# IMPROVING THE EFFICIENCY AND RELIABILITY OF AM BROADCAST TRANSMITTERS THROUGH CLASS-E POWER


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# IMPROVING THE EFFICIENCY AND RELIABILITY OF AM BROADCAST TRANSMITTERS THROUGH CLASS-E POWER

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**Abstract:** Class-E is a novel means of power amplification which overcomes many of the shortcomings of conventional Class-D power amplifiers. As compared to Class-D power amplifiers, Class-E circuits offer improved efficiency, reliability and performance into non-unity VSWR's. These features give Class-E power amplification the distinct advantage in broadcasting applications.

This paper covers the theory of operation of Class-E power amplifiers, and compares the operation and performance of a typical Class-D power amplifier with a working Class-E power amplifier circuit.

## INTRODUCTION

The development of power MOSFET technology has made possible the creation of solid-state AM transmitters. It has been all too often apparent to the designers and operators of these transmitters that in comparison to the venerable vacuum tube, a transistor is much more sensitive to and less forgiving of thermal and electrical stresses. Consequently, in the interest of system reliability, the designer of a solid-state transmitter must reduce wherever possible the stresses on the power amplifier transistors.

This paper compares the operation of Class-D and Class-E power amplifiers and predicts how the performance and reliability of each is affected by different non-ideal conditions likely to occur in an AM broadcast transmitter.

### MOSFET Reliability

Admittedly, the task of the designer of solid-state AM broadcast transmitters has been made much easier in recent years by the development of MOSFET devices which are much more rugged than those available a decade ago. This has not, however altered the fact that there are still operating conditions in which MOSFETs fail and operators of solid state broadcast transmitters continue to experience device failures.

The most readily identifiable enemy of the power MOSFET is heat. All other variables being equal, an elevation in MOSFET junction operating temperature of 26 C° will result in a ten-fold decrease of device lifespan.[1] This will be manifested as an increase in "random" failures otherwise unrelated to any identifiable stress. Furthermore, the "on" resistance of the MOSFET increases with junction temperature, causing an increase in MOSFET conduction losses and a decrease in power amplifier efficiency, further aggravating the over-temperature situation.

The following electrical stress factors have been identified as causing device failure:

a) Gate insulation breakdown, which occurs as the result of excessive voltage on the gate. The oxide gate insulation will be punctured, and instantaneous failure of the device will occur. With proper MOSFET driver design, this is a relatively uncommon occurrence.

b) Drain-source overvoltage, which causes avalanching within the device. This could be the result of either high reflected power or excessive levels of peak audio modulation within the transmitter. While in the earlier-generation MOSFETs, this would result in localized hot spots and rapid device destruction, in the new, rugged devices this has been largely eliminated as an "instantaneous" failure mode. Avalanche breakdown will however increase the junction temperature of the device, leading to an increase in the "random" failures as noted above.

c) Turn-off dV/dt stress. Intrinsic to the MOSFET device is a parasitic bipolar transistor, whose base-collector junction actually comprises the body diode of the MOSFET. It is possible, through the application of a rapid positive-going transient to the drain of the

device, to induce current flow in this bipolar transistor. Current flow in the intrinsic bipolar will tend to localize in a single point of the device, destroying it. The MOSFET is particularly susceptible to this type of damage when a high dV/dt (rate-of-change of voltage per time) is applied to the drain while the body diode is undergoing reverse recovery.[2] Additionally, elevated junction temperatures increase the gain of the MOSFET's intrinsic bipolar transistor, further increasing its susceptibility to damage. The likelihood of the MOSFET encountering potentially damaging turn-off dV/dt is determined by the topology of the circuit in which it is applied, and the load into which it operates.

