

Use of BiMOSFETs in Modern Radar Transmitters

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Abstract-- Many applications today require reliable and efficient switches that operate efficiently at high Voltages. It is rare to find MOSFETs above 1000 VDC and their high $R_{DS(on)}$ make their operation at high Voltages unattractive. BiMOSFETs are devices, which have combined strengths of MOSFETs and IGBTs. Non-epitaxial construction and new fabrication processes involved in making BiMOSFETs are described. Many characteristics such as forward Voltage drop, Gate Charge & switching times are shown with the help of curves. Taking into consideration their many advantages, some designs of power supplies for radar transmitters and pulse modulators using BiMOSFETs are presented here. Judicious selection of resonant mode ZVS/ZCS techniques, combined with current fed mode, yields power supplies with many attractive features and benefits for powering TWTs, Klystrons and Magnetrons. The same approach can be used for building high Voltage power supplies for innumerable other applications.

Index Terms-- BiMOSFET, MODING, RADAR, ZVS/ZCS

I. INTRODUCTION

The conventional construction for both MOSFETs and IGBTs is commonly referred to as DMOS (double-diffused-metal-oxide-silicon), which consists of a layer of epitaxial silicon grown on top of a thick, low resistivity silicon substrate. However, at Voltages in excess of 1200V, the thickness of the N-silicon layer required to support these blocking Voltages makes it more attractive and less costly to use a non-epitaxial construction as illustrated in Fig. 1. This type of construction is also known as "homogeneous base" or "non-punch through" (NPT).

Referring to Figure 1, the typical pnpn-structure for the IGBT has been maintained, but note that an N+ collector-short pattern has been introduced in order to reduce the current gain of the PNP transistor and consequently its turn-off switching behavior. However, now there is a "free" intrinsic diode from emitter to collector, like that found in a MOSFET, which led us to coin the acronym 'BiMOSFETTM transistor.' The turn-off behavior of the BiMOSFETTM transistor is controlled by the amount of collector shorting. In order for the diode to be usable and not cause commutating dv/dt problems, the lifetime of the minority carriers must be

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reduced by irradiation. The end result is a device, which can be optimized for either high frequency or low frequency switching by tailoring its collector short pattern along with suitable amounts of irradiation.

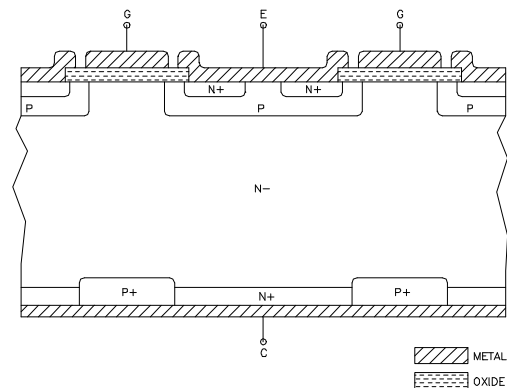


Fig. 1 BiMOSFETTM cross-sectional view

Let us compare IXBH40N160 BiMOSFET's electrical performance to that of a 1000V MOSFET (IXFH12N100) and a 1200V DMOS constructed, SCSOA rated IGBT (IXSH35N120A); all three parts being constructed using the same silicon chip size (7.11mm x 8.64mm). The comparison is conservative because both competing parts are lower-Voltage rated.

1. The threshold Voltage of the BiMOSFETTM is the highest of all but its $Q_{g(on)}$ is comparable. This is due to its relatively low Miller gate capacitance resulting in low Miller gate charge as can be seen in Figure 2. In one sense, a high threshold Voltage can be considered as an advantage in electrically noisy environments.

