET would have nearly one tenth the conduction losses. This reduced on-state drop is, however, at the expense of an increase in switching energy as the IGBT displays a distinctly slower turn-off. Another feature of the IGBT is the absense of an inherent diode, whose recovery losses add to the total loss, as in the case of a power MOSFET. Designers, however, can select an external reverse diode to suit the application. Table 1 summarizes the comparison between IGBTs and MOSFETs.

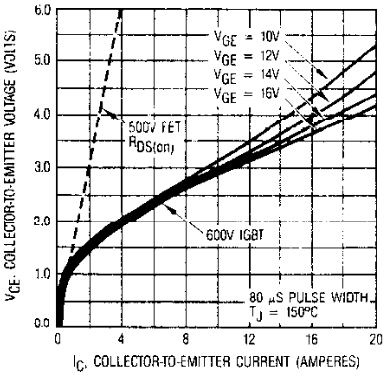


Figure 3. Comparison of forward voltages

Table 1

IGBTs	MOSFETs
1. Minority/majority carrier Conduction	Majority Carrier Conduction
2. Low Forward Drop	High $R_{DS(on)}$
For similar die size, voltage rating and current	
3. Turn-off time 500 ns	Turn-off time <100 ns MHz operation possible.
4. No internal diode	Reverse internal parasitic diode
5. 4-layer device	3-layer device

Comparison of Losses in a Three-Phase AC Drive Application

For various applications the relative importance of switching loss and conduction loss can be very different. This application note compares the performance of IGBTs and MOSFETs in 3-phase motor drive applications, where a 3-phase sinusoidal waveform is constructed using a PWM technique. The devices are assumed to operate from a rectified 220V line.

Various horsepowers from one-quarter to 5 hp are analyzed. Each hp is evaluated at PWM switching frequencies of 5 kHz and 20 kHz. Various die sizes are evaluated at every current rating to yield the most cost effective solution. External fast recovery freewheeling diodes are assumed around the IGBTs (HEXFETs already have a built-in reverse diode).

The total losses are calculated over a cycle. These include the conduction losses in the device, the conduction losses in the diode, the turn-on and turn-off losses due to the device, and the switching losses associated with the Q_{rr} and t_{rr} of the diode.

To calculate conduction losses over a cycle (with a sinusoidally varying "chopped up" current waveform as shown in Figure 4), a knee voltage + dynamic resistance type of model is assumed for all the switches. For HEXFET power MOSFETs which are purely resistive (unlike the IGBTs or the diodes) the knee voltage is zero. As the die size goes up, the dynamic resistance decreases proportionately and thus the conduction losses decrease.

The turn-on and turn-off losses are assumed to be linearly dependent on current. The losses related to t_{rr} and Q_{rr} depend on the current in a non-linear way, and thus a linearization is resorted to, for easier manipulation of the equations.

The resulting conduction and switching losses are converted into a bar graph format, Figures 5b thru 12b, where losses for all devices evaluated at a particular hp can be compared. The bars are divided into switching and conduction losses for ease of comparison.

The next step is to evaluate the costs of the various solutions as it is usually the prime criterion for device selection. The user costs assumed for the devices are projected mature high volume market prices.

To the device costs is added the cost of the heatsink required to cool the device to a maximum T_j of 110°C at normal full load operating power. The heatsink cost represents a significant part of the total costs and, in fact, can often result in a larger size of silicon being chosen to reduce the heatsink size and cost, as will be seen later. Mounting and wiring costs have not been included.

Finally, the cost information relating to each hp is put together in a per unit bar graph format, Figures 5a thru 12a, similar to that for losses. The costs are split up into per unit device (IGBT + diode or HEXFET) and per unit heatsink costs, so that the user can appreciate the significance of the heatsink costs. Thus, the information presented in the cost and loss graphs provides the designer with a spectrum of choices that can be exercised.

