ANALYSIS OF MAGNETIC PROPORTIONAL DRIVE CIRCUITS
FOR BIPOLAR JUNCTION TRANSISTORS

R.L. Avant W.T. Michael D.J. Shortt R.E. Palma

Naval Research Laboratories
Space Systems Technology Division
Washington, D.C. 20375

ABSTRACT

A comparison is presented of some advantages and disadvantages of three popular magnetic proportional drive circuits for bipolar junction transistors (BJT) used in spacecraft switched mode power supplies (SMPS). A generic classification of these drives is introduced. A novel adaptation of one of these drives, the multiple mode proportional drive (MMPD), is developed to provide a total proportional drive for BJT's using resonant turn-off snubbers. Circuit operational description and design rational is presented for this new MMPD.

1.0 INTRODUCTION

A basic low power (<1KW power generation) spacecraft may easily require a dozen or more distinct SMPS to provide power conditioning for the platform's instrumentation and telemetry plus other housekeeping and utility functions (exclusive of payload). These SMPS are usually low power (<150W).

Spacecraft qualified SMPS are usually burdened with a number of subcircuits and design constraints which reduce total power conversion efficiency. Qualified flight units have typical overall low bus conversion efficiencies ranging from around 55% at the less than 5W output level to around 75% at the 50W output level even though the switching stage subcircuit may have a conversion efficiency of greater than 90% [9].

Many spacecraft programs impose the design constraint that SMPS use a BJT as the main power switch when the spacecraft is to be tasked to operate in an ionizing radiation exposure which may lead to total integrated dosages in the several kilo-rad range [4].

The BJT base drive subcircuit is usually a significant contributor to losses in the converter. It is also a critical functional unit in the control of the dynamics of the power

converter. For these reasons, a significant portion of the design effort of a converter is concentrated on the BJT base drive subcircuit.

Often designers chose to use magnetic parts in the base drive subcircuit. Motivations for this choice may include such things as the need for DC-isolation, the need for impedance matching, the need for ruggedness and reliability, and the need to provide main BJT base current proportional to its collector current (proportional drive).

Forward proportional drive is most often implemented for the purpose of controlling the conductivity modulation of the main BJT's collector neutral region during on-time. This improves switch performance when collector current varies over a wide range by limiting saturation pullout at high collector currents or excessive storage times at low collector currents.

Collector current varies during a single switching cycle on-time due to snubber reset and due to inductive load magnetization. It varies from cycle to cycle due to load current changes and input voltage shifts.

Reverse proportional drive scales the turn-off reverse base current, IBR, to be proportional to the collector current, IC, during the collector storage time. Analysis has shown [5] that when

$$IBR \leq IC (.5 + 1/h_{fe0})$$

then a highly resistive region is re-established near the n- to n+ transition region of the lightly doped collector neutral region prior to a depletion layer occurring at the base to collector junction. This highly resistive region supports a rapid initial collector voltage rise while the absence of a base - collector depletion region maintains maximum base width and thus reduced transport factor in the base.

2.0 MAGNETIC PROPORTIONAL DRIVES

Magnetic circuits are most often chosen to implement proportional drives. This selection is not without drawbacks. Some of these are:

- o limited linear range for core materials
- o high frequency compliance problems due to leakage inductance
- o evacuation of core magnetization energies
- o high level of design skill required
- o need for custom fabrication

On the other hand, magnetics provide some significant advantages to support their use in proportional drive circuits. Among the most significant are:

- o reliability
- o efficiency
- o ease of sensing the collector current

2.1 Generic Classification of Proportional Drives

A number of proportional drive circuit papers have been published in recent years. Often the circuits are highly similar in their basic operational concepts but are highly distinctive in how critical events such as

turn-on, turn-off, and magnetic core flux levels are controlled. The circuits vary from simplistic to extraordinarily complex based on the requirements imposed by the host SMPS.

Based on a survey of SMPS circuits and literature available to the authors, the proportional drive circuits currently developed are felt to be grouped into three generic categories. They are listed and defined as follows:

- o The regenerative proportional drive (RPD) [1,2], (refer to figure 1)
- o The proportional inductance drive (PID) [4]. (refer to figure 2)
- o The multiple mode proportional drive (MMPD) [3], (refer to figures 3 and 4)

Proper selection and subsequent design of the selected generic drive configuration requires an indepth understanding of the SMPS operational dynamics and of the physical electronics of the BJT to be switched.

