A DC CIRCUIT BREAKER FOR AN ELECTRIC VEHICLE BATTERY PACK

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Abstract

Electric vehicle battery packs require DC circuit breakers for safety. These must break thousands of Amps DC at hundreds of Volts. The Sunshark solar racing car has a 140V 17Ahr battery box which needs such a breaker. A static design using 200V MOSFETs to interrupt the fault current is presented. The design specification, decisions and proposed solution circuit are given. The current sensing technique, MOSFET overvoltage protection, and DC bus capacitor precharging scheme are specific focuses. Simulation results are presented and discussed.

1 MECHANICAL OR SEMICONDUCTOR?

1.1 The application

Electric vehicles and Hybrid electric vehicles currently rely on a series string of batteries to provide their motive power and peak power respectively. These battery strings typically have potentials between 72 and 288 Volts, and are capable of supplying hundreds of Amps for several seconds. With internal impedances in the milliOhms, fault currents can be over one thousand Amps.

Our specific application was for the Sunshark solar car's battery box. The Sunshark's battery box is a sealed carbon-fibre box containing ten series connected 12V 17Ah sealed lead acid batteries. The batteries have an extremely low internal impedance (0.007 Ohm quoted) and are capable of over 1000A short circuit current. It was desired to place some form of circuit breaker protection within the battery box, since the battery box is disconnected from the car electronics regularly, leaving two shrouded but none-the-less accessible contacts.

The nominal operating current of the batteries in a solar car should actually be zero. All the power from the 1000 to 1500W of solar cells should flow directly to the motor. However, for hill climbing, overtaking, and sprints to the finish line, a peak current determined by the motor and motor controller may be drawn from the batteries. For the Sunshark, a peak continuous current rating of 50A was chosen, allowing a peak power draw of approximately 7kW with fully charged batteries. The fully charged voltage of the string of ten lead-acid batteries would be about 140V.

1.2 Commercial circuit breakers for DC

Most circuit breakers designed for interrupting large fault currents are designed for the 50Hz AC power network. The presence of current zero crossings greatly eases the circuit breaker's task by naturally extinguishing the arc which forms when the contacts of the circuit breaker open under load. The inductance of the fault circuit also limits the fault current.

In a DC circuit, the circuit's inductance in the fault condition can only limit the initial rate of rise of the fault current, but not its final value. Further more, no natural current zero crossings exist to extinguish the arc at the opening circuit breaker contacts. The current can only be driven to zero, and the circuit opened, by forcing the arc voltage to exceed the DC source voltage.

Circuit breakers and contactors specifically designed to break DC are available commercially. A number of schemes often used in combination act to increase the arc voltage. The first method is to use arc chutes, which force the arc to take a convoluted path, and also cool or quench it. In another technique, “magnetic blowout”, the arc traverses a magnetic field. This imposes a force perpendicular to the path of the arc, “blowing” it sideways, and stretching it. The third technique is to form the arc in a vacuum or hydrogen, or other atmosphere which does not favour arcing [6].

Kilovac are manufacturers of specialist relays including high voltage and high current DC relays. As an example, their “Czonka II EVX” contactor is rated at 320Vdc, 400A. To operate as a circuit breaker, some extra overload detection circuitry would be required to control the contactor coil.

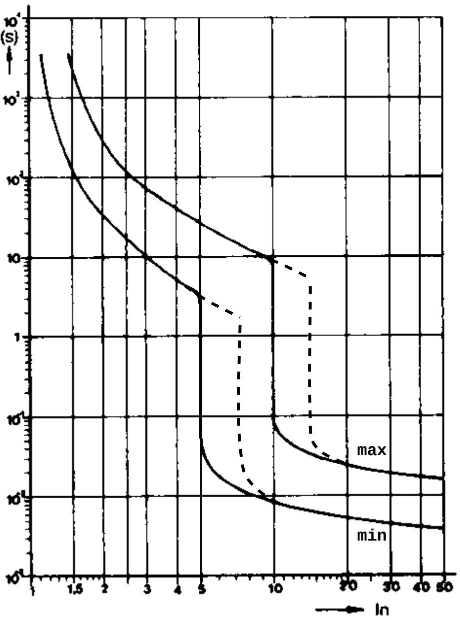

Figure 1: The time current curves for the Terasaki Din T10 circuit breaker. The variation in response time for DC operation is shown dotted.

Some AC circuit breakers are rated to break DC at a considerably derated (lower) voltage. This voltage rating may be sufficient for some lower pack voltages. When multiple poles of a multipole breaker are placed in series, a higher DC rating may be allowed. A higher conduction (contact) loss will result, however this is usually small.

