

# Minimum-Heating IDS120h Resistive Magnet Pulsed at 15 Hz

$$MW_{\text{avg}} \& V_{\text{max}} \text{ if } I_N = i_0 + \sum_{n \text{ odd}}^N i_n \sin[15n\pi t], N = 1, 3, 5, \dots, 11$$

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## Parameters:

Peak current, I = 12.58 kA  
 Peak power, P = 11.49 MW  
 Peak resistive voltage, V ≡ P/I = 913 volts  
 Resistance, R ≡ V/I = 72.6 mΩ  
 Magnetic energy, U = 4.10 MJ  
 Inductance, L ≡ 2 U/I<sup>2</sup> = 51.8 mHy  
 Time constant ≡ L/R = 0.71 seconds

See Table 1, cols. 2, 5, 8, 11, 14 & 17 for the harmonic components of current,  $i_n$  (N = 1, 3, 5, 7, 9, 11). For example,  $I_{N=5} = -3.12 + 8.06 \sin(15\pi t) - 2.76 \sin(45\pi t) + 4.88 \sin(75\pi t)$  [kA].

Table 1: Coefficients of current  $i_n \sin[15n\pi t]$  to minimize resistive heating in magnet IDS120h

	12.58 kA		11.49 MW		0.073 ohms		4.10 MJ		0.052 Hy		0.714 sec
$i_0$	-7.57		4.50		-3.12		2.36		-1.89		1.61
$i_1$	20.15		0.22		8.06		0.09		4.89		0.02
$i_3$			-7.86		-2.76		-4.10		-1.69		-2.77
$i_5$					4.88		2.50		2.97		1.67
$i_7$							-3.53		-2.15		-2.38
$i_9$									2.76		1.86
$i_{11}$											-2.27
Integral	4.799		2.716		1.865		1.415		1.138		0.951
Sum	4.800	4.87	2.717	5.82	1.865	8.33	1.415	10.94	1.138	13.58	0.951

I have computed the average resistive heating in the magnet,  $MW_{\text{avg}} = \frac{R}{\pi} \int_0^{\pi} I^2(x) dx$ , where  $x = 15t$ , both analytically and numerically (respectively the penultimate, "Integral," and bottom, "Sum," line of Table 1). When  $N = 5$ ,  $MW_{\text{avg}} = R \left[ \frac{2i_0^2 + i_3^2 + i_5^2}{2} + \frac{4i_0(i_1 + i_3/3 + i_5/5)}{\pi} \right]$ . Numerical integration to corroborate the analytic integration uses the trapezoid rule with 90 time intervals over the 1/15-second pulse length.

Fig. 1 plots the resistive heating  $R I^2(t)$  and voltage  $R I_N(t) + L \frac{dI_N(t)}{dt}$  as a function of time for  $N = 1$ ,  $N = 5$  and  $N = 11$ .

$R I^2(t)$  and  $V(t)$  of Minimum-Heating IDS120h Resistive Magnet Pulsed at 15 Hz to  $N^{\text{th}}$  Harmonic