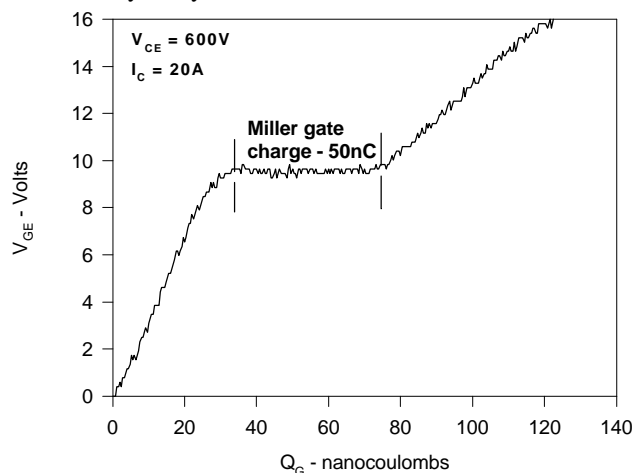


Figure 2. Gate Charge

Table 1: Electrical Performance Table

DC Parameters	IXBH 40N160 BiMOSFET	IXSH 35N120A IGBT	IXFH 12N100 MOSFET
BV_{DSS} @ 3mA	1600V	1200V	1000V
$V_{GE(th)}$ @ 4mA	5-9V	4-8V	2-4.5V
$V_{CE(sat)}$ @ I (125°C)	7V @ 25A	4V @ 35A	13.9V @ 6A
g_{FS} @ I	20S	26S	10S
C_{ISS} (25V)	3275pF	3750pF	4000pF
C_{OES} (25V)	210pF	235pF	310pF
C_{RES} (25V)	28pF	60pF	70pF
$Q_{g(on)}$	121nC	150nC	122nC
$I_{c(on)}$	110A	170A	48A

Switching ($T_J = 125^\circ\text{C}$)

$t_{d(on)}$ ($R_g = 5\Omega$)	50ns	80ns	21ns
t_{ri}	195ns	150ns	33ns
t_{fi} ($R_g = 22\Omega$)	240ns	1100ns	32ns
E_{off}/A (960V)	0.12mJ/A	0.26mJ/A	0.04mJ/A

2. Its transconductance and peak on-state current are lower than the IGBT, making the latter the preferred switch for low frequency applications. In order to survive short circuit testing at higher Voltages, low transconductance is required so that the BiMOSFETTM can be used in applications where survivability to this type of fault is a must.

3. $V_{CE(sat)}$ of BiMOSFET at 125 °C is higher than the IGBT but its on-state Voltage drop at 20A is only 15% of an 1000V MOSFET of equal silicon area. In actuality, the V_{DS} of a 1500V rated MOSFET would go up by another factor of 2.4.

4. Fig. 3 plots the temperature dependence of BV_{CES} , $V_{GE(th)}$ and $V_{CE(sat)}$ normalized to their corresponding values @25 °C. The forward Voltage drop of the intrinsic diode V_F also has a positive temperature co-efficient. Behavior of BV_{CES} and $V_{GE(th)}$ with temperature is the same as an IGBT. However, note that since both $V_{CE(sat)}$ and V_F have a positive temperature coefficient, these devices will be much easier to parallel than IGBTs, which require very close matching to ensure equal current sharing when used in parallel.

