Class-E amplifiers and applications at MF, HF, and VHF

Arturo Mediano[1], and Francisco Javier Ortega-Gonzalez[2]
[1]I3A, University of Zaragoza, Zaragoza, E50018, SPAIN
[2]GIRA, Polytechnic University of Madrid, Madrid, 28031, SPAIN

***Abstract*— Class E amplifiers have been used in a very broad frequency range. This paper expose a general review of the basic application of class E amplifiers for lower frequencies (MF, HF, VHF), including typical components, applications, and results.**

***Index Terms*— Class E, power amplifiers, switching amplifiers, MF, HF, VHF**

I. INTRODUCTION

The Class-E amplifier [1], [2], is a type of the so called switchmode amplifiers family. Switchmode amplifiers are characterized by using transistors as switches instead of current sources [3].

Employing switching mechanisms in power amplifiers at high frequencies was a concept hard to assume some decades ago by RF and MW engineers used to work with the slow and low power gain RF power solid state devices available at that moment. They considered that switchmode operation of transistors was appropriated for “low frequency” power supplies, not RF power amplification.

That perception was not fully wrong because the long switching times and parasitics of the solid state power transistors of the 70s and 80s that precluded the use of those devices not only in switchmode but also in some conventional amplification classes such as Class-C with reasonably performance.

That’s why it took a lot of time to the switchmode high efficiency amplification techniques to be widely accepted even nowadays some inertia of the old days still remains to use the conventional amplification design recipes in many applications that could clearly be benefited by the use of high efficiency switchmode amplification.

Traditionally, in the low frequency range (up to 1MHz), class D amplifier was preferred because efficiency and power capability, but in many cases class E amplifier is a better option because simplicity, cost, and size requirements: only one transistor and driver is used. And, increasing frequency, class E is preferred to avoid the cross conduction effect during switching times in two transistors topologies.

Transistors parasitics are the reason why switchmode amplification is difficult to implement at high frequencies, as a matter of facts this is the ultimate reason that preclude the use of power semiconductors in power amplifiers above a determinate frequency, independently of its class of operation. From a waveform point of view transistor parasitics acts as slowing down components that distort the voltage and current waveforms required to operate in a determinate class of operation.

Class-E is designed to cope with the output shunt intrinsic capacitance of a power transistor that is one of its most disturbing parasitics. That output shunt parasitic capacitance of a power transistor is used as a part of its load network at least up to a determinate maximum frequency.

Besides, Class-E is relatively tolerant against slight load impedance tolerance and requires a simple harmonic termination which makes easy the design of wideband circuits.

Class-E amplifiers can even operate beyond its maximum theoretical frequency for nominal operation with some efficiency degradation.

For all these reasons Class-E is among the most popular and effective high efficiency power amplification classes available today for RF and MW power applications [4].

However, Class-E also exhibits some drawbacks such as high peak drain voltage and nonlinear behavior that are being solved by the contributions of new solid state and electronic technologies.

Advancements in linearization techniques such as EER, outphasing, etc. known from some decades ago, but that have experimented a tremendous development in the past few years thanks to latest advancements in digital signal processing and circuit integration, have come to solve the nonlinear limits of Class-E amplification.

Actually the whole RF spectrum from some kHz up to 1GHz can be virtually covered using Class-E switchmode amplifiers even in its nominal mode of operation regardless the application [5], [6], [7].

Class-E amplification allows operation bandwidths of almost one octave (even wider bandwidths [8] are possible if special circuits or some performance degradation is tolerated).

This means, for instance, that virtually any communication service from 10 kHz up to 1 GHz at any output power level can benefit from this technology meeting all its technical requirements while simultaneously achieving considerable improvements in power efficiency compared to conventional amplification techniques.

Additionally, industrial, medical, and scientific applications can use class E amplifiers to generate RF efficiently for a broad range of applications in the MF, HF, and VHF bands.