For example, of the 240/415Vac Din-T range of circuit breakers manufactured by Terasaki, the T6, T10 and T15 (6kA, 10kA and 15kA interruption capability) series only have a 48Vdc rating, and 110Vdc for two series connected poles. The Din-T10H range is rated for 125Vdc for two poles, and 250Vdc for four poles, which is sufficient for this application.

The thermal trip curves of the circuit breaker define the trip time as a function of the overload current (see Fig. 1). Since these are based on RMS currents, they remain the same for DC operation. At twice the rated trip current, the Din-T10 series may take anywhere between 30 and 300 seconds to trip. The Din-10H would take between 1 and 60 seconds. Since they are designed to limit thermal overloads, the trip time reduces approximately exponentially with increasing current up to the magnetic trip point.

At the magnetic trip point, the current in the breaker is sufficient to unlatch the breaker contacts, via an magnetic coil. This magnetic trip is designed to occur at 5 to 10 times the rated trip current (IEC C curve). It is rapid, taking only 10 to 100ms to trip the breaker. Since it is caused by a magnetic event, the magnetic trip current for DC current flow is 1.4 times the AC trip rating.

The delay in acting inherent in a thermal breaker's operation is useful for protecting loads such as AC transformer and motor circuits which may draw large surge currents for a short period at turn on. For faults, the magnetic trip rapidly opens the breaker.

In a specific application such as the Sunshark, the maximum current drawn is well defined and controlled by the power electronics. Any current which exceeds this can be immediately identified as abnormal, and should cause a rapid trip of the breaker. For example, any current greater than 75A (150% of 50A) should cause an immediate trip. In a conventional breaker, this would take at least two minutes to trip, and perhaps as long as 30 minutes.

To cause a trip to occur in milliseconds rather than seconds requires a fault current of between 350 and 700 Amps for a DC circuit to activate the magnetic trip. Since the inductances are small, in the several milliseconds it takes the breaker to open, the currents can rise to extremely high values limited only by the circuits impedances. Although undesirable, extra inductance could be introduced into the circuit to limit the rate of rise of fault current. However, either way, the energy stored in the circuit's inductances becomes very significant, since $W = \frac{1}{2}\, I^2 L$.

The power loss in a circuit breaker is small, being 4.5W per pole at 50A. To afford protection to a 50A * 140V = 7000W power flow, a 20W (0.28%) power loss would be considered acceptable.

1.3 Static (semiconductor) DC circuit breakers

An alternative to the mechanical circuit breaker is to use an semiconductor switch to interrupt the DC fault current. A semiconductor switch additionally has the capability of being remotely switched both on and off, in a manner similar to a contactor rather than providing just the fault protection properties of a circuit breaker.

This switching cannot be considered to provide isolation in the same manner as a set of open mechanical contacts. If total galvanic isolation is required for safety reasons, a mechanical isolation switch can be installed in series with the semiconductor breaker.

It would appear advantageous to have a contactor arranged to bypass the semiconductor switch under normal operation to achieve low conduction losses. Switch sequencing would ensure that this mechanical breaker does not interrupt the current (ZVS). However, the operation time of the mechanical contactor is still measured in milliseconds. During this time the fault current will ramp quickly to many times its detection level, unless additional inductance is inserted into the circuit.

In this application, the semiconductor switch alone is a better solution. At the power levels considered in this circuit, power loss is manageable. Moreover, as discussed earlier, the desired power flow in the battery pack is zero in this solarcar application.

The semiconductor switch can limit current as it closes. This “precharge” phase in important for limiting the inrush current into the large filter capacitors in the vehicle’s inverters.

2 PREVIOUS WORK

Two papers specifically discussing DC circuit breakers were examined. The first used a forced commutated thyristor circuit, and had a 1000V, 4000A rating[1]. Its voltage and current ratings were much higher than the Sunshark application required.

A MOS Controlled Thyristor (MCT) was used for a 300V 75A “Self protecting contactor” [2]. The 600V device had a low voltage drop, and was easily controlled.

Thyristors are not a good choice for this lower voltage work, where MOSFETs an offer lower conduction losses, especially at lower currents. At high voltages, IGBTs may be suitable.

In both these papers, the contactor or breaker was required to deal with source inductance as well as load inductance. Interrupting the current causes the voltage at the breaker output contacts to fall towards zero. The energy stored in the inductance of the load circuit can be dissipated in load by commutating it to a freewheeling diode as the output voltage attempts to go negative. Both papers take this approach, as does this design.