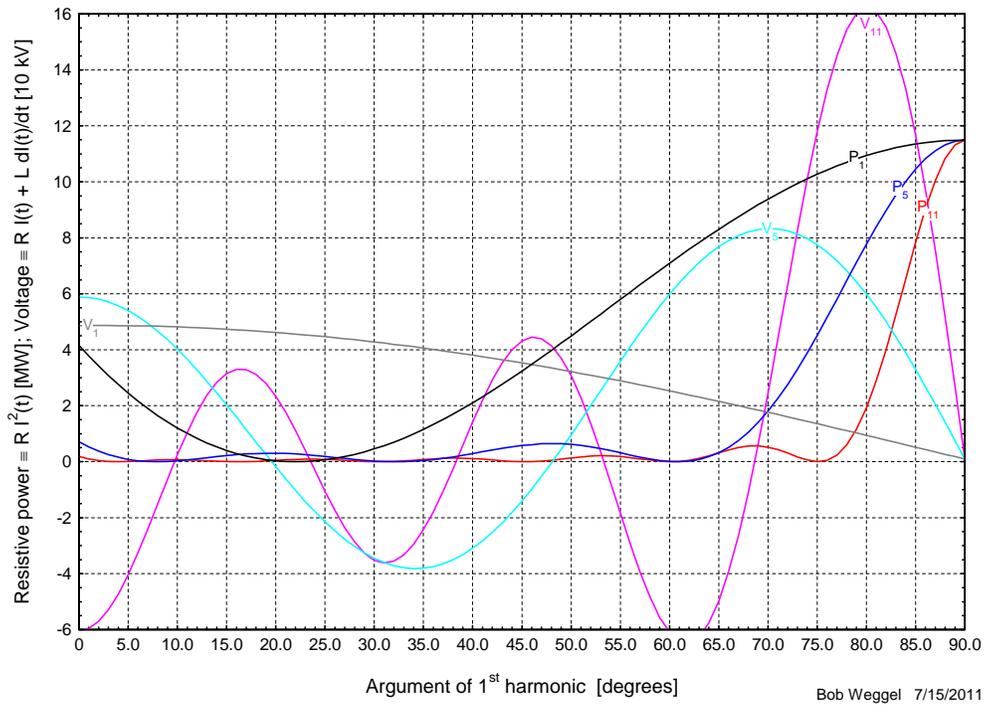


Fig. 1: Resistive heating  $R I^2(t)$  and voltage  $R I_N(t) + L \frac{dI_N(t)}{dt}$  as a function of time for  $N = 1, N = 5$  and  $N = 11$ .

Fig. 2 plots the average resistive power and peak voltage in the magnet.

Minimum-Heating IDS120h Magnet Pulsed at 15 Hz:  $MW_{\text{avg}}$  and  $V_{\text{max}}$  vs. Highest Harmonic

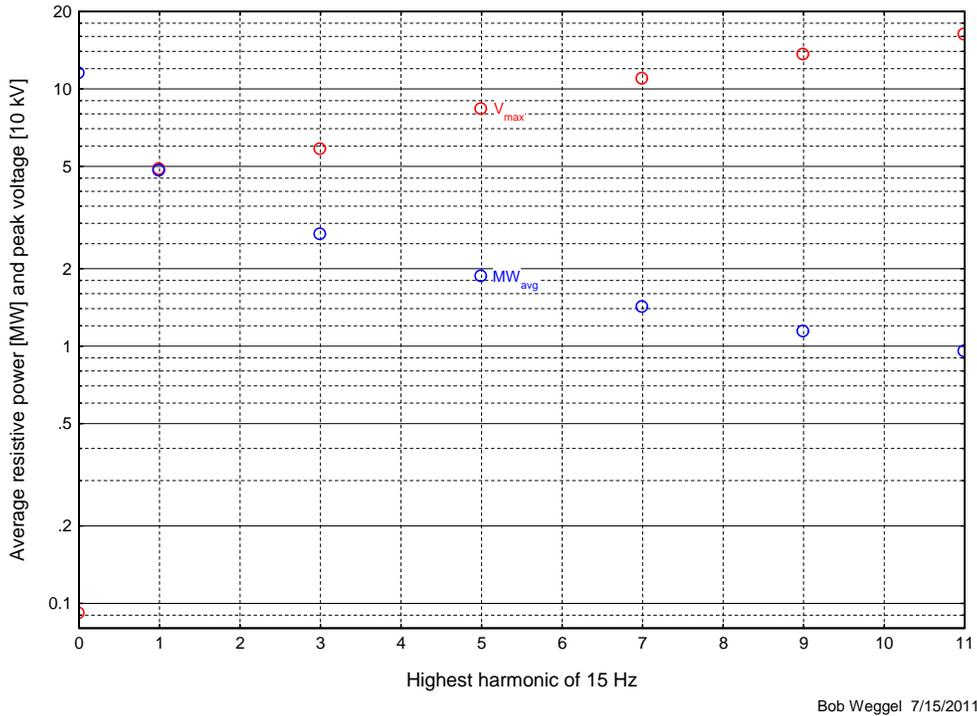
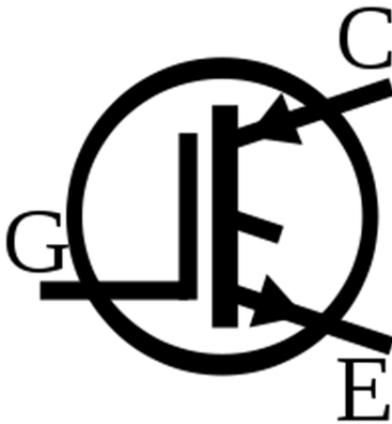


Fig. 2: Average resistive power and peak voltage in minimum-heating magnet IDS120h pulsed at 15 Hz.