II. BUILDING TECHNIQUES AND COMPONENTS FOR CLASS E POWER AMPLIFIERS AT HF AND VHF

The proper selection of solid state technology, circuit topology, components, and RF building techniques are crucial to meet the high efficiency goal in class E amplifiers.

A. Building techniques.

Building techniques for high efficiency switchmode amplifiers such as the Class-E amplifier are not different than the techniques used to build other power amplifiers classes at the same frequency band. As a general rule, in order to keep the efficiency as high as possible it is recommended to use low-loss load (matching) networks including low-loss components exhibiting the highest unloaded Q possible.

Low loss lumped components such as porcelain capacitors, air core inductors and ferrite loaded transmission line transformers are usual at the HF band. Inductors can be replaced by transmission lines (usually microstrip printed lines) from VHF and above, once their size is reasonable to be fitted in PCB layouts.

Component parasitic strongly evidences at RF & MW and it evidences much more when currents are high, as it happens in power amplifiers scenarios.

Other practical aspect to take into account is to be aware of the peak voltage and current levels that may be present in the circuit and choosing components that can manage them safely.

It must be noted that peak voltage levels as high as three or four times the power supply voltage, and high current must be expected in some points of the circuit, so, the power capabilities of transistors, passive components and PCB tracks must be known and considered.

Short circuits to ground are often required in power amplifiers but they are extremely difficult to build properly at RF and microwave frequencies (on hybrid circuits using PCB substrates).

Usually arrays of plated via holes or plated slots are used in order to try to get the best possible short circuit but some inductive effects cannot be avoided.

Fig. 1. Components typical for PAs in the HF/VHF range.

An important aspect to take into account is the proper driving of Class-E amplifiers. In spite of its low efficiency, sinusoidal driving is the most usual method to drive Class-E power amplifiers above the HF band because the driving waveforms constraints imposed by circuits parasitics, especially those added by the package of power transistors.

B. Transistors.

From the sixties to the present, semiconductor technology for RF power applications has experienced slow but continuous improvement and today it is possible to use transistors in switchmode at high frequencies with good performance.

Silicon solid state technology allows using switchmode amplification up to high VHF and low UHF regions. MOSFETs and, especially LDMOS, devices are used with great success in the MF to UHF bands.

AsGa technology allows building high efficiency switchmode amplifiers up to the microwave region with low and moderate output power levels and more recent advancements in GaN technology allows using switchmode amplification techniques at the microwave region in high power level applications successfully competing against any other amplification technologies

Especially suitable for Class-E operation where high peak drain voltage is experimented are the new wide-bandgap semiconductors in form of GaN or SiC devices that exhibit very good voltage breakdown performance.

C. Capacitors.

Capacitors no longer work as capacitances beyond their series resonant frequency but sometimes they are used deliberately above its resonant frequency in RF power amplifiers (broadband coupling and DC blocking). High Q capacitors are crucial in RF power amplifier scenarios where impedances and currents are high and consequently power losses are potentially high.

The most used low loss capacitor in power amplifier design using transistor is the porcelain multilayer type. Several manufacturers provide low loss capacitors that can provide unloaded Q above 500 or 1000. There are other capacitor technologies really good for HF-VHF ranges based on mica dielectrics such as “metal clad mica” and “dipped silver mica” capacitor (very common in the past).

Variable capacitors are not very common in power amplifier designs. Usual technologies were mica compression and air dielectric (piston, etc.) that provide reasonable high unloaded quality factors and current handling. Variable capacitors were mainly used in narrow band amplifiers that required manual tuning and maintenance. Nowadays it is not common to see variable capacitors in new power amplifier designs, especially modern broadband designs.

D. Inductors.

Air core inductors provide, in practice, the highest unloaded quality factors and are the favorite in power amplifier design in the HF and VHF regions. Using low loss plated cooper wire also contributes to keep inductor losses low but achieving quality factors above 150 or 200 is difficult. So inductors are usually the elements with more losses in power amplifier circuits and designers try to avoid them when it is possible.