A Closer Look at the 0.75 HP Example

A total of four different devices as shown in Figures 7a and 7b (two HEXFETs and two IGBTs) are investigated at each frequency. As would be expected, the total losses decrease as the device size goes up. Obviously, increasing the silicon content implies increasing device costs, but this can be offset by decreasing heatsink cost. This implies that the smallest silicon size may not automatically be the lowest cost solution.

For example, an IRF830 HEXFET can be used in a 0.75 hp inverter at 20 kHz, but as is shown in the charts the power dissipated is so large that a hugh heatsink is required to keep the die temperature within design limits. The IRF840 HEXFET turns out to be a much more inexpensive solution, with the added advantage of increasing the system efficiency. However, the IGBT 1 size device turns out to be even less expensive than HEXFET power MOSFETs at 20 kHz, with even better system efficiency.

The picture is slightly different at 5 kHz as the IRF830 can handle the power loss with a relatively smaller heatsink cost which turns out to be the lowest cost solution (though the one with the highest losses). Looking at the IRF840 costs, it is apparent that the price penalty to be paid for going from 5 kHz to 20 kHz is less than 20%, which is not very significant in terms of the overall drive cost.

Crossover Point for IGBTs and HEXFETs

If the cost figures are normalized with respect to their horsepower ratings, and arranged as shown in Figures 13 and 14, the crossover points between IGBTs and HEXFETs becomes apparent. At 5 kHz, IGBTs tend to be the lowest cost solution above 1 hp and HEXFETs are most cost effective below 1 hp. At 20 kHz the crossover point shifts down and IGBTs tend to be most cost effective above 0.75 hp. This is because the IRF830, the device of choice at 5 kHz, cannot handle the extra switching loss at 20 kHz and therefore, cannot be used. The next higher die size costs more than the IGBT solution, making the IGBT the most cost effective solution at 20 kHz. The crossover points are a function of device and heatsink pricing available to the designer; in the immediate future they will probably be a bit higher than 1 hp.

Cost Efficiency Trade Off

In most designs, cost as well as efficiency is very important. This application note has attempted to provide a complete overview of the cost-efficiency tradeoff for the designer. Figures 15 and 16 present the summary of this exercise. Each set of bar graphs represent two different switching frequencies. On the X-axis are the various horsepowers, and on the Y-axis are the efficiencies that can be achieved with various implementations at those horsepowers. Each hp column has two sub bars. The left one represents the HEXFET solution and the right one represents the IGBT solution. As there are usually two or three die sizes being evaluated, these are represented by several horizontal lines with the smallest die size (lowest efficiency) circled. Each horizontal line has a number associated with it which represents the normalized cost associated with that implementation. For example, if a designer would like to see a comparison of devices at 1 hp and plans to use 20 kHz switching frequency, he would see that three HEXFET die sizes have been evaluated, (3, 4, 5) and two IGBTs (1, 2) have been evaluated. The lowest cost solution would be the IGBT 2 (with 1.57 per unit dollar cost) at about 95% efficiency. The IGBT 2 solution is less expensive than the IGBT 1 solution as the heatsink cost has boosted the system cost, tilting the tradeoff towards silicon rather than aluminum. This is true even for the FETs where the HEX-4 solution (at 2.41 per unit dollars) is more economical than a HEX-3 solution (at 5.81 per unit dollars).

Conclusions

There are two main conclusions resulting from this comparison analysis of insulated gate bipolar transistors versus power MOSFETs:

1. For most power conversion applications, there exists a tradeoff between silicon and aluminum i.e., a smaller die size could be used (with its higher losses and poorer thermal performance) coupled with a big heatsink *or* a larger die size could be used (leading to lower losses and better R_{thjc}) and a smaller heatsink. The choice depends upon the relative costs of the components, and any constraints on the size, weight, or cost of the final system. Often it is more cost effective to choose silicon rather than aluminum.