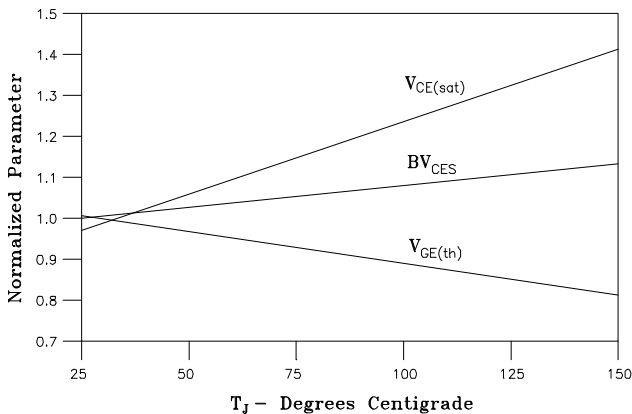


Fig. 3 Temperature Dependence of BV_{CES} , $V_{GE(th)}$ and $V_{CE(sat)}$

IXBH40N160 - Turn-off I/V Waveforms

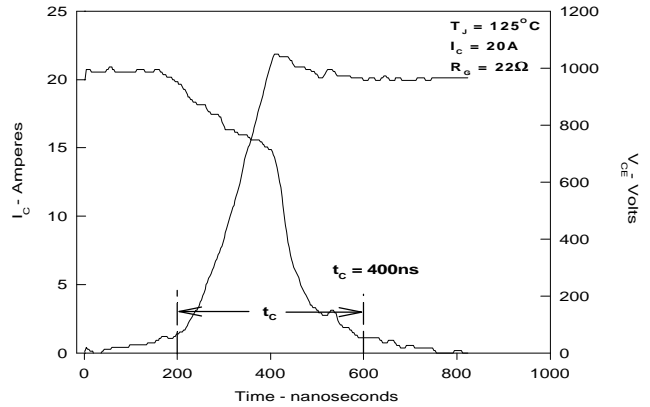


Fig. 4 Turn-off Current and Voltage Waveforms of IXBH40N160

Fig. 4 illustrates IXBH40N160 turning off a 20 A inductive load into a 1000 V clamp at the elevated temperature of 125 °C. There is relatively little tail current so that $E_{(off)}$ is 2.4mJ, which is 50% less than a comparable IGBT. Fig. 5 gives a comparison between an equally rated 1200 V IGBT and a 1000 V MOSFET at $T_J=125^\circ\text{C}$. It is interesting to note that in the range of $F_{sw} = 5\text{KHz}$ to 75 KHz, BiMOSFET performs creditably.

IXBH40N160: Switching Frequency Comparison

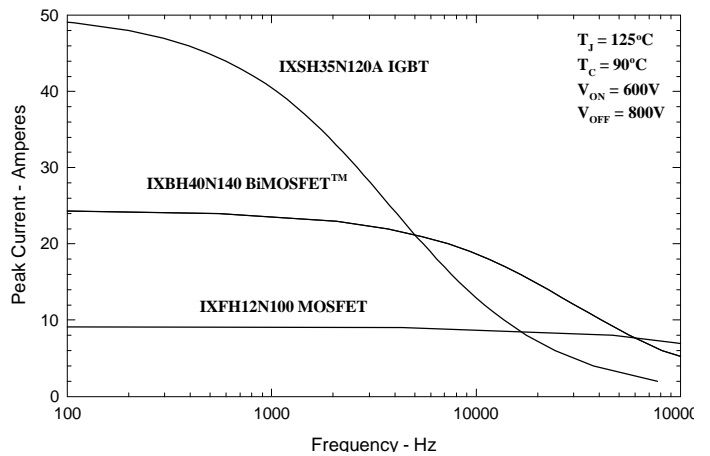


Fig. 5 Comparison of the current carrying capability of the BiMOSFET to that of 1200 V IGBT and 1000 V MOSFET

Making use of outstanding specifications of BiMOSFETs, efficient high Voltage, high current power supplies can be built with excellent regulation and low ripple, which are ideally suited for radar transmitters. Even pulse modulators for radars can meet stringent design goals, using BiMOSFETs. In what follows, both above subjects are dealt with.

II RADAR TRANSMITTERS

The acronym RADAR stands for Radio Detection And Ranging. It is a system, which transmits electromagnetic

waves in a specified direction and receives the same waves reflected by various targets (moving or stationary) and, by processing the received signals & their time of arrival, determines some of the characteristics of targets; such as height, shape, velocity and direction. By transmission of regularly spaced short pulses (instead of continuous waves), three benefits accrue simultaneously:

1. The transmitted power could be increased, while keeping the average power quite low.
2. The radial distances of the targets (and its velocity and direction) could be computed easily, by measuring the time difference between transmission and reception of the same pulses.
3. Same antenna can be used for transmission as well as reception.

The term pulse radar was given to such systems. Fig. (6) shows block diagram of pulse-modulated Doppler radar system. Here target detection is based on sending the Doppler frequency generated by target movement. Straight pulse modulation will detect & indicate both fixed and moving targets. Other type is called "self coherent pulse radar". Both of these belong to the most popular form: M.T.I. (Moving Target Indicator) radar systems.