Interrupting the source current causes the voltage across the breaker input to rise. This input overvoltage must be limited to the rating of the semiconductor switches in a static breaker. There are a number of alternatives for absorbing or dissipating this energy including RC or RCD snubbers, metal-oxide varistors (MOVs), and the series combination of MOVs and spark gaps [1, 6]. If the source inductance is accessible, active devices can short circuit it as the breaker opens [1]. Another alternative is to operate semiconductor switches in their active region to provide well defined over-voltage clamping [2]. Using these techniques, the clamping voltage is usually chosen to be between 1.5 and 2 times the DC supply voltage, which is a compromise between semiconductor breakdown voltages and the energy dissipated in the energy absorption components [2].

In this application, the inductance inserted on the load side of the breaker is used to set the acceptable rate of rise of fault current. The breaker is located at the source (in the battery box itself) and so the source inductance can be reduced to a very low value, which greatly reduces the energy which must be dissipated. It also means that capacitors placed at the switches along with source resistance is enough to reduce the overvoltage to less than 33% of the DC supply voltage.

In high voltage high current applications such as the 1000V 4000A breaker developed for the 700V track feeder circuit of a mass-rapid-transit system [1], thyristors with forced capacitor commutation was appropriate. A 600V 75A MCT (MOS controlled thyristor) was also chosen for its low conduction losses for a 300V DC breaker, with a parallel IGBT to both assist in commutation of the MCT and to perform active clamping [2].

MOSFETs will offer the lowest conduction losses for the Sunshark’s battery voltage of 150V maximum. This is particularly true when the devices are operating well below their current rating for significant periods of time. Avalanche rated devices with a 200V rating were used for the brushless DC motor inverter, and it was hoped they could be used again here. As explained, it is shown that the overvoltage can be kept below this breakdown voltage.

The fast turn off of MOSFETs is also advantageous, since it means the fault current can be commutated rapidly to the flyback diode. This will minimise the switch power dissipation during this period.

3 BATTERY BOX BREAKER DESIGN

3.1 Design Specification

To assist in the understanding of the design decisions made, the following design brief is quoted here.

The design specifications called for a loss of less than 2W at 10A, and 50W at the maximum rated current of 50A. The breaker should disconnect the source from the load in less than 1ms when the load current exceeds 60A. The maximum source voltage is 150Vdc.

To permit battery charging, the breaker should pass current in both directions with low loss. However, the overcurrent trip function is not required to operate when the batteries are being charged, as this source can be assumed to have its own overcurrent protection, or be by nature current limited (as is the solar array).

This breaker cannot provide isolation. If isolation is considered necessary, a separate mechanical isolation switch will be placed in series with the breaker. The breaker will only disconnect one terminal of the battery string, that is the breaker will be single pole. This is sufficient since the breaker is internal to the sealed, insulated battery box.

It would be advantageous if the breaker could also perform the function of a contactor, allowing the battery string to be disconnected electronically from the vehicle electrics. The breaker will also need to be able to be reset or reclosed after being tripped off. An extra set of “coil” contacts will need to be brought out of the sealed battery box. These should preferably be isolated from the batteries, or at least high impedance low voltage connections.

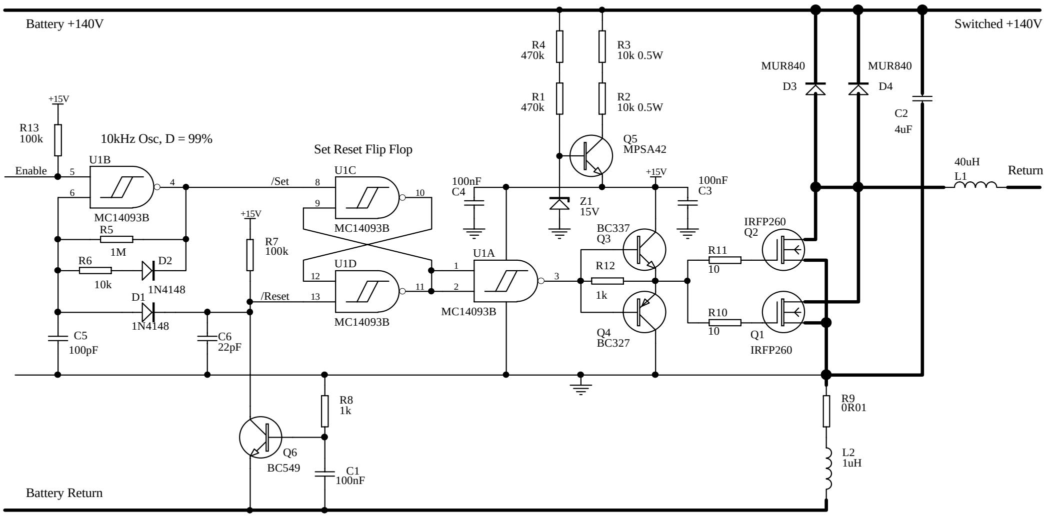

Figure 2: The circuit diagram of the DC circuit breaker.