2. IGBTs tend to be more cost effective than MOSFETs in motor drive/UPS applications above 1 hp. This study has focused on inverters consisting of discrete components to arrive at the 1 hp crossover point. However, if all the power components were to be packaged together in a single module, the crossover point could, in fact, be at a lower power because a much smaller IGBT can do the job of a HEXFET power MOSFET. As the cost of a module significantly depends on its size, an IGBT module could be less expensive than a HEXFET module, thus driving the crossover point down. □

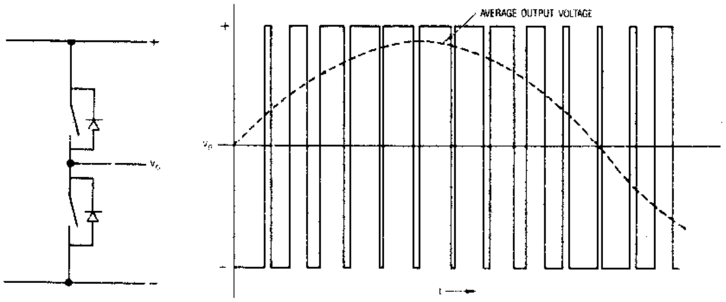


Figure 4a. Output voltage

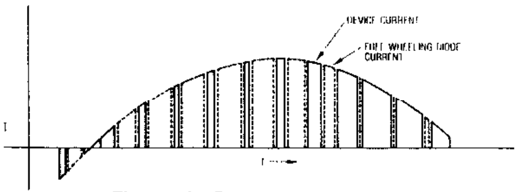


Figure 4b. Output current

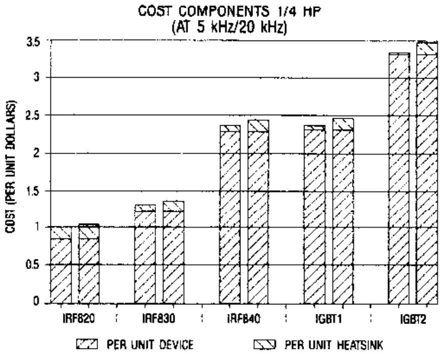


Figure 5a

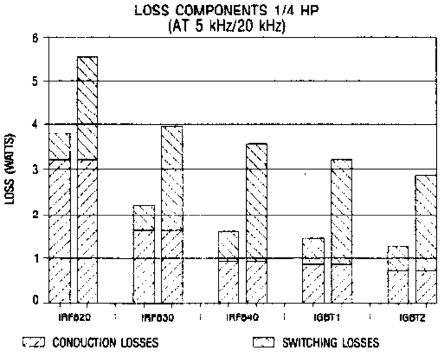


Figure 5b

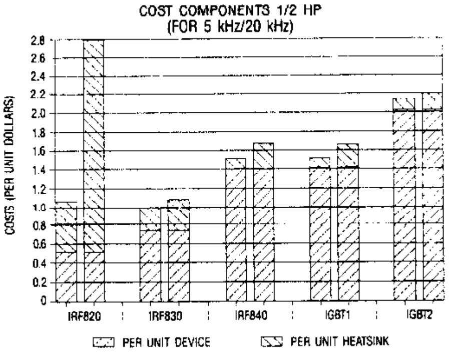


Figure 6a

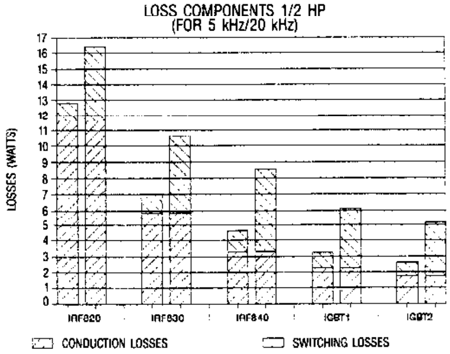


Figure 6b

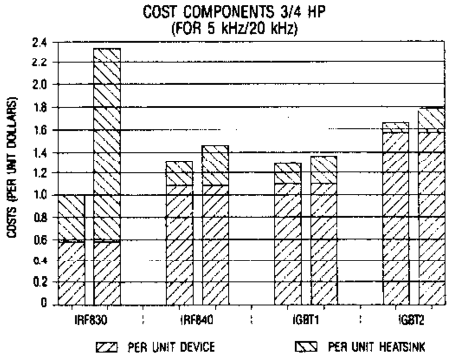


Figure 7a

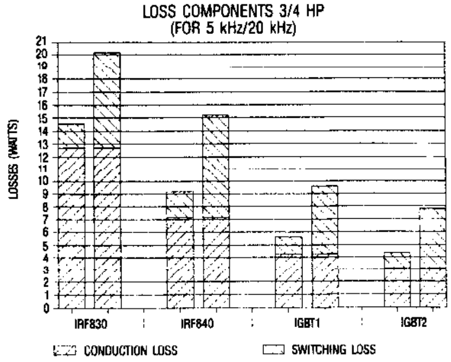


Figure 7b