Notice the presence of "pulse modulator" and "transmitter", which uses microwave Power tubes, such as TWT (Travelling Wave Tubes), Klystrons or Magnetrons, all of which need stable & ripple free high Voltage, high current power supplies. For a pulse modulator and EHT power supply, BiMOSFETs can be advantageously used.

In the proliferation of radars for various applications throughout the world, different power levels and different frequency bands are employed for achieving optimum results for a given application. They are listed below:

1. Application : Long Range Detection (approx. 10000Km)
 - a. Transmitted power (Mean) : 2MW
 - b. Transmitted power (Peak) : 50MW
 - c. Median Frequency : VHF Band
 - d. Pulse Duration : 2 ms
 - e. Pulse Repetition Frequency : 20 HZ
 - f. Duty Cycle : 0.04
2. Application : Medium Range Detection (approx. 3000Km)
 - a. Transmitted power (Mean) : 1MW
 - b. Transmitted power (Peak) : 100 MW
 - c. Median Frequency : C band app. 5 GHz
 - d. Pulse Duration : 100 usec
 - e. Pulse Repetition Frequency : 100 Hz
 - f. Duty Cycle : 0.01
3. Application : 3D Air Surveillance radar (range: approx. 400 km.)
 - a. Transmitted Power (Mean) : 30KW
 - b. Transmitted Power (Peak) : 30MW
 - c. Median Frequency : 3 GHz

- d. Pulse Duration : 5 usec
 - e. Pulse repetition frequency : 200 Hz
4. Application: Low Altitude Detection: (range: approx. 100 Km)

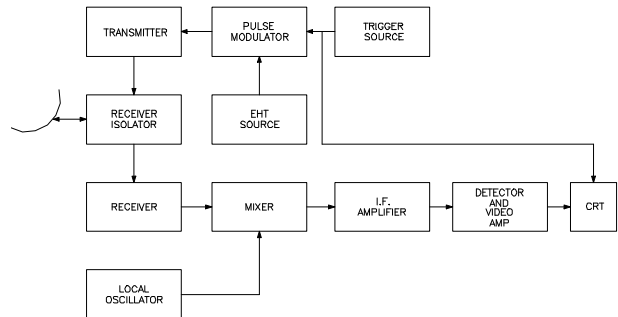


Fig. (6) Pulse modulated radar system

- a. Transmitted Power (Mean) : 100 W
- b. Transmitted Power (Peak) : 1.3 KW
- c. Median Frequency : 1 GHz
- d. Pulse Duration : 10 usecs
- e. Pulse Repetition Frequency : 1 KHz

Other forms of radars are: multimode radar for a Surface-to-Air weapon system, which works in X-band and multimode radars, working in X or K-band on-board combat aircrafts.

Underlying all these various forms of radars are two predominant requirements:

- 1.They all need High Voltage, High Current Power Supplies, with required regulation & low ripple, with overload and short circuit protection.
- 2.They all need Pulse Modulators

III HIGH VOLTAGE, HIGH CURRENT POWER SUPPLIES

In what follows, new designs are described, which yield highly efficient, fool-proof, light-weight equipment, using modern power semiconductors, magnetic components, and employing resonant modes, with (ZVS) Zero-Voltage-Switching techniques, with added feature of current source.

The advantages of using ZVS techniques are:

1. ZVS ensures zero power- "lossfree"- Switching.
2. No high peak currents are encountered.
3. Eminently suitable for high DC bus Voltage inputs, giving efficient performance.
4. Reduced gate drive requirement (as there is no "Miller" effect).
5. Short circuit tolerance is built in.