The motor drive and other power supplies have significant filter capacitance on their DC input supplies. This capacitance will require precharging at a current limited rate, before the contactor can be closed. Either a separate precharging circuit, or the breaker itself will need to perform this bus capacitor precharging.

The breaker circuitry should draw insignificant quiescent current, since it may be left connected to the batteries for long periods. An absolute maximum power consumption of one Watt is initially proposed.

3.2 High current design

The circuit diagram of the DC breaker is shown in Fig. 2.

To better 2W at 10A, the internal on resistance of the contactor must be less than 20mΩ. The IRFP260 200V N-ch MOSFETs used in the motor drive (three in parallel for each switch) have an on resistance of 55mΩ (at 25°C). Four of these in parallel would allow a small margin for a sense resistor and connection losses. The simulations and design here is shown with two of these MOSFETs. Since the MOSFETs are N-ch devices, they are placed in the negative or return path to ease their drive requirements.

The flywheel diodes will usually carry no current, but under a fault condition, carry the fault current until it falls to zero. With a loop voltage drop of two volts (possible with a output short circuit) and a 40μH current limiting output inductor, it only takes 1ms for a 50A load current to fall to zero. Two MUR840 400V 8A fast recovery diodes are shown here. Their single halfwave sinewave pulse rating (10ms) of 100A make them quite adequate for this duty.

3.3 Current sensing

A number of methods could be used to sense the load current, and detect an overcurrent condition. The accuracy of the current measurement is not particularly critical, but the speed of detection is fairly important. A small inductor is used to limit the rate of rise of fault current. With the 40μH inductor shown, and a 150V source and a short circuit load fault, the current can rise 20A (50A to 70A) in approximately 5μs. This is considered sufficient time to sense the fault and commutate the current from the MOSFETs to the flywheel diodes.

Current transformers are immediately unsuitable since the load current is DC. Hall effect current transducers could be used, however these have significant quiescent power consumption and do not have the required bandwidth for rapid fault detection.

A resistive shunt is the simplest solution, and consumes no quiescent power. However, it does incur significant power losses at high load currents, unless the shunt is made very small, which then hinders noise free current measurement. The value chosen of 10mΩ has a voltage drop of 700mV at the 70A, which allows a transistor to set the trip point, and detect the overcurrent.

Rather than try to completely eliminate the parasitic inductance of the sense resistor, it has been assigned a small but significant value. During periods of rapid current increase (such as during a fault condition), it increases the voltage across the sense impedance. By matching the time constant of the RL shunt impedance with an RC filter before the sensing transistor, the actual value of the current is again measured, but with better noise immunity. The RL shunt has 10mΩ of resistance, and 100nH of inductance, and will be formed from an air-cored loop or coil of “Eureka” resistance wire.

A similar technique was suggested for current sensing for short circuit protection of IGBTs [3]. Rather than rely only on IGBT collector voltage for collector current estimation, the voltage across the connecting wire inductance of an IGBT pack was integrated, as seen across the packs power and kelvin emitter terminals.

Sensing the voltage drop across the MOSFETs themselves is attractive. No additional shunt is required, and so conduction power loss is minimised. In the MOSFETs linear region (akin to the BJTs saturation region), the MOSFET does behave as a resistor for a constant gate source voltage. However, this on resistance R$_{on}$ is not well defined from device to device, so would require calibration after construction, or whenever the MOSFETs were replaced. The on resistance is also very temperature dependent and would require temperature compensation. For the IRFP260, the on resistance doubles as the die temperature rises from 25°C to 125°C.

The final difficulty is that the current can only be sensed while the MOSFET is in its linear region. During the turn on and turn off transients, no meaningful measurement of drain current can be inferred.

For these reasons, the much simpler compromise of a separate shunt resistor was chosen.