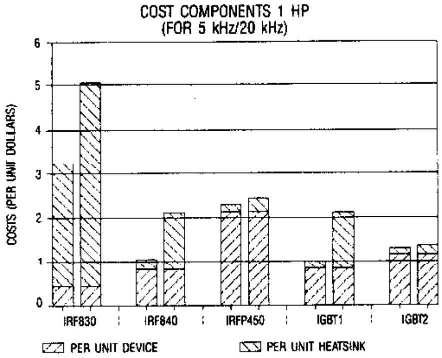


Figure 8a

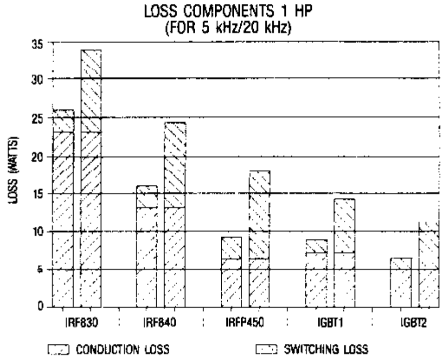


Figure 8b

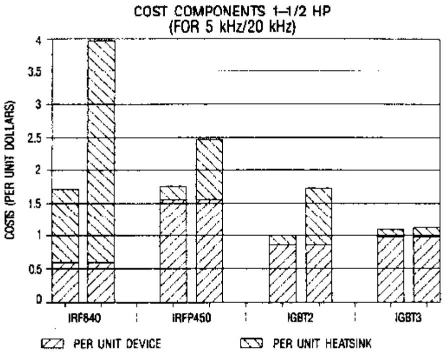


Figure 9a

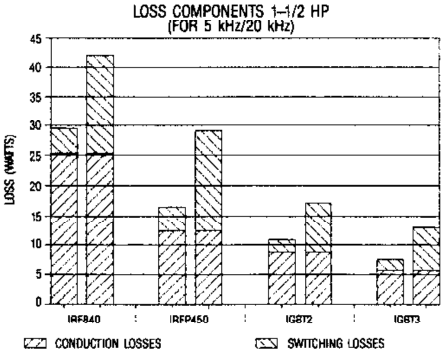


Figure 9b

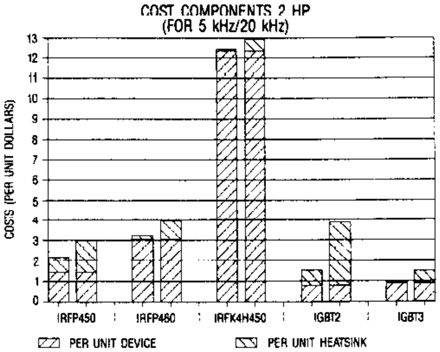


Figure 10a

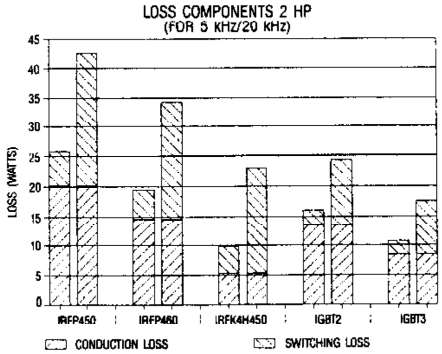


Figure 10b

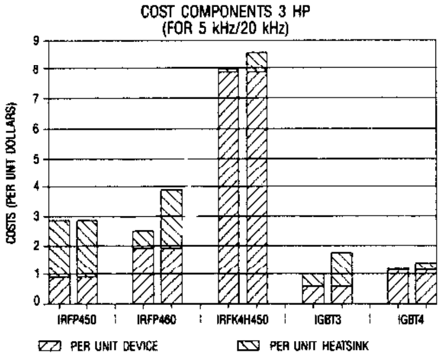


Figure 11a

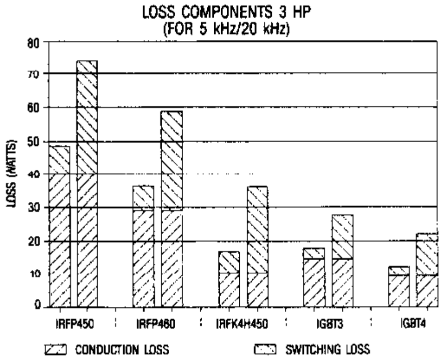


Figure 11b

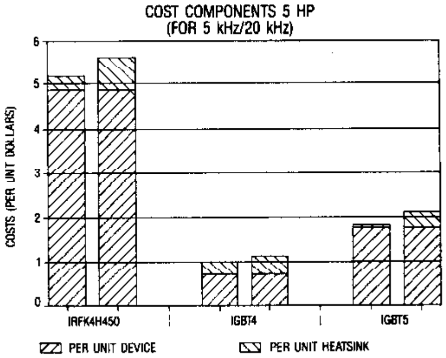


Figure 12a

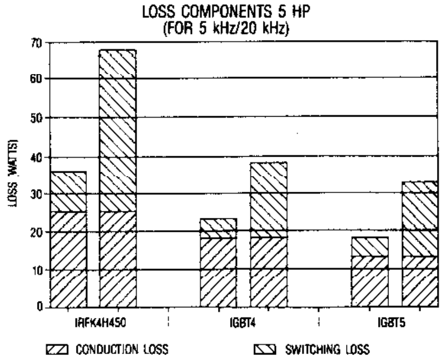