## The Class-D Power Amplifier

The Class-D circuit, which currently finds near-universal application in solid-state AM broadcast transmitters, consists of an 'H' bridge of switching transistors (Figure 1) each driven at a nominal 50% duty in such a manner that at any time the diagonal opposite transistors conduct. Consequently, the voltage waveform impressed across the output is a square wave at the carrier frequency. Connected to the output nodes of the power amplifier is a load network possessing a finite, resistive impedance at the carrier frequency, and much higher impedances at the harmonics of the carrier frequency. Since the harmonics are rejected, the load current is sinusoidal, and the MOSFET drain-current waveforms resemble a half-wave rectified sine wave. Assuming that the switch is ideal, i. e. possessing no parasitic inductances or capacitances, the efficiency of the Class-D power amplifier can approach 100%. MOSFET's are, however not ideal switches, so there will exist in any MOSFET power amplifier conduction losses equal to the product of square of the RMS drain current of the MOSFET and its 'on' resistance. Additionally, the MOSFET possesses a substantial output capacitance $C_{OSS}$, which in the Class-D power amplifier is alternately charged to B+ potential and discharged again through the MOSFET during each RF cycle. This results in a power dissipation in each MOSFET;

$$\text{Switching Loss} = (B+)^2 \cdot C_{OSS} \cdot F \tag{1}$$

where

B+ = power amplifier supply voltage

$C_{OSS}$ = parasitic MOSFET output capacitance, and

F = carrier frequency.

For example, consider a Class-D power amplifier comprised of IRF360 MOSFETs, which at 150 volts $V_{ds}$ possess a nominal $C_{OSS}$ of 210 pF.[3] When operating at 1.6 MHz with a B+ voltage of 300 volts, the resultant switching loss per MOSFET will equal 31 watts. This loss usually equals or exceeds that attributable to conduction loss, and due to its frequency-dependence is the biggest limiting factor in the higher-frequency application of Class-D switching technology.

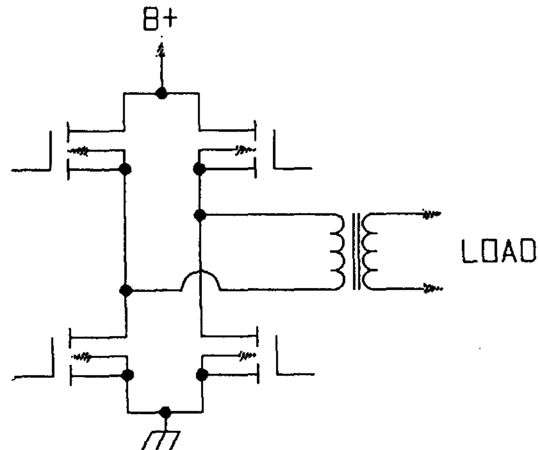


Figure 1. Class-D Power Amplifier

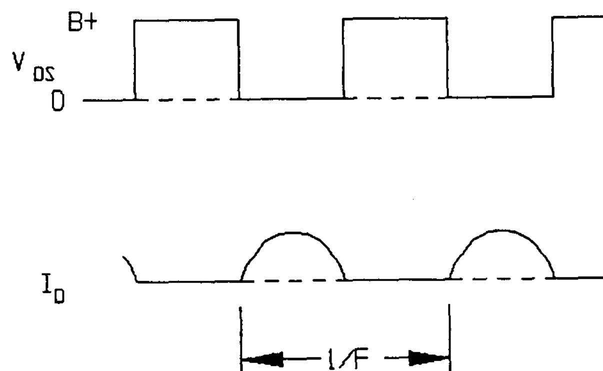


Figure 2. Class-D Voltage and Current Waveforms

In the ideal Class-D power amplifier, the drain current waveform resembles that of a half-wave rectified sine wave. However, if the transmitter utilizing Class-D power amplifiers operates into a load with non-unity VSWR, it is possible to shift the phase of the MOSFET drain current with respect to that of the square wave of drain-source voltage in such a way that the body diode