In our proposed unique converter, ZVS techniques are combined with current mode control, giving additional advantages. Fig. (7) shows an approach of current fed, ZVS resonant mode inverter switching at fixed frequency, giving pure sine wave at the primary of the H.V./H.F. Transformer. The full bridge arrangement lends itself for high power output. The BiMOSFETs are connected in parallel, as it is quiet easy to share the currents equally amongst them, because of the positive temp co-efficient of $V_{CE(sat)}$ and V_F of BiMOSFETs as well as the Anti-Parallel diode. The sine

wave output of the inverter at fixed frequency enables one to design an optimum H.F./H.V. transformer. It is also possible to have a full bridge inverter configuration, which is fed from a full SCR bridge controlled rectifier, followed by a L-C filter and again an inductor, which gives a constant current source. The current sensing Hall effect sensors, in all these configurations enable not only monitoring but also control of the current fed operations. Due to the pure sine wave at fixed frequency of these inverters, the EMI/RFI is minimum and stresses on the active and passive components is minimum. Mathematical analysis becomes simpler and predictable. The advantage of this approach is to make the power stage operate as a Voltage controlled current source. The resultant benefits of this approach for powering microwave tubes are explained below:

1. A high frequency current source for anode supply has very low amount of stored energy and provides automatic current limiting, even with a shorted load. Thus power to microwave tubes can be shut down in microseconds after detection of a fault by stopping the drive signals from reaching the gates of the BiMOSFETS.
2. Although the microwave tubes are capable of delivering kilowatts of microwave power to the antenna, they themselves can't absorb even a tiny percentage of this. Hence the need to have a specially designed power supply having low level of stored energy, which can't damage the microwave tubes even under fault conditions.
3. In conventional designs, power is controlled by adjustment of magnet current, which results in response times measured in seconds, compared with milliseconds in the current source designs.

4. By using this unique approach, even during microwave tube's arcing or moding the output Voltage can't increase and the current can be brought down to acceptable levels without need to activate other trip mechanisms, like MCBs.
5. For properly controlling the filament supply, an additional DC to DC converter is introduced with control features that enable correct tracking of the filament current relative to anode current. If this is not done, any crudely controlled filament Voltage source could cause damage due to moding or excessive temperature, to the microwave tubes or could cause incorrect filament emission. Please note also that even the filament power is supplied by the same power supply unit through an added DC to DC converter, which can be controlled to give flexibility in adjusting the filament current. When filament current is optimum, the RF output of the microwave power tube is cleanest with minimum side bands in the RF spectrum.
6. One more operational convenience offered by this approach of current source power supply is that it allows the user to explore different operating characteristics of magnetrons. By this we mean that the anode Voltage, anode current and the magnet current can be independently adjusted to achieve desired operating point. The current source design can also enable use of permanent magnet instead of electromagnet. This can eliminate magnet power supply and thus, reduce weight and bulk.

While on this subject, let us also examine the prudent choice of several secondaries in a high Voltage transformer, connected to high Voltage rectifiers as is true in Fig. (7). A