In the low frequency range, inductors with core need to be designed with core so saturation effects, increased parasitics and losses are a limitation in some applications. Magnetic design in those designs is a key for success. In Fig. 2 and Fig.

4 some typical inductors (with and without core) are shown for the HF/VHF ranges.

A side effect of inductor losses is the RF energy radiation that can be also an important problem to meet some EMI or EMC requirements.

E. Transmission lines.

At frequencies above UHF transmission lines are used to replace inductors but this is not common at HF/VHF ranges. When used, planar transmission lines printed on the amplifier PCB are usually employed in these cases being the microstrip transmission line the most popular by far. Using PCB printed lines focus on the RF performance of PCB substrates: Bakelite or Composite epoxy materials (CEM) PCB substrates are uncommon in power amplifier design because their high losses and poor RF performance. The popular glass-reinforced epoxy substrates such as FR-4 is successfully used up to the UHF region (usually below 700 MHz), at higher frequencies its dielectric losses are sometimes unacceptable for many applications and other substrate materials based on low loss dielectrics such as PTFE or ceramics are mandatory. Gold or silver plating of the transmission lines tracks is also important to reduce power losses.

Capacitors can be hardly be replaced by transmission lines below 1.000MHz because their large size and it is usual to employ mixed networks containing lumped capacitors and printed lines at UHF and above.

F. Transformers.

Transformers are very effective components for impedance transformation in power amplifier design. Their main advantage is its superior broadband impedance transforming capabilities over other impedance transformation technologies such as discrete or mixed impedance transformation networks. They also allow the unbalanced to balanced transformation required by the push-pull amplifier topologies.

At RF frequencies different transformer technologies are used depending on the operating frequency of the amplifier:

- Magnetic coupled transformers (discrete) can only be used at “low” frequencies up to 30 MHz (MMIC exception) because the limits imposed by their parasitics.

- Cable transmission line transformers are used from low HF (3MHz) up to high UHF (1000 MHz).

- Low loss RF cables (semi-rigid PTFE, etc.) are used to implement these transformers because their length is still too long to be implemented using microstrip lines and their topology is not planar. Sometimes these transformers are “loaded” with ferrite cores to improve their performance at low frequencies (providing some magnetic coupling) and to achieve multi-octave operation.

Transmission line transformers typical at MW frequencies (Quarter-Wave, Multi section, Tapered lines) are not preferred in the low frequency range if wavelengths associated require “long” planar transmission lines.

III. TYPICAL APPLICATIONS AT MF/HF/VHF

The range of frequencies from 10kHz to 1GHz covers a lot of applications were class E topologies have been applied with success in communications, industry, medical, and scientific applications. A short review is included in Table I:

TABLE I
EXAMPLES OF CLASS E APPLICATIONS IN HF AND VHF

APPLICATION	**FREQ**
Broadcasting	AM 500kHz-1,6MHz
Broadcasting	FM 88-108MHz
Ham radio	SSB, CW 27MHz, AM/FM from 1.8MHz
Mobile communications	VHF and UHF bands (470MHz)
RFID/NFC RF IDentif. Near Field Comm.	ISM (125kHz, 13.56MHz, 433MHz, 868MHz, etc.)
Transcutaneous implants	AM,ASK,FSK (100kHz-1MHz)
WPT (Wireless power transfer)	CW (30kHz-30MHz)
Induction cooking Induction heating (industry)	CW (30kHz-10MHz)

IV. EXAMPLES AND RESULTS

Two amplifiers in the selected frequency range have been included as examples for the class E technology.

A. Wideband 40m HF band class E PA.

The first example shows a wideband Class-E amplifier for the 40m HF band (Fig. 2).