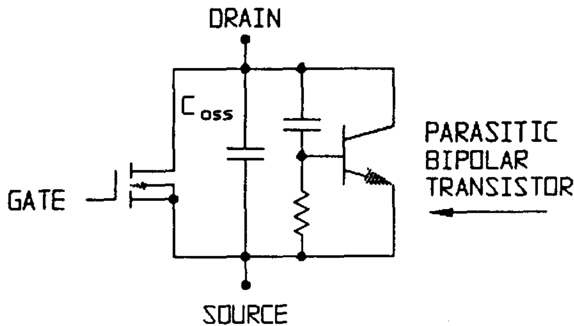


Figure 3. MOSFET Equivalent Circuit Showing Parasitic Components

of the MOSFET is induced to conduct. If the power amplifier is presented a load containing a capacitive reactive component, the MOSFET will then be turned off during the reverse recovery of its body diode, which is one of the known means of destroying the device. Some of the newer "rugged" MOSFETs specify the maximum safe limit for the reverse-recovery dV/dt which can be withstood. For example, the International Rectifier IRF360 is rated to withstand 4 V/ns reverse-recovery dV/dt.[3] A Class-D power amplifier will typically possess switching times roughly one-tenth that of the MOSFET's conduction period during each cycle. A Class-D power amplifier operating at 1.6 MHz with a B+ voltage of 300 volts could then have a switching slew rate of 9.6 V/ns, which if occurring during IRF360 MOSFET reverse recovery, could cause device failure.

It is noteworthy that the reverse recovery period of a typical MOSFET body diode is in the neighborhood of 500 ns.[3] This corresponds quite closely to the conduction period of the MOSFET when operated in the AM broadcast band. In a Class-D power amplifier operating in conditions of a capacitive load, during the period of the diode reverse recovery, the recovered charge flows from the B+ power supply, through the other MOSFET in the half-bridge, which conducts during this interval. Based on the specifications for the IRF360 MOSFET, the recovered charge following 25 amps of body diode forward current is typically 7 $\mu$C.[3] When operating a Class-D power amplifier from 300 volts B+ at 1.6 MHz, this would result in over 3300 watts of additional MOSFET dissipation and the near-immediate destruction of the device! This diode-recovery loss is roughly equal to

$$10^{-6} \cdot F \cdot (\text{VSWR} - 1) \cdot (\text{Operating Power-per-Device}) \qquad (2)$$

Consequently, to obtain reliable operation, the manufacturers of broadcast transmitters utilizing Class-D power amplifiers must take great pains to ensure that the MOSFETs do not operate in any of these conditions which are known to cause device failure or significant increase in device dissipation. One technique used to accomplish this end is to strictly limit the VSWR conditions in which the transmitter is allowed to operate. During reflected power transients, such as those occurring during near-by lightning hits, or during high-frequency modulation into narrow-band antennas, the transmitter will mute itself, to the annoyance of listeners. One means which has been used to prevent MOSFET body diode conduction, and its related problems, has been to parallel each MOSFET by a Schottky diode, which by virtue of its lower junction voltage drop, will conduct the reverse current instead. Since high-voltage Schottky diodes are of limited availability, the MOSFETs used in such a power amplifier circuit must be limited to 100-volt devices. While operation of a Class-D power amplifier from a low-voltage supply will also reduce the $(B+)^2 \cdot C_{OSS} \cdot F$ losses, the added junction capacitance of the Schottky diode parallelling the MOSFET's $C_{OSS}$ tends to offset this. Furthermore, Schottky diodes themselves possess a failure mode associated with high dV/dt, which for Schottky diodes typical of this application, must be limited to less than 1 volt-per nanosecond.[4] Consequently, the Schottky diodes intended to protect the MOSFETs may themselves be the least-reliable component in the Class-D power amplifier.