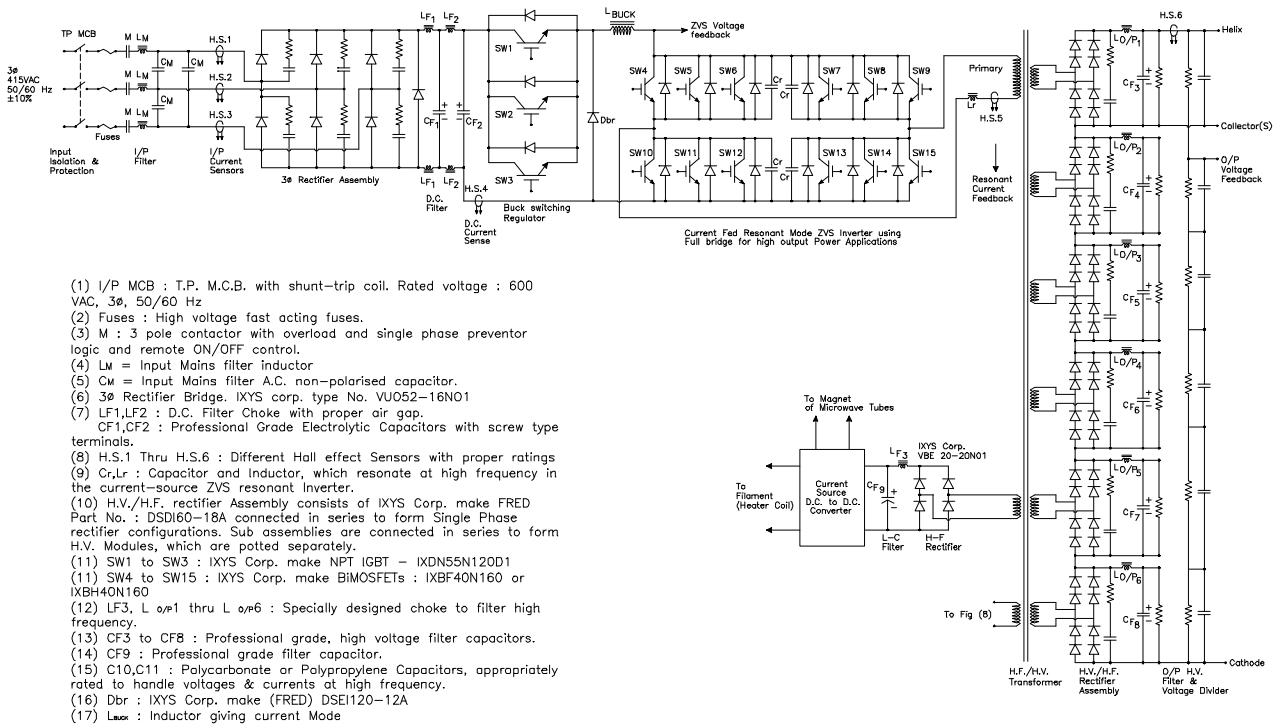


Fig (7) Circuit Schematic of Efficient High Voltage, Power Supply for the Microwave Tubes of High Power Radar Transmitter.

single secondary for a high Voltage output can cause problems as described later in this report. Also it is difficult to find FRED diode with required speed and PIV rating. In our approach we have put two FRED Type No: DSDI60-18A in series and made up a full wave rectifier on each secondary. These rectifiers are then connected in series to make up the required high Voltage. Precaution should be taken to see that no FRED is put to a Voltage stress of more than 75% of its rated Voltage of 1800 V. The snubber network helps relieve the FRED from unwanted dv/dt stresses and Voltage spikes. The inductor that is connected in series with the output of each rectifier module helps not only to eliminate ripple, but also to decrease di/dt stress on the FREDs. Needless to say, this inductor is designed to filter 50KHz rectified output. It also helps store just the required energy in conjunction with the filter H.V. capacitors to help deliver the pulse energy required by the microwave tube.

Notice also that the Voltage divider consists of several resistors connected in series. When high Voltage is applied to a single high value resistor, it no longer behaves linearly. Also carbon film resistors are not recommended at high Voltages. It is a good practice to use several wirewound resistors of proper wattage rating in series to make a desirable Voltage divider. Also it is a good practice to use capacitor across each resistor so that Voltage division is maintained even under dynamic conditions.

IV PULSE MODULATOR

Fig. (8) depicts circuit diagram of radar pulse modulator, showing one more use of BiMOSFET as a fast switch. The

