Class-E, Class-C, and Class-F Power Amplifiers Based Upon a Finite Number of Harmonics

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***Abstract*—Class-E operation at UHF and microwave frequencies is achieved by using transmission-line networks to provide the drain harmonic impedances of an ideal class-E power amplifier (PA). This paper develops a technique for analysis of such amplifiers that are based upon a finite number of harmonics. The technique is generally applicable to classes E, C, and F as well as PAs with harmonic reactances not corresponding to those of established classes. The analysis shows that the maximum achievable efficiency depends not upon the class of operation, but upon the number of harmonics employed. For any set of harmonic reactances, the same maximum efficiency can be achieved by proper adjustment of the waveforms and the fundamental-frequency load reactance. The power-output capability depends upon the harmonic reactances and is maximum for class F.**

***Index Terms*—Amplifier, class C, class E, class F, power.**

I. Introduction

CLASS-E power amplifiers (PAs) employ a combination of switching action of the active device and the transient response of the load network to achieve high efficiency [1]. Class-E PAs have traditionally been implemented using lumped elements and operated so that the drain capacitance is discharged at the time of turn on, thus eliminating switching loss associated with the drain capacitance.

At UHF and microwave frequencies, lumped-element implementations become impractical, and switching by the active device is far from ideal. More importantly, the capacitance of the drain or collector exceeds that needed for optimum or high-efficiency suboptimum operation [2]. Consequently, implementations at these frequencies use transmission-line networks to adjust the impedance at the fundamental frequency and the reactance at one or more harmonics to those of class E. Since the harmonic impedances of a class-E PA are the result of the drain-shunt capacitance and decrease with frequency, and the third and higher harmonics are of relatively small amplitudes [3], it is held that correct impedances are required only at the fundamental and second harmonic. Beginning with Mader, a number of researchers have successfully used this approach to implement approximations of class-E operation from UHF through X-band [4]–[7].

Virtually all analyses to date are based upon time-domain (transient-response) characteristics [1], [8], [9]. Consequently, a great many things about the several-harmonic approximations of class E are not yet known. These include the benefits of different numbers of harmonics, the effect of variations in harmonic reactances, the optimum impedances for a given implementation, and the like.

Class-F power amplification is based upon a small number of harmonics used to shape the drain waveforms. One or more resonators, traps, or transmission lines cause some harmonic impedances to be high (open) and others to be low (shorted). Typically, the drain voltage contains odd harmonics and approximates a square wave and the drain current contains even harmonics and approximates a half sine wave [10]. However, the shaping of the voltage and current can be reversed [11].

Analyses for class-F operation are available for maximally flat waveforms [12], maximum-power/efficiency waveforms [13], and reduced conduction angles [14]. However, virtually all analyses are based upon ideal open and shorted harmonic terminations and, therefore, do not address the question of the effects of nonideal harmonic impedances as are produced by real filters. High-efficiency operation has also been demonstrated at intermediate impedance levels [15], but the mechanism for this is not explained by existing theory.

Class-C amplification is traditionally defined [16] by a narrow current pulse defined with attendant large numbers of harmonics. As with class E, UHF and microwave implementations are subject to gain rolloff in the transistor. However, the performance of a class-C PA with a finite number of harmonics has yet to be characterized.

This paper develops frequency-domain analysis that is applicable to class-E and class-C PAs, as well as class-F PAs. The method of analysis is then used to determine the behavior of class-E and class-C PAs implemented with a finite number of harmonics. It is also used to determine the characteristics of PAs with harmonic impedances in between those of established classes, e.g., [15], [17]. The results suggest a new fundamental principle for ideal RF PAs implemented with a finite number of harmonics: The number of harmonics determines the maximum attainable efficiency and the harmonic impedances determine the power-output capability.

II. Basic Principles and Definitions

The block diagram of a generic PA is shown in Fig. 1. Active device Q1 (which is shown as an FET, but can be a bipolar junction transistor (BJT) or any other suitable device) is controlled by its drive and bias to act as a current source or switch. DC current $I_{\rm dc}$ is supplied from supply voltage (drain bias) V_{DD} through the RF choke. Load network FL1 is linear and lossless. It provides drain load impedance $R_1 + jX_1$ at the fundamental

Manuscript received August 18, 2000. The work was supported in part by the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration.

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Publisher Item Identifier S 0018-9480(01)06139-7.

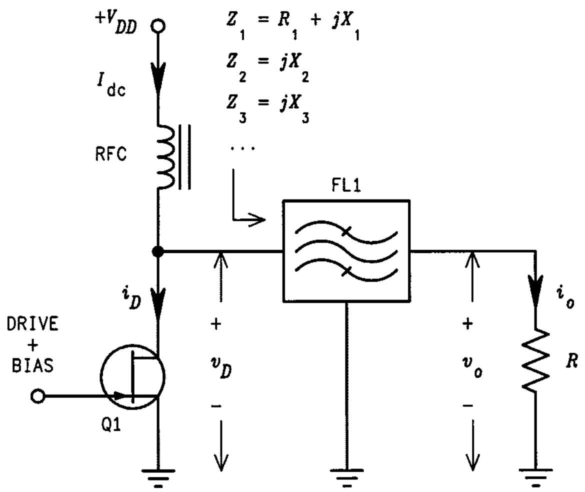

Fig. 1. Generic PA.