## The Class-E Power Amplifier

In order to avoid the shortcomings inherent in the Class-D power amplifier, a new approach is required. This has been realized in the form of the Class-E power amplifier, invented by Alan and Nathan Sokal.[5] A variation of their basic patent is used in the Broadcast Electronics AM-1, one-kilowatt AM broadcast transmitter. Depicted in Figure 4, the circuit comprises two MOSFETs driven push-pull at a nominal 50% duty. The circuit load is coupled to the drains of the MOSFETs via an output transformer, the primary of

which is center-tapped. The transformer center-tap connects to the power supply voltage B+ through an RF choke. Each MOSFET is shunted by an external capacitance into which the MOSFET parasitic capacitance, $C_{OSS}$, is absorbed. The circuit load appearing at the secondary of the output transformer presents a high impedance to the harmonics of the carrier frequency, and at the fundamental contains an inductive reactive component, resonating with the capacitors to produce the characteristic 'Class-E' waveforms. The equations required to calculate the proper component values to achieve these waveforms has been treated extensively in the literature.[5,6] Software is also available to greatly ease the design process.[7]

In operation, the Class-E power amplifier has features of both Class-D and Class-C circuits. As in a Class-D power amplifier, the Class-E circuit utilizes MOSFETs as 50% duty switches. The load circuit of the Class-E circuit comprises a resonant tank, as in a Class-C circuit, and the Class-E MOSFETs are switched "on" as the load voltage on the MOSFET's drain approaches zero. However, unlike the Class-C circuit, the Class-E tank circuit is relatively low-Q, tuned in such a manner that immediately prior to the MOSFET entering its conduction period, the MOSFET drain voltage waveform is nominally zero, and the time-derivative of drain voltage (dV/dt) at this instant is also nominally zero. As a result, the $C_{OSS}$ energy of the MOSFETs are zero immediately prior to the turn-on of the devices, *so there are no* $(B+)^2 \cdot C_{OSS} \cdot F$ *losses as there are in a Class-D power amplifier.* Due to the elimination of these frequency-proportional switching losses, the Class-E power amplifier is unique as it may operate as efficiently at 1600 KHz as it does at 530 KHz. A highly-efficient Class-E power amplifier utilizing conventional power MOSFETs has been demonstrated at frequencies as high as 6 MHz.[6]

## COMPARISON OF CLASS-D AND CLASS-E POWER AMPLIFIER PERFORMANCE

The efficiency of a power amplifier is a determining factor both of the electrical expense of operating a transmitter, and of system reliability. With MOSFET junction temperature a strong determinant in device failure rate, the efficiency and junction temperature rise of hypothetical Class-D and Class-E power amplifier circuits operating under similar conditions may be calculated and compared as criteria for judging relative merit of each design. Consider Class-D and Class E power amplifier circuits utilizing IRF360s generating 300 watts of RF per device, with 300 volts peak drain voltage, operating at 1.6 MHz:

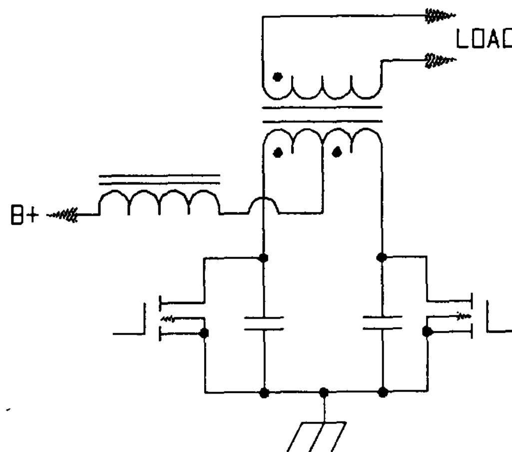


Figure 4. Class-E Power Amplifier

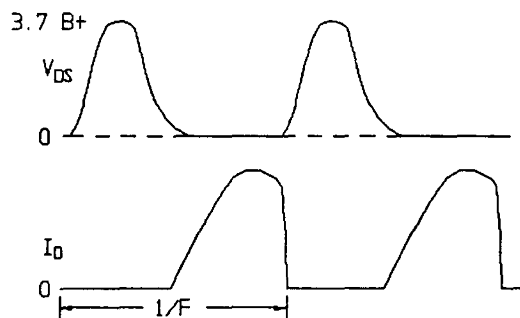


Figure 5. Class-E Voltage and Current Waveforms

Since the DC power consumption of each power amplifier is equal to the product of B+ voltage and average drain current, the Class-D power amplifier generating 300 watts per device, or 600 watts-per-half bridge, operating from 300 volts B+, consequently possesses 2 amps average drain current. The current waveform of a Class-D power amplifier has an RMS-to-average ratio of $\pi/2$, therefore, in this example, the Class-D power amplifier circuit has an RMS drain current of 3.14 amps. The conduction losses of each MOSFET will equal the product of the square of the RMS drain current and the "on" resistance ($R_{ds}$) of the MOSFET. An IRF360 has an $R_{ds}$ of 0.2 $\Omega$, so a 3.14 amp RMS drain current will result in 1.97 watts of conduction loss.[3] The $(B+)^2 \cdot C_{oss} \cdot F$ switching loss for these conditions has already been calculated to be 31 watts. The total loss in the Class-D power amplifier is therefore 33 watts, which at 300 watts-per device yields an efficiency of 89%. If the MOSFET junction-to ambient thermal resistance for the circuit is 2 C°/W (a value not atypical for most solid-state AM broadcast transmitters), the junction temperature of this Class-D circuit will be 66 C° above ambient.

In the case of the Class-E power amplifier, the peak drain voltage is approximately 3.7 times the B+ voltage. Consequently, to operate with 300 volts peak drain voltage as does the Class-D power amplifier in this example, the Class-E power amplifier circuit in this example must operate with a B+ of 81 volts. Operating at 300 watts-per-MOSFET, the average drain current per MOSFET is then 3.7 amps. The drain current waveforms of the Class-E power amplifier have an RMS-to average ratio of approximately 1.5, so the RMS drain current per MOSFET for this circuit is 5.6 amps. The conduction loss of 5.6 amps RMS through the 0.2 $\Omega$ $R_{ds}$ of the IRF360 in the Class-E circuit equals 6 watts. On the basis of MOSFET conduction losses alone, the Class-D power amplifier is superior to the Class-E circuit. However, unlike the Class-D power amplifier, the Class-E power amplifier possesses no $(B+)^2 \cdot C_{oss} \cdot F$ losses. Therefore, the Class-E circuit in this example, possessing only 6 watts loss while producing 300 watts of RF power is therefore 98% efficient! Assuming, as in the Class-D example, a MOSFET junction-to-ambient thermal impedance of 2 C°/W, the junction temperature rise above ambient of the Class-E MOSFET will only be 12 C°, 54 C° cooler than that of the MOSFETs in the Class-D circuit of this example. Solely on the basis of this decrease in MOSFET junction temperature, compared to those of the Class-D circuit, the devices in the Class-E circuit of this example will experience an approximate one-hundred-twenty-fold improvement in reliability.[3]

VSWR Performance

It has been shown that the Class-E power amplifier offers improved efficiency and reliability over a Class-D circuit under ideal conditions of the comparison above. However, from a cursory examination of the circuit and its waveforms it is possible to attain the misconception that the Class-E circuit, being a "tuned" power amplifier would be more succeptable than a Class-D circuit to damage when operated into non-unity VSWR conditions. An examination of the behavior of the Class-E circuit under these non-ideal loads can dispel this perception:

When comparing the drain current waveforms of Class-D and Class-E power amplifiers, the most striking difference present within the Class-E waveforms is that the value of drain current in the Class-E power amplifier is non-zero immediately prior to the end of the MOSFET conduction interval. This contrasts with the drain-current waveform of the Class-D power amplifier which is zero at the beginning and end of the MOSFET conduction interval. In any Class-D power amplifier where the MOSFETs are unprotected by shunt Schottky diodes, any capacitive VSWR condition will cause a negative phase shift of the drain current waveform, resulting in MOSFET body diode current prior to MOSFET turn-off. This will lead to a further increase in MOSFET dissipation from the reverse recovery current of this diode, and can lead to turn-off dV/dt failures of the MOSFET. The Class-E power amplifier, on the other hand, would require a capacitive VSWR at carrier frequency of approximately 20:1 before such an occurrence of body diode current. Even then, a comparison of the respective circuit waveforms reveals that the turn-off dV/dt of the Class-E MOSFET drain voltage, as well as the likelihood of the resultant failure, is much lower than that occurring within a comparable Class-D power amplifier. The dV/dt of a Class-E circuit operating at 300 volts peak drain voltage at 1.6 MHz is only 3 V/ns, compared with 9.6 V/ns for a comparable Class-D circuit.

The Class-E power amplifier does exhibit an increase in losses in the presence of a capacitive VSWR. In these conditions, the drain voltage waveform does not return to zero before the MOSFET is turned on. As a result, the stored energy in the capacitor parallelling the MOSFET is dissipated in the MOSFET. Regardless of operating voltage or frequency, this loss is approximately equal to

$$.05 \cdot (VSWR - 1)^2 \cdot \text{Operating Power-Per-Device} \quad (3)$$

A Class-E power amplifier delivering 600 watts (300 watts per device) into a 1.5:1 capacitive VSWR will experience an additional 3 watts dissipation per device. When delivering 600 watts into a 2:1 VSWR, a Class-E power amplifier will dissipate an additional 15 watts per device. It is not until this Class-E power amplifier is operated into a 2.5:1 capacitive VSWR that the additional MOSFET losses exceed the 31 watts of $(B+)^2 \cdot C_{oss} \cdot F$ losses per MOSFET previously calculated to occur within the 300 volt, 1.6 MHz Class-D power amplifier *operating at unity VSWR*. Comparing equation (2), that of body diode reverse recovery loss as a function of VSWR in a Class-D power amplifier, with equation (3), that of non-zero drain voltage switching loss as a function of VSWR in a Class-E power amplifier, it is not until an 30:1 capacitive VSWR is reached in both circuits that the VSWR-related losses of a Class-E power amplifier exceed those of the Class-D.

To allow reliable transmitter operation into any kind of "real world" VSWRs, a Class-D power amplifier must therefore be designed with a much higher derating factor than for a comparable Class-E power amplifier to withstand the increased stresses it would encounter.

Optimum MOSFET Voltage Rating

Since the $(B+)^2 \cdot C_{oss} \cdot F$ switching losses of the Class-D power amplifier are proportional to the power amplifier operating voltage squared, the efficiency, and consequently, the reliability of the Class-D circuit can be improved by operating it from lower B+ voltages. Additionally, Class-D power amplifiers which have been designed to avoid the problems associated with MOSFET body diode conduction incorporate Schottky diodes in parallel with each MOSFET. These MOSFETs must then be 100 volt rated parts to correspond with the maximum voltage rating of available Schottky diodes. The Class-E power amplifier, on the other hand, has much less susceptibility to body-diode conduction problems and no $(B+)^2 \cdot C_{oss} \cdot F$ losses, so there is no similar incentive to utilize lower-voltage MOSFETs. When only conduction losses are considered, what then is the optimum voltage rating of MOSFET devices for maximum power-per-device?