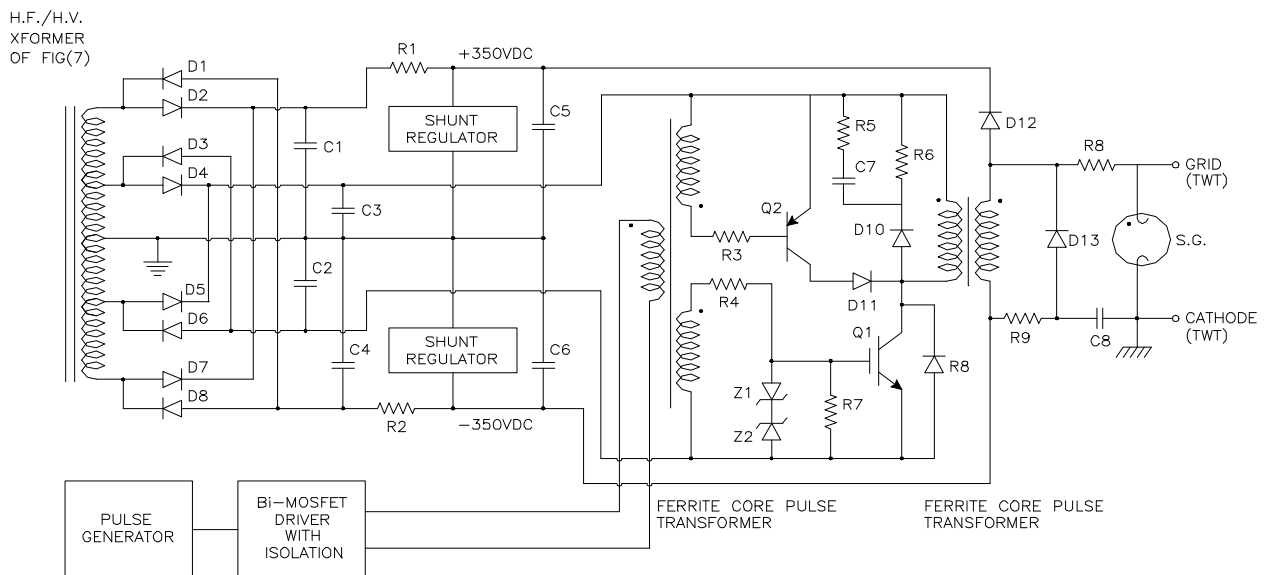
rise time of the grid pulse is limited only by the switch on time of Q1 (which is a BiMOSFET with excellent switching characteristics) and the ferrite core pulse transformer (which has to be designed, keeping leakage inductance and parasitic capacitance to the minimum).

Diodes D1 through D8 form two full wave rectifiers, giving +ve and -ve rectified Voltages, with respect to center tap ground. The presence of linear shunt regulators has to be justified. TWTs have considerable grid electrode phase sensitivity (nearly 4.5 degrees/volt). The ripple generated by poorly regulated DC Bus Voltages in a pulse modulator circuit could cause phase shifts that disturb radar operating in MTI mode. Pulse to pulse Voltage stability has to be maintained and to do so shunt regulators are made a part of pulse modulator circuit.

Pulse generator generates pulses with very fast rise & fall times and its width is as per the design, say, variable from 200 nsecs to 10 microseconds. The PRF (Pulse Repetition Frequency) could be between 5KHz to 20KHz. The rise and fall times of the final pulse to the TWT grid could be about 100 nsecs.

The BiMOSFET Driver circuit provides necessary boost, before feeding the pulse into a tightly designed ferrite core pulse transformer.

Secondary of this pulse transformer applies this pulse to the gate of BiMOSFETS Q1 through gate resistance R4, whose value will determine the desired rise time. R7 could be about 10K. Precisely at the end of the grid pulse, the tertiary winding of the pulse transformer turns on Q2, a pnp bipolar high Voltage fast transistor, which charges parasitic



- Q1 : IXYS Corp. make IXBH 9N140 BiMOSFET
- D1...D13 : IXYS Corp. make DSEI 12-10A
- Q2 : High Voltage Bipolar transistor
- C1...C6 : High Voltage Professional Grade Electrolytic Capacitors with low E.S.R. & E.S.L.
- Z1,Z2 : 18V,1Watt Zener
- S.G. : Spark gap (for protection)

Fig. 8 Pulse Modulator

capacitance of other pulse transformer. After this, leakage inductance of the other pulse transformer gets discharged through diode D10, R6 and R5 & C7. It is the second pulse transformer which feeds pulse into the Grid. Presence of Q2 helps maintain fall time of the grid pulse comparable to the rise time.

BiMOSFET IXBH9N140 has rise time of 60 nsecs and fall time of 40 nsecs for inductive load @ $T_j = 125^\circ\text{C}$, $L=100\ \mu\text{H}$, $V_{GE}=15\text{V}$, $R_G=10\ \text{ohms}$. This excellent switching performance helps obtain necessary rise time of the final pulse arriving at the Grid of the TWT. The network of R9, C8 and D13 enables grid pulse back-swing to be completely eliminated.