Figure 12b

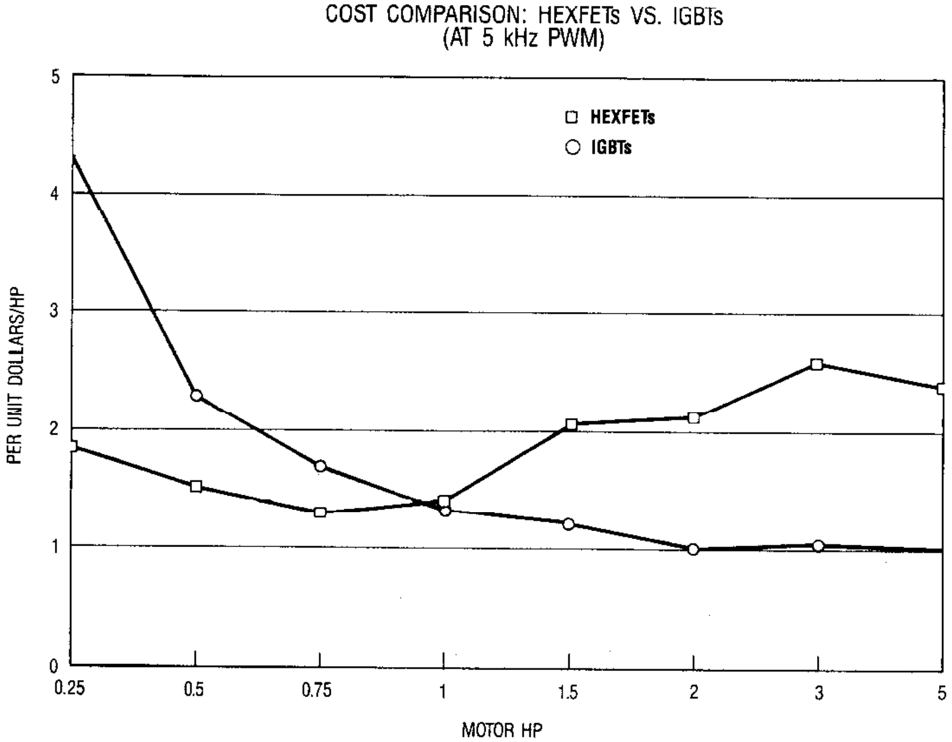


Figure 13

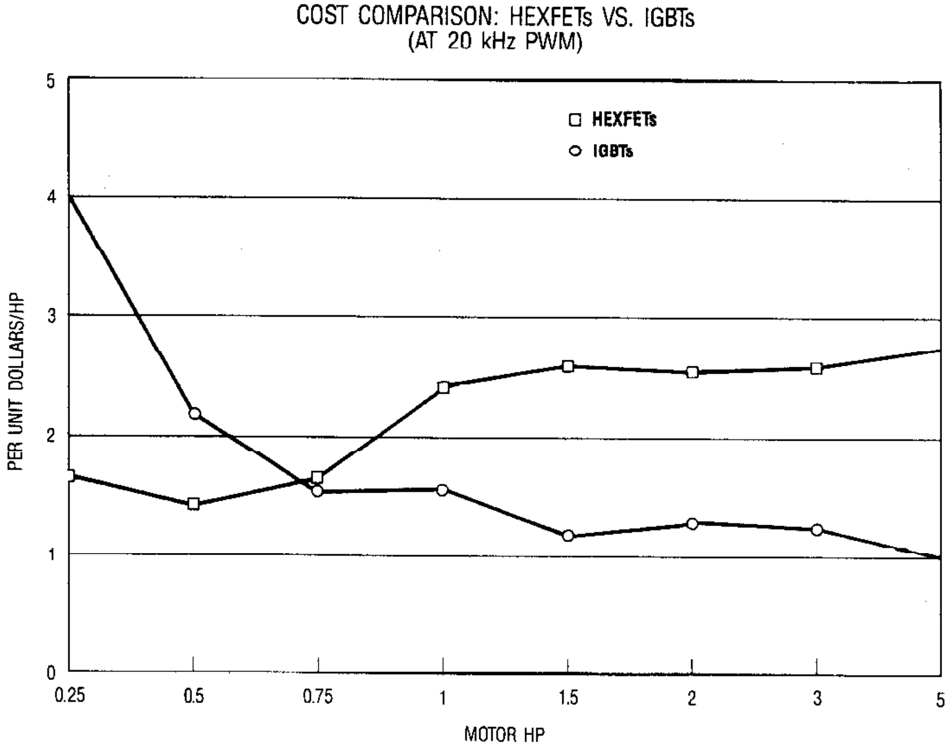


Figure 14

SYSTEM COST/EFFICIENCY TRADEOFF: HEXFETs AND IGBTs AT 5 kHz PWM

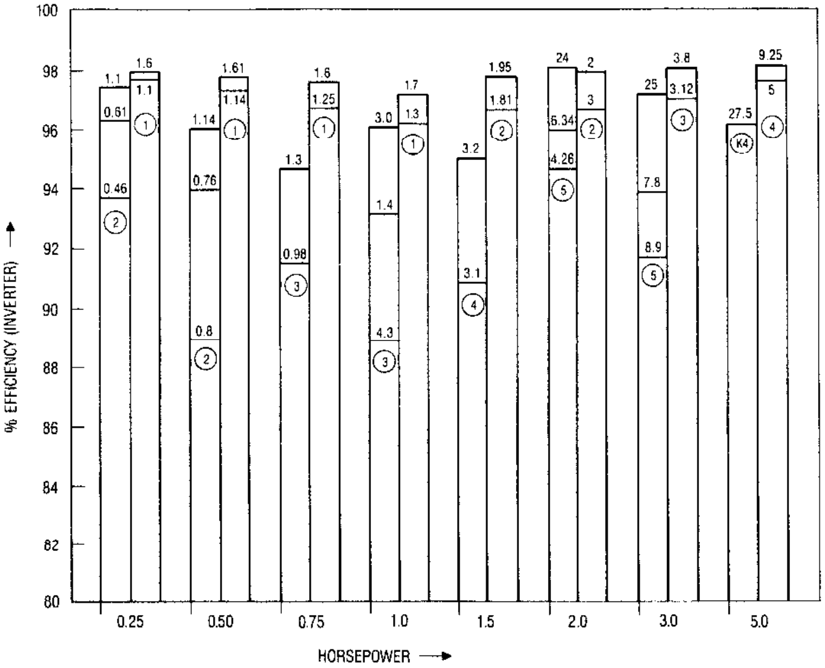


Figure 15

LEGEND (Figures 15 and 16)

1) Each pair of bars indicate HEXFET choices available (left bar) and IGBTs available (right bar) for a given inverter hp rating.

2) ② – Indicates smallest HEX die size evaluated. Subsequent bar extensions represent next die size (apprx. 