A properly designed proportional drive can not only provide highly efficient power transistor operation, but also can reduce storage times to a few hundred nano-seconds even when switching from a BJT on-state V_{ce} of less than .5 volts. This coupled with very rapid collector current rise and fall times can enable substantially higher switching frequencies.

Figures 1,2, and 3 show previously published examples of the three generic classifications and list some of the advantages and

FIGURE 1. BASIC REGENERATIVE PROPORTIONAL DRIVE (RPD)

Regenerative Proportional Drive (RPD)

Advantages

- o Excellent starting for turn on
- o Requires no pilot transistor
- o Inherently provides DC isolation
- o Forward drive circuit design is very simple
- o Can incorporate a snubber reset current sense winding

Disadvantages

- o Possible dV/dt turn-on
- o Somewhat difficult to design turn-off circuitry
- o Reverse drive is not proportional
- o Many problem areas with switch turn-off especially tail-out

FIGURE 2. BASIC PROPORTIONAL INDUCTANCE DRIVE (PID)

Proportional Inductance Drive (PID)

Advantages

- o Very simple to design
- o Wide dynamic range
- o Transfers excess power to output
- o Provides proportional reverse drive during storage time
- o Holds reverse drive during Vce rise
- o Clamps main BJT VBE base-emitter back bias
- o No dV/dT turn-on
- o Positive turn-off
- o Deep saturation of pilot transistor not required
- o Best for very low forced beta
- o Can incorporate a snubber reset current sense winding
- o Can modify to use a low voltage pilot transistor

Disadvantages

- o Not fundamentally DC isolated
- o Not good for continuous mode unless using a strong pilot drive
- o Pilot transistor snubber will cause turn-off delay
- o Must be considered in stability analysis

FIGURE 3. MULTIPLE MODE PROPORTIONAL DRIVE (MMPD) OF REFERENCE 4.

Multiple Mode Proportional Drive (MMPD)

Advantages

- o Turn-on is very rapid
- o No dV/dT turn-on
- o Pilot switch gives positive turn-off
- o Turn-off drive is proportional during storage time
- o Turn-off starts at end of pilot switch storage time
- o Self quenching reverse drive
- o Easy to design basic circuit
- o Good for continuous and discontinuous mode
- o Can modify to use a low voltage pilot transistor
- o Can incorporate a snubber reset current sense winding

Disadvantages

- o Previous design only for high power (low power presented here)
- o Not fundamentally DC isolated
- o Deep saturation of pilot transistor desired
- o Core reset may cause oscillatory turn-off problem for emitter sense winding
- o Magnetic saturation during on-time may be destructive
- o Turn-off drive may be lost if core saturates too soon

disadvantages typical of each generic classification. The literature references in the above paragraphs provide adequate discussion of the operation and the design for the specific circuits shown in figures 1,2, and 3; however, it is the intent of this paper to discuss a new proportional drive circuit which is to be generically grouped with the circuit of figure 3 and is therefore classified a MMPD.

3.0 A NEW MMPD CIRCUIT

The essence of a multiple mode proportional drive (MMPD) is that the drive is adaptively altered throughout the switching cycle of the driven transistor. The author of [3] defines four modes of operation pertinent to the high power inverter circuit application to which the drive was being applied when developed. The mode definitions of [3] are easily modified to define the generic MMPD circuit if the transistor blocking mode is dismissed as trivial.

- o Supplemental Mode(s) - additional current variables are added to the forward mode current which may be induced without sense winding control.
- o Forward Drive, FD, Mode - forward base drive is proportional to collector current.
- o Reverse Drive, RD, Mode - reverse base drive current is proportional to collector current.
- o Collector Voltage Rise, CVR, Mode - reverse drive potential is maintained during collector voltage rise.

The MMPD shown in figure 3 was developed to serve in a high power inverter application [3]. While studying the requirements for a magnetic proportional drive circuit to be employed in a series of low power (<150W), continuous-mode, flyback-type DC-to-DC converters for spacecraft applications, it was decided that the MMPD was the preferred approach.