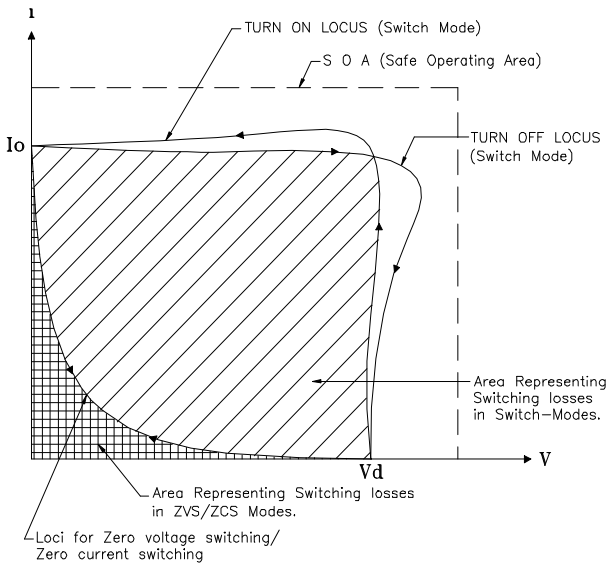


Fig (9) S O A and switching Loci for Switch-Mode and ZVS/ZCS Modes

V PRECAUTIONS IN HANDLING HIGH VOLTAGES

Successful High Voltage engineering requires proper blend of several technologies. In high Voltage designs, our goals should be:

1. Corona minimization
2. Corona immunity
3. Design for arc-proofness

To achieve foolproof design, several steps have to be taken. Recommended guidelines are given below:

1. Use screened low corona components and materials
2. Avoid sharp corners & edges for all components and for all interconnections.
3. Keep 50% margin in Voltage/mil rating for properly processed oil as insulating medium. 400 volts/mil is equivalent to 160KV/cm
4. For AC, use only 30% of DC rating; e.g. Keep limit of 300 volts AC P to P on 1000 volts DC rated parts.

5. Avoid voids in solid encapsulated components and assemblies. This is an often-overlooked design pitfall and can destroy a part or subassembly due to corona.
6. Use Voltage multipliers using properly rated high Voltage fast diodes and capacitors, wherever possible.
7. In case of step-up high Voltage transformer, use several lower Voltage windings with series arrangements after rectification.
8. Use specified processed oil or vacuum as dielectric medium.
9. Make geometry, layout and entire design with proper spacing such that it is arc proof.
10. Ensure burn-in of parts & sub-assemblies at expected high Voltages, before final assembly.
11. Highly successful designs use components that are designed and tested for high Voltage use.
12. Careful geometrical control such as geometrical rings can result in highly reliable operation.
13. Proper spacing, as per above described norms, and proper surface finish increase reliability
14. Improper encapsulation or impregnation, thus allowing voids, can cause corona leading to failures
15. Full knowledge of behavior of dielectric materials is necessary. Unfortunately literature is scanty and not enough evidence is reported on use of solid, gas or vacuum dielectric in other than low power use. Access to classified materials could help.

VI CONCLUSION

BiMOSFETs have excellent switching specifications. Especially in most demanding high Voltage inductive switching tasks, they perform creditably and hence land themselves favorably for designing efficient high Voltage, high current power supplies for modern radar transmitters. They are also an excellent choice for radar pulse modulator, wherein their super fast switching specifications make them an ideal choice, especially in high Voltage environment. Topology of H.V./H.F. power supply is described, with particular emphasis on Zero Voltage Switching, resonant mode, resulting in lowest losses in switches. Fig. (9) shows a graph of comparison between (switching losses in) switch mode and resonant mode for a semiconductor switch, showing quantitatively the savings in switching losses. Advantages of current-fed method coupled with ZVS resonant mode are described with particular reference to microwave tubes. It is easy to appreciate the overall reductions in size & weight. Other benefits are negligible RFI/EMI. The energy stored in such inverters operating at high frequency, of the order of 50KHz, in resonant mode is so small that even in the event of a fault, such as arcing or moding in a microwave tube, no damage occurs and corrective steps can be taken.

One can even employ a microcontroller, with control and monitoring algorithms suited to a particular application.

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