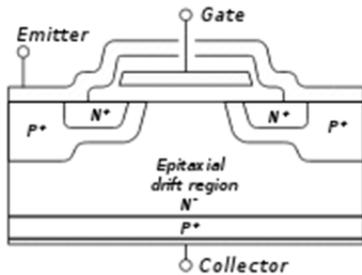
Pulsing the magnet with current that is the optimum combination of DC and a sinusoid of 15 Hz half cycle can reduce the average power from 11.5 MW to 4.8 MW, a factor of 2.4—but at the cost of a 53-fold increase in peak voltage: 913 volts to 48.7 kilovolts. Including harmonics through order 11 reduces the average power to 0.951 MW (a factor of 12), but requires a peak voltage of 162 kV (a factor of 177). Whether this trade-off is favorable awaits a reply from power-supply engineers at Dynapower, Inc., of Burlington, Vermont. The candidate technology is IGBT: insulated-gate bipolar transistor (see below).

### Insulated-gate bipolar transistor

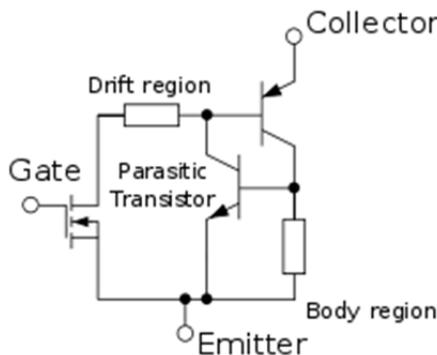
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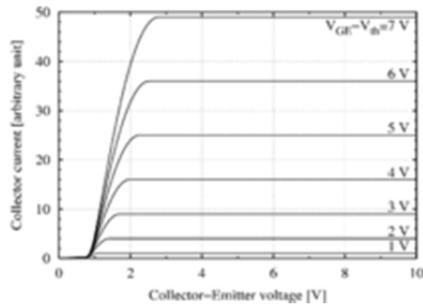
 [Electronic symbol](#) for IGBT



 Cross section of a typical IGBT cell. The illustration is not to scale.



 Equivalent circuit for IGBT



Static characteristic of an IGBT.

The **insulated gate bipolar transistor** or **IGBT** is a three-terminal [power semiconductor device](#), noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with [switching amplifiers](#). Since it is designed to turn on and off rapidly, [amplifiers](#) that use it often synthesize complex waveforms with [pulse width modulation](#) and [low-pass filters](#).

The IGBT combines the simple gate-drive characteristics of the [MOSFETs](#) with the high-current and low-saturation-voltage capability of [bipolar transistors](#) by combining an isolated gate [FET](#) for the control input, and a bipolar power [transistor](#) as a switch, in a single device. The IGBT is used in medium- to high-power applications such as [switched-mode power supply](#), [traction motor](#) control and [induction heating](#). Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of [amperes](#) with blocking voltages of 6000 [V](#), equating to hundreds of [kilowatts](#).

The IGBT is a fairly recent invention. The first-generation devices of the 1980s and early 1990s were relatively slow in switching, and prone to failure through such modes as [latchup](#) (in which the device won't turn off as long as current is flowing) and [secondary breakdown](#) (in which a localized hotspot in the device goes into thermal runaway and burns the device out at high currents). Second-generation devices were much improved, and the current third-generation ones are even better, with speed rivaling MOSFETs, and excellent ruggedness and tolerance of overloads.<sup>[1]</sup>

The extremely high pulse ratings of second- and third-generation devices also make them useful for generating large power pulses in areas like [particle](#) and [plasma physics](#), where they are starting to supersede older devices like [thyratrons](#) and [triggered spark gaps](#).

Their high pulse ratings, and low prices on the surplus market, also make them attractive to the high-voltage hobbyist for controlling large amounts of power to drive devices such as solid-state [Tesla coils](#) and [coilguns](#).