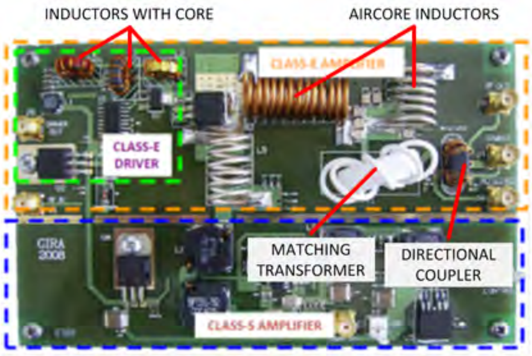

Fig. 2. Wideband Class-E power amplifier for the HF band linearized by means of EER [5]

This amplifier featured 60% fractional bandwidth @7 MHz, 90% peak drain efficiency and 50 Watts output power.

It was designed by means of the admittance synthesis technique providing proper load for Class-E nominal operation at fundamental and harmonics.

The load admittance required to operate the transistor into nominal Class-E was synthesized over almost one octave using a mixed load network made of discrete components and a wideband transmission line transformer. An inexpensive Si MOSFET for switching power applications was used as active device.

The amplifier was driven by a new experimental wideband driver based on another Class-E amplifier designed to decrease driving losses at high frequencies.

The whole amplifier was linearized by means of an Envelope Elimination & Restoration (EER) system.

In Fig. 2 a high efficiency Class-S amplifier section can also be identified that was used as envelope amplifier for the RF Class-E stage.

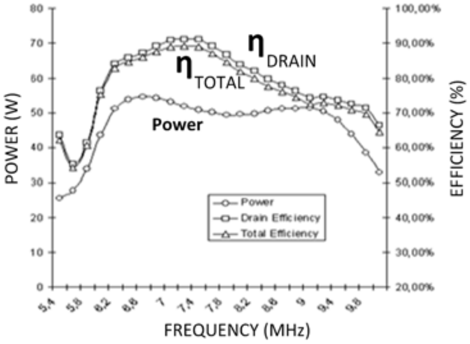

Fig. 3. Output power, drain efficiency and PAE of amplifier [5].

B. Wideband VHF band class E PA.

The second example shows a wideband Class-E amplifier designed for the mid VHF band (Fig. 4).

This amplifier featured 40% fractional bandwidth @100 MHz, 90 % peak drain efficiency and 150 Watts output power.

It was also designed by means of the admittance synthesis technique.

Its relatively high output power (150W), low supply voltage (28 VDC) and transistor package parasitics made difficult the synthesis of the load admittance required at the “virtual drain” plane of the transistor to operate in Class-E over the required wide bandwidth.

A mixed load network made of lumped components and a transformer made of low loss semi-rigid coaxial cable was used to provide the required load to the Si LDMOS packaged transistor used in the amplifier.

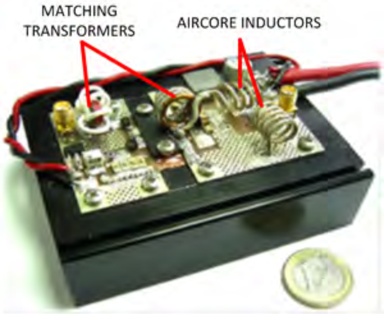

Fig. 4. Wideband class-E power amplifier for the VHF band [6].

V. CONCLUSION

A general review of the basic application of class E amplifiers for MF, HF, and VHF, including typical components, applications, and results has been presented.

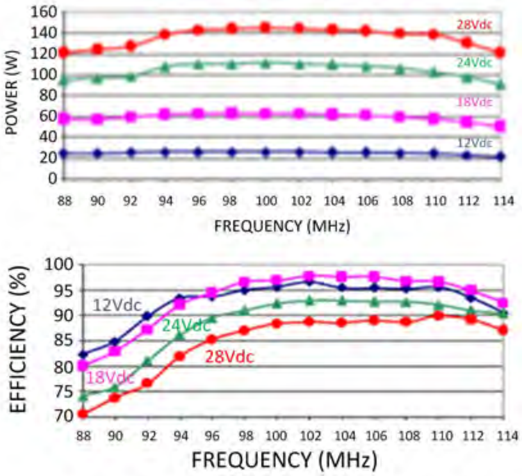

Fig. 5. Measured output power and efficiency versus Vdc [6].

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