3.1 Requirements for The New MMPD

For a variety of reasons, the MMPD circuit of figure 3 was judged not compatible with the circuit of the intended low power application. The rationale of that judgement involves a lengthy discourse on the complex interactions of the figure 3 MMPD throughout its modes. That discourse will not be presented here. This paper will present only the requirements imposed on the new MMPD and it will present the circuit developed to meet those requirements. The requirements are summarized as follows:

- (a) The MMPD will use a low voltage pilot transistor
- (b) The MMPD will provide enhanced turn-on drive as its first supplemental mode.
- (c) The MMPD will sense snubber reset currents and maintain proportional drive during snubber reset
- (d) The MMPD will allow the main BJT to enter saturation at turn-on and remain in saturation throughout the on-time.
- (e) The MMPD will operate effectively in both continuous and discontinuous modes of the converter flyback transformer
- (f) The MMPD will use snubber charging currents to drive the CVR mode
- (g) The MMPD will have its core biased below the residual flux level to reduce core size requirements

To meet the above requirements the circuit of figure 4 was designed. The operation and

FIGURE 4. A NEW MMPD CIRCUIT

FIGURE 5.

CIRCUIT VARIABLE
DYNAMICS OF THE
NEW MMPD OF
FIGURE 4.

basic design of the circuit is presented in the following paragraphs. The presentation is keyed to figure 5 which shows the operational dynamics of the key circuit variables for the new MMPD of figure 4. Design features to meet the above listed drive circuit requirements are introduced in the following sections in the course of discussing the circuit dynamics.

3.2 Initial turn-on, t_0 -to- t_1

Initial turn-on is illustrated in the waveforms of figure 5 by the interval t_0 -to- t_1 . The base drive current is characterized by a sharp high amplitude spike at initial turn-on as illustrated in figure 5(a). This spike is derived from the displacement currents of

charging the gate-to-source capacitance, CGS, of the MOSFET pilot switch during turn-on.

The choice of a MOSFET pilot switch enabled the circuit to meet requirement (a) of section 3.1. Even though the drain is at ground potential the MOSFET physical structure directs the majority of gate charging current through the gate-to-source path. This current then charges the BJT base-to-emitter circuit which responds with collector current and the drive becomes self-sustaining. A BJT pilot transistor will not function in this manner without an auxiliary diode in the collector similar to D2 in figure 3. This diode contributes to losses as well as parts count and core size requirements.

The use of the MOSFET also enabled requirement (b) of section 3.1 to be met easily. Many PWM integrated circuit control chips can source or sink high amplitude, short duration currents without damage. The MOSFET CGS need be only a few hundred pico-farads to allow sufficient charge transfer to the BJT to insure turn-on. When the CGS of the MOSFET is charged to the gate drive voltage, current flow ceases from the gate drive integrated circuit and therefore efficient operation is produced.

Hard on and off switching of the pilot switch is not absolutely necessary for the circuit to operate. For this reason, the use of the MOSFET in the pilot switch application is a lower risk in the presence of ionizing radiation than the use of a MOSFET for the main power switch. Substantial gate threshold voltage shift for the pilot transistor can be tolerated without catastrophic effect on circuit performance.

3.3 Resonant Snubber Reset Interval, t_1 -to- t_2

Most turn-off snubber circuits have their reset cycles initiated by main switch turn-on. Such is the case for the basic two-loop resonant snubber shown in figure 4.

Snubber reset loop peak current is independent of the collector load-circuit current. Even at peak collector load circuit current, the snubber-reset peak current is usually a substantial contributor to the total collector current. At light load current, the snubber-reset peak current may be expected to be the dominate part of the total collector current. In either case, provision must be made in the base drive to accommodate the snubber reset current. If not, the main BJT will not be saturated during snubber reset and may be destroyed.

The new MMPD meets requirement (c) of section 3.1 by having snubber reset current flow through a sense winding, N2, of the proportional drive transformer, T1 of figure 4. During snubber reset, T1 is driven by two primaries, N1 and N2 of figure 4. Forward proportional drive

current is induced in N3 and maintains Q1 saturation throughout the interval t_1 -to- t_2 .

3.4 The Bulk on-time interval, t_2 -to- t_3

During the interval t_2 -to- t_3 of figure 5, the proportional drive performs in the classical manner and is very similar to the performance of the circuit of figure 3 described in [3]. Collector load current is sensed by N1 and proportional drive induced into N3 is supplied to Q1 to maintain proper saturation. Requirements (d) and (e) of section 3.1 are satisfied in this manner.