Availability of affordable, reliable IGBTs is an important enabler for [electric vehicles](#) and [hybrid cars](#).

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## History

The IGBT is a semiconductor device with four alternating layers (P-N-P-N) that are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action. This mode of operation was first proposed by Yamagami in his Japanese patent S47-21739, which was filed in 1968.<sup>[2]</sup> This mode of operation was first experimentally discovered by [B. Jayant Baliga](#) in vertical device structures with a V-groove gate region and reported in the literature in 1979.<sup>[3]</sup> The device structure was referred to as a 'V-groove MOSFET device with the drain region replaced by a p-type Anode Region' in this paper and subsequently as the insulated gate rectifier (IGR),<sup>[4]</sup> the insulated-gate transistor (IGT),<sup>[5]</sup> the conductivity-modulated field-effect transistor (COMFET)<sup>[6]</sup> and "bipolar-mode MOSFET".<sup>[7]</sup>

Plummer found the same IGBT mode of operation in the four layer device (SCR) and he first filed a patent application for the device structure in 1978. USP No.4199774 was issued in 1980 and B1 Re33209<sup>[8]</sup> was reissued in 1995 for the IGBT mode operation in the four layer device (SCR).

Hans W. Becke and Carl F. Wheatley invented a similar device for which they filed a patent application in 1980, and which they referred to as "power MOSFET with an anode region".<sup>[9]</sup> This patent has been called "the seminal patent of the Insulated Gate Bipolar Transistor."<sup>[10]</sup> The patent claimed "no thyristor action occurs under any device operating conditions." This substantially means that the device exhibits non-latch-up IGBT operation over the entire device operation range.

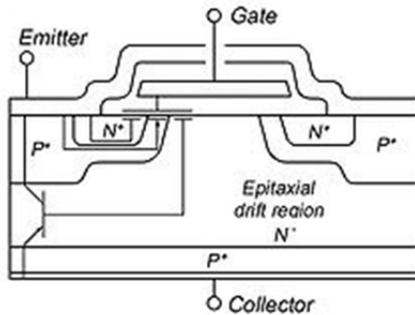
Devices capable of operating over an extended current range for use in applications were first reported by Baliga *et al.* in 1982.<sup>[4]</sup> A similar paper was also submitted by J.P. Russel *et al.* to IEEE Electron Device Letter in 1982.<sup>[11]</sup> The applications for the device were initially regarded by the power electronics community to be severely restricted by its slow switching speed and latch-up of the parasitic thyristor structure inherent within the device. However, it was demonstrated by Baliga and also by A.M. Goodman *et al.* in 1983 that the switching speed could be adjusted over a broad range by using electron irradiation.<sup>[5][12]</sup> This was followed by demonstration of operation of the device at elevated temperatures by Baliga in 1985.<sup>[13]</sup> Successful efforts to suppress the latch-up of the parasitic thyristor and the scaling of the voltage rating of the devices at GE allowed the introduction of commercial devices in 1983,<sup>[14]</sup> which could be utilized for a wide variety of applications.

Complete suppression of the parasitic thyristor action and the resultant non-latch-up IGBT operation for the entire device operation range was achieved by A. Nakagawa *et al.* in 1984.<sup>[15]</sup> The non-latch-up design concept was filed for US patents.<sup>[16]</sup> To test the lack of latchup, the prototype 1200V IGBTs were directly connected without any loads across a 600V constant voltage source and were switched on for 25 microseconds. The entire 600V was dropped across the device and a large short circuit current flowed. The devices successfully withstood this severe condition. This was the first demonstration of so-called "short-circuit-withstanding-capability" in IGBTs. Non-latch-up IGBT operation was ensured, for the first time, for the entire device operation range.<sup>[17]</sup> In this sense, the non-latch-up IGBT proposed by Hans W. Becke and Carl F. Wheatley was realized by A. Nakagawa *et al.* in 1984. Products of non-latch-up IGBTs were first commercialized by Toshiba in 1985.