3.4 Control Electronics

The control electronics is based around a set-reset flip flop constructed from 4000 series CMOS schmitt input NAND gates. The reset pulse is delivered by the overcurrent sensing transistor and pull up resistor, with a capacitor to stretch the pulse. The active low flip-flip output is inverted, and drives a pair of emitter followers which control the gate.

In this initial design, a 10kHz oscillator delivers a regular 1μs active low set pulse. When enabled, it will continually reset the breaker should it trip and so the breaker actually operates more as a current limiter. By operating at a low frequency, the output current becomes discontinuous and the average fault current can be made small — a kind of foldback current limiting. The frequency chosen allows the breaker to precharge the distributed 140V bus capacitance with an initial average current of approximately 30A (see Fig. 4).

The enable for this oscillator can be taken external to the box using high impedance connections to avoid any shock hazard. However, some protection and filtering of the input would be required, but is not shown in this initial schematic. Since the flip-flip is reset dominant, an alternative method of control would be to place a single switch in parallel with the overcurrent reset transistor (the /reset node). Again since the pull-up is 100kΩ, these connections could be high impedance and diode clamped to limit any fault current which might flow in them. A totally isolated solution could be arranged with an optocoupler, but this requires an external source of power to supply the optocoupler LED on the initial power-up.

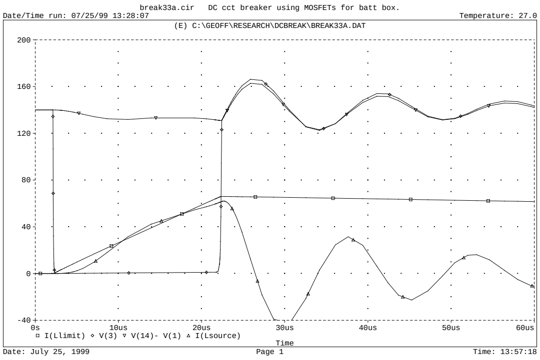

Figure 3: The PSpice simulation of the breaker turning on into a short circuit fault, and subsequently tripping off. Shown are the MOSFET drain voltage V(3), the battery voltage V(14)-V(1), the output current I(Llimit) and source current I(Lsource).

The control electronics power is supplied by a very crude series regulator (an emitter follower) with a zener diode shunt regulator as a reference. When the circuit is in its quiescent state (either off or on), the transistor wont even be biased on. In this state, the quiescent current draw is under 150μA, or about 20mW.

4 SPICE SIMULATION

An estimation of the source inductance of the battery box was required to choose an appropriate snubbing capacitance. Based on a single turn circular loop of wire (admittedly only 28SWG), Ian Hickman offers the rule of thumb of 1nH per millimeter circumferential length [4].

More formally, the inductance per meter of a two wire transmission line is

$$L = 4 \times 10^{-7} \ \ln \frac{D}{0.78\, r} \qquad \mathrm{H/m}$$

where D is the separation of the conductors and r is the conductor radius [5]. If we estimate the path of the conductors in the battery box to be 0.5m in length, separated by 0.5m, with radius of 5mm, then the inductance $L = 0.97\mu$H.

Using a value of 100mΩ + 1μH for the 140V battery string impedance and a 4.4μF capacitor snubber across the MOSFETs led to a MOSFET peak voltage of 165V when breaking a 66A load current. Other simulations showed that for any value up to 20μH of source inductance and a 10μF snubber capacitor, the voltage across the MOSFETs remained below 200V.

Figure 3 shows a PSpice simulation of the breaker turning on (at 2μs) into the discharged DC bus capacitance — essentially a short circuit fault. The MOSFET drain

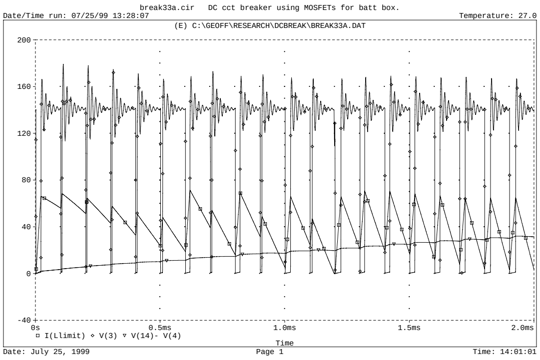

Figure 4: By reclosing the breaker at a 10kHz rate, the DC bus capacitance is slowly charged from 0V. Shown are the load current I(Llimit), the MOSFET drain source voltage V(3), and the output voltage V(14)-V(4).

voltage falls from the battery voltage of 140V to 0V. The output current and source current rise linearly until they reach 66A. The MOSFET turns off, the battery voltage and current resonate, and the output current begins to slowly fall having commutated to the flywheel diode.