An improvement in MMPD performance is achieved during this interval by use of the MOSFET pilot switch as opposed to a BJT and diode combination. That improvement results in a lower magnetization rate of the T1 core of figure 4 along with excellent switching speed.

3.5 Storage Charge Removal Interval, t_3 -to- t_4

The reverse drive mode is initiated at t_3 of figure 5. The MMPD presented here performs, during this interval, in a manner essentially identical to the MMPD of figure 3 as described in [3]. When Q2 of figure 4 is turned off, the forward proportional drive winding, N3, is open circuited. Voltage induced in the reverse proportional drive winding, N4, reaches sufficient level to force current flow in the zener diode, DZ1. At this time, Q1 base current, IB, reverses and becomes negative, IBR.

Although this new MMPD performs much like the previous MMPD of [4], a significant performance improvement is achieved by reduced voltage requirements for the zener diode. Since the pilot switch has zero drain voltage initially at the start of turn-on and is maintained at low voltage throughout the on-time, then the reflected voltage from N3 into N4 is also very low during all times in which N4 must remain static. As a consequence, the zener voltage requirement is reduced to virtually nil. It is considered optional based on turns ratios and leakage inductances for a specific design.

3.6 Collector Voltage Rise Interval, t_4 -to- t_5

The collector voltage rise (CVR) mode is one of the most important modes of the MMPD. During this interval, the base-collector depletion region is being developed to support the rising collector-emitter voltage. The charge being swept out of the collector region as the depletion region forms is injected into the base neutral region where it stimulates emitter injection. Due to the high base transport factor at this time, the electrons injected from the emitter appear as collector current and are the cause of the collector current tail-out effect.

To minimize this effect, charge injected into the base during t_4 -to- t_5 must be removed from the base as quickly as possible. Additionally, the base-emitter junction should be slightly reverse biased. Many transistors may sustain base-emitter junction breakdown for a short period without damage.

The MMPD maintains a strong reverse drive during the CVR mode by routing the snubber capacitor charging current through the load current sense winding (N1 of figure 4 and N1 of figure 3) of the MMPD during this mode. Voltage is thus induced in the reverse drive winding (N4 of figure 4 and N3 of figure 3) of the MMPD. This voltage acts to reverse bias the base-emitter junction and sweep out the charge injected into the base due to collector voltage rise.

During this period, the voltage reflected into the sense winding, N1, is a function of the zener voltage, VDZ1, the diode voltage, VD1, and the base-emitter reverse bias, -VBE.

The magnetization rate of the core of T1 increases sharply during this event as is illustrated in figure 5(e). The new MMPD of figure 4 has improved performance over the MMPD of figure 3 since the zener voltage, VDZ1 may be somewhat less.

3.7 The Core Reset Interval, t_5 -to- t_0

Following the completion of the collector voltage rise, externally induced currents in the T1 windings cease. During the on-time of the transistor, the T1 core will usually have become magnetized beyond its residual flux level, B-residual, and will reset to B-residual at a rate depending on the terminal voltages induced on the collective windings N1 through N5. Due to the use of a bias winding, N5 in the new MMPD of figure 4 this magnetization excursion beyond B-residual is minimized and no specific circuitry is provided to dispose of the magnetization energy.

Following the flyback reset of the core to B-residual, the bias winding, N5, restores the core to a magnetization set point determined by the dynamic range requirements of the MMPD.

4.0 SUMMARY

This paper has presented two things. The first item presented is a generalized comparison of the advantages and disadvantages of three popular magnetic proportional drive circuits currently in use. The second item presented is a description of a new magnetic proportional drive circuit.

When comparing magnetic proportional drive circuits, those circuits having fundamentally similar operating principles were grouped together as a generic type and a simplified

circuit provided to illustrate the classification. The generic classifications assigned were the regenerative proportional drive (RPD), the proportional inductance drive (PID), and the multiple mode proportional drive (MMPD).

The new proportional drive circuit employs the fundamental operating principles consigned to the MMPD. The new circuit rearranges the basic parts of a MMPD to best suit the requirements when the host circuit is a flyback type DC-to-DC converter. In addition, three unique features are incorporated into the new circuit. They are a MOSFET pilot transistor, a snubber reset sense winding, and a core magnetization bias winding. With these features the new MMPD offers substantial performance improvement for MMPD applications in low power (<150w) converters.

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