Once the non-latch-up capability was achieved in IGBTs, it was found that IGBTs exhibited very rugged and a very large [safe operating area](#). It was demonstrated that the product of the operating current density and the collector voltage exceeded the theoretical limit of bipolar transistors,  $2 \times 10^5 \text{ W/cm}^2$ , and reached  $5 \times 10^5 \text{ W/cm}^2$ .<sup>[10][17]</sup>

## Device structure

An IGBT cell is constructed similarly to a n-channel vertical construction [power MOSFET](#) except the n+ drain is replaced with a p+ collector layer, thus forming a vertical PNP [bipolar junction transistor](#).



Cross section of a typical IGBT showing internal connection of MOSFET and Bipolar Device

This additional p+ region creates a cascade connection of a PNP bipolar junction transistor with the surface n-channel [MOSFET](#).

### Comparison With Power MOSFETS

An IGBT has a significantly lower forward voltage drop compared to a conventional MOSFET in higher blocking voltage rated devices. As the blocking voltage rating of both MOSFET and IGBT devices increases, the depth of the n- drift region must increase and the doping must decrease, resulting in roughly square relationship increase in forward conduction loss compared to blocking voltage capability of the device. By injecting minority carriers (holes) from the collector p+ region into the n- drift region during forward conduction, the resistance of the n- drift region is considerably reduced. However, this resultant reduction in on-state forward voltage comes with several penalties:

- The additional PN junction blocks reverse current flow. This means that unlike a MOSFET, IGBTs cannot conduct in the reverse direction. In bridge circuits where reverse current flow is needed an additional diode (called a [freewheeling diode](#)) is placed in parallel with the IGBT to conduct current in the opposite direction. The penalty isn't as severe as first assumed though, because at the higher voltages where IGBT usage dominates, discrete diodes are of significantly higher performance than the body diode of a MOSFET.
- The reverse bias rating of the N- drift region to collector P+ diode is usually only of tens of volts, so if the circuit application applies a reverse voltage to the IGBT, an additional series diode must be used.
- The minority carriers injected into the n- drift region take time to enter and exit or recombine at turn on and turn off. This results in longer switching time and hence higher switching loss compared to a power MOSFET.
- The on-state forward voltage drop in IGBTs behaves very differently to that in power MOSFETS. The MOSFET voltage drop can be modeled as a resistance, with the voltage drop proportional to current. By contrast, IGBT has a diode like voltage drop (typically of the order of 2V) increasing only with the [log](#) of the current. Additionally, MOSFET resistance is typically lower for smaller blocking voltages meaning that the choice between IGBTs and power MOSFETS depend on both the blocking voltage and current involved in a particular application, as well as the different switching characteristics mentioned above.

In general high voltage, high current and low switching frequencies favor IGBTs while low voltage, low current and high switching frequencies are the domain of the MOSFET.

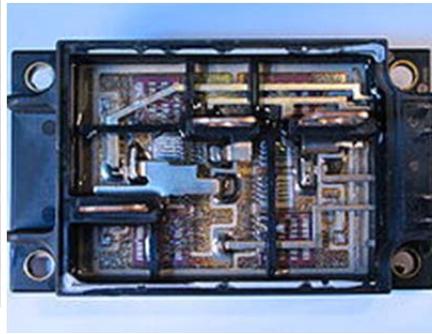
### IGBT models

Rather than using a [device physics](#)-based model, [SPICE](#) simulates IGBTs using Macromodels, a method that combines an ensemble of components such as [FETs](#) and [BJTs](#) in a [Darlington configuration](#).<sup>[[citation needed](#)]</sup> An alternative physics-based model is the Hefner model, introduced by Allen Hefner of the [NIST](#). It is a fairly complex model that has shown very good results. Hefner's model is described in a 1988 paper and was later extended to a thermo-electrical model and a version using [SABER](#).<sup>[[18](#)]</sup>

### Usage



IGBT-Module (IGBTs and free wheeling diodes) with a rated current of 1,200 A and a maximum voltage of 3,300 V



Opened IGBT module with four IGBTs (half [H-bridge](#)) each rated for 400 A 600 V



Small IGBT module, rated up to 30 A, up to 900 V

- [Bipolar junction transistor](#)
- [Bootstrapping](#)
- [FGMOS](#)
- [Power electronics](#)
- [Power MOSFET](#)
- [Solar inverter](#)
- [Variable-frequency drive](#)

## References

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