By retriggering this cycle at a 10kHz rate, a simple buck converter is formed which charges up the DC bus capacitance (see Fig. 4). The integral of the switch power dissipation over the 2mS interval shown is 28.6mJ, which suggests a combined MOSFET power dissipation of less than 15W in this current limiting mode. Most of the power dissipation occurs in due to switching rather than conduction losses, due to the relatively slow switching speeds.

5 CONCLUSIONS

Mechanical DC circuit breakers are slow to respond to small overloads, and require large fault currents to trip them quickly (which is still relatively slowly). A static DC circuit breaker using MOSFETs is presented. The MOSFET peak overvoltage is studied, and shown to be limited due to the small source inductance. A small load inductance limits the rate of rise of fault current, and rapid and accurate fault detection is achieved by the use of a separate resistive inductive shunt. By using CMOS circuitry, the quiescent power consumption is very low, 20mW. The switch conduction loss is 2W at 10A.

References

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[6] CII technologies, *Kilovac Product Guide*, Nov 1998.

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break33a.cir   DC cct breaker using MOSFETs for batt box.
* Geoff Walker
* define the reference node to be node 2
Rgnd     2  0  1R
vdd     20  1  140V
Rsource 20 21  0.1
Lsource 21 14  1.0uH
RLsource 21 14  1k
Csnub2  14  2  4.4uF  ic 140V
Lsense  2  22  0.1uH
Rsense  22  1  0.01
Rint    2  13  1k
Cint    13  1  10nF
Qoff    8  13  1  bc549bp
* MOSFET switch 2* IRFP260  200V  46A @ 25degC  55mOhm
*       d   g   s
XM1     3  10  23  irfp260
XM2     3  12  23  irfp260
* to measure Isw
Vsw     2  23   0V
Rg1     11 12   10R
Rg2     11 10   10R
R15V    14  17  940k
D15V    2   17  D15Vzener
R16V    14  16  20k
Q15V    16  17  15  ZTX458
C15V    15  2   200nF  ic  15V
* SR flip flop
Xnand1  8  6  7  15  2  cmos_nand
Xnand2  9  7  6  15  2  cmos_nand
Xinv1   7  5     15  2  cmos_inv
Rrst    8  15   100k
Crst    8  2    22pF  ic=0V
Rg      5  11   1k
Qpu    15  5  11    BC549BP
Qpd     2  5  11    BC559AP
*              PULSE (<v1> <v2> <td> <tr> <tf> <pw> <per>)
Von      9 2  pulse ( 12V  0V  2us 50ns 50ns 1us 100us)
Dclamp   3  14  D_irfp260
Cinit  3  14  10pF  ic  0V
Cbuss    14 25   2640uF  ic 0V
Rcbuss   25  4   0.025
Rlimit   4  24   0.02
Llimit   24  3   40uH    ic 0A
RLlimit  24  3   40k
.model D15Vzener    D(Is=1u Rs=10 Bv=15 Ibv=1u)
.subckt cmos_nand 1 2 3 4 5
* a simple 74C00  A B Y + -    Geoff Walker
* uses switch n+ n- nc+ nc- model
.model nch_fet VSWITCH (voff=2V von=8V ron=200 roff=1e9)
.model pch_fet VSWITCH (voff=2V von=8V ron=250 roff=1e9)
  ca   1 5     5pF
  cb   2 5     5pF
  sna  3 6 1 5 nch_fet
  snb  6 5 2 5 nch_fet
  spa  4 3 4 1 pch_fet
  spb  4 3 4 2 pch_fet
  cy   3 5     5pF
.ends cmos_nand
.subckt cmos_inv  1  3 4 5
* a simple 74C04  A  Y + -     Geoff Walker
* uses switch n+ n- nc+ nc- model
.model nch_fet VSWITCH (voff=2V von=8V ron=200 roff=1e9)
.model pch_fet VSWITCH (voff=2V von=8V ron=250 roff=1e9)
  ca   1 5     5pF
  sna  3 5 1 5 nch_fet
  spa  4 3 4 1 pch_fet
  cy   3 5     5pF
.ends cmos_inv
.lib irfp260.lib
.lib \pspice\lib\zmodels.lib
.tran 100us 2ms
.probe
.end break33a.cir
```

Figure 5: The PSpice circuit file used to generate the simulation results shown in this document.