When considering conduction losses as the sole limiting factor for the MOSFET power handling capability as is the case for the Class-E power amplifier, there exists a figure of merit for silicon utilization, in terms of maximum power-output capacity per MOSFET die area as a function of device drain voltage rating. This Silicon Utilization factor is inversely proportional to the ratio of MOSFET conduction loss to output power. It is given by the following equation:

$$SU = \frac{V_{ds} \cdot \Theta_{jc}^{1/2}}{R_{ds}^{1/2}} \quad (4)$$

where
SU = silicon utilization factor
$V_{ds}$ = peak drain voltage for part
$R_{ds}$ = 'on' resistance for part, Ω
$\Theta_{jc}$ = thermal resistance, junction-to case, C°/W

The Silicon Utilization factors for selected MOSFETs are listed in Table 1. From this it can be seen that the power-per-device of a given die area is maximum for devices in the 500 to 600 volt range. The values here are nearly twice that of 100 volt devices. Consequently, the conduction losses of a power amplifier utilizing 100 volt MOSFETs can be nearly halved by utilizing 500 volt devices. Consequently, unlike the Class-D power amplifier, the Class-E circuit can most reliably utilize the higher-voltage-rated MOSFETs and exploit the higher operating efficiencies inherent in their use.

Combining of Power Amplifier Outputs

The waveforms present at the output of the Class-E power amplifier are roughly sinusoidal in nature. Compared to the 'square-wave' voltage waveforms generated in a Class-D power amplifier, those of the Class-E circuit have their high frequency harmonics attenuated by roughly 6 dB-per-octave. This means that the Class-E power amplifier is less likely to excite any high frequency resonances which may be present in the power amplifier output combining transformer. Furthermore, the task of harmonic filtering a Class-E power amplifier is eased, as well.

Failure Performance

When MOSFETs do fail, the failure mode is typically a short circuit from drain to source, or from drain to gate, which by virtue of the MOSFET gate drive circuitry will also present a low-impedance path from drain to source. In a Class-D power amplifier, after the failure of one MOSFET, the MOSFET occupying the other leg of the half-bridge will then see a low impedance path between B+ and its return during its conduction period. Consequently, its drain current will only be limited by its "on" resistance, and the source impedance of the B+ supply. This will result in the rapid over-heating of this other MOSFET, and its destruction also. As a result, MOSFET failures in a Class-D power amplifier tend to

Table 1. Silicon Utilization Factor for Selected Devices

| Part Number | $R_{ds}$ | $\theta_{jc}$ | $V_{ds}$ | Silicon Utilization Factor |
|---|---|---|---|---|
| IRF150 [8] | 0.055 | 0.83 | 100 | 388 |
| IRF250 | 0.085 | 0.83 | 200 | 624 |
| IRF350 | 0.3 | 0.83 | 400 | 665 |
| IRF450 | 0.4 | 0.83 | 500 | 720 |
| IXTM10N60A | 0.55 | 0.83 | 600 | 737 |
| IXTM6N80A | 1.4 | 0.83 | 800 | 615 |
| IXTM5N100A | 2 | 0.83 | 1000 | 644 |

occur in pairs, doubling the necessary repair effort. On the other hand, a MOSFET failure in a Class-E power amplifier causes no similar stress in the opposite device, allowing protection circuitry time to act before damage to other components occurs. Failures in a Class-E power amplifier, when they occur, therefore tend to be isolated to a single device.

## SUMMARY

For applications within the AM broadcast band, when compared to a Class-D power amplifier circuit, a Class-E power amplifier of similar power output per number of MOSFETs will exhibit improved efficiency due to the elimination of $(B+)^2 \cdot C_{oss} \cdot F$ switching losses. The Class-E circuit also shows a less rapid decrease in efficiency when operated into non-unity VSWRs, and is virtually immune to turn-off dV/dt failures. These factors combine to make the Class-E power amplifier a more reliable and efficient choice for application in AM broadcast transmitters.


## Acknowledgements

The author wishes to extend thanks to Nat Sokal of Design Automation for assistance in understanding the operation of Class-E circuits, and to Chris Renard and Sandy Blickhan of Broadcast Electronics for assistance in preparing the illustrations used in this paper.


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