2x larger). Die progression is ② ③ ④ ⑤ ⑥ (K4). For a detailed description of HEX die sizes, see Application Note AN-964.

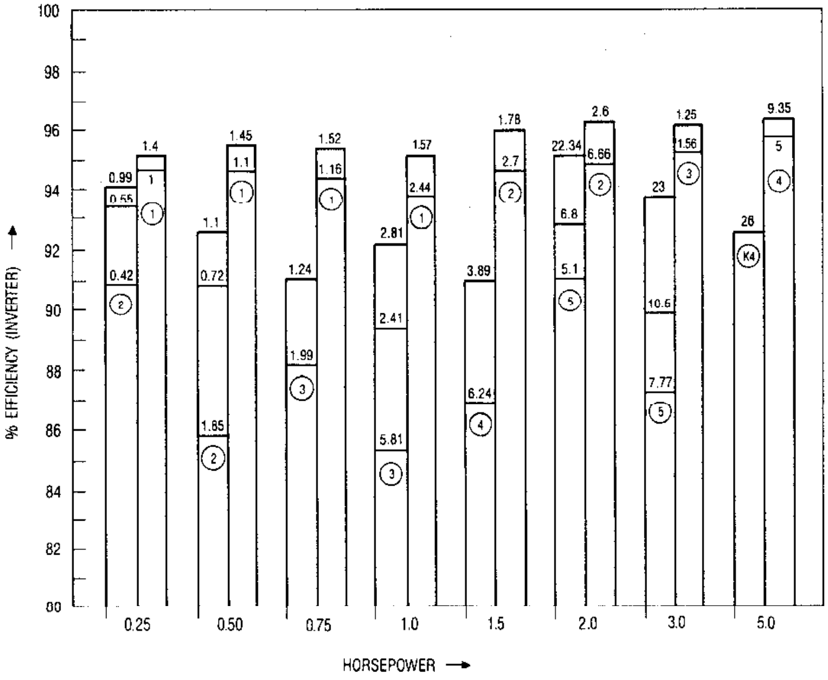
3) (K4) – HEXpak module containing four HEX-5 die in parallel.

4) ① ② ③ ④ – Indicates smallest IGBT die size evaluated.

5) Normalized per unit dollar cost (e.g., 1.45) is shown at each horizontal level.

6) See page 3 for further explanation.

SYSTEM COST/EFFICIENCY TRADEOFF: HEXFETs AND IGBTs AT 20 kHz PWM



See Legend above for explanation of bar symbols.

Figure 16