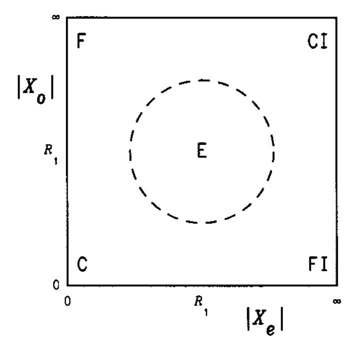

Fig. 2. Classes of amplification.

frequency and pure reactances X_k at the harmonic frequencies. For purposes of analysis, load network FL1 incorporates the reactances of the RF choke and drain capacitance of Q1, which is assumed not to be voltage variable.

The PAs considered in this paper generate power at only the fundamental frequency. In class-C operation, harmonics are present only in the drain current, hence, no power is produced at the harmonic frequencies. In class F, a given harmonic component is present in either the drain voltage or drain current, but not both; hence, no harmonic power is produced. In class E, all or most harmonics are present in both the drain–voltage and drain–current waveforms. However, the voltage and current components are in-phase quadrature and, therefore, do not constitute power at the harmonic frequency.

Generally accepted definitions of classes A–F can be found in [16] and other literature. A mechanism for differentiating the various classes of operation of PAs implemented with small numbers of harmonics is shown in Fig. 2. It is based upon the relative magnitudes of the even (X_e) and odd (X_o) harmonic impedances relative to the fundamental-frequency load resistance R_1. The following definitions are used in this paper for PAs whose operation can be characterized in terms of a small number of harmonics.

- **Class F:** Even-harmonic reactances are low and odd-harmonic reactances are high so that the drain voltage is shaped toward a square wave and drain current is shaped toward a half sine wave.
- **Inverse Class F (FI):** Even-harmonic reactances are high and odd-harmonic reactances are low so that the drain voltage is shaped toward a half sine wave and drain current is shaped toward a square wave.
- **Class C:** All harmonic reactances are low so that the drain current is shaped toward a narrow pulse.
- **Inverse Class C (CI):** All harmonic reactances are high so that the drain voltage is shaped toward a narrow pulse.
- **Class E:** All harmonic reactances are negative and comparable in magnitude to the fundamental-frequency load resistance.
- **Inverse Class E (EI):** As above, but with positive harmonic reactances.

As shown subsequently, the transition from "low" to "comparable" occurs in the range from $R_1/3$ to $R_1/2$. The transition from "comparable" to "high" similarly occurs in the range from $2R_1$ to $3R_1$. The circular boundary is for illustration only. The point at which an amplifier transitions from one class to another is somewhat judgmental and arbitrary, as there is not an abrupt change in the mode of operation. Consequently, it is not productive to try to define precise boundaries between the classes.

All PAs degenerate to class-A operation when there is but a single frequency component (the fundamental). Class B is a special case of class C (conduction angle of 180°) and is approximated by waveforms based upon even harmonics. Class D can be regarded as a push–pull class-F PA in which the two active devices provide each other with paths for the even harmonics.

III. Theory

Analysis of the finite-harmonic PAs is similar to that of the class-F PA, with modifications to allow for effects of harmonic impedances that are neither high nor low relative to the load and presence of reactance at the fundamental frequency.

A. Waveforms

The drain voltage and current waveforms are represented as Fourier series. In analysis of class-F operation [12]–[14], it is sufficient to include only selected harmonic terms (e.g., dc, fundamental, and odd harmonics). However, the allowance of midrange harmonic impedances implies that all harmonic components can, in general, be present in both the voltage and current waveform. The waveforms are, therefore, represented by the forms

$$v(\theta) = V_{DD} + a_{V1}\cos\theta - b_{V1}\sin\theta + a_{V2}\cos 2\theta - b_{V2}\sin 2\theta + \cdots \quad (1)$$

and

$$i(\theta) = I_{\rm dc} + a_{I1}\cos\theta - b_{I1}\sin\theta + a_{I2}\cos 2\theta - b_{I2}\sin 2\theta + \ldots \quad (2)$$

where $\theta = \omega t$. The fundamental-frequency component of either the voltage or current can be set to a convenient value; all other Fourier coefficients are then defined relative to that value. In the subsequent waveform plots, $a_{V1} = 0$ and $b_{V1} = -1$ so that the fundamental-frequency component of the $v(\theta)$ is always $\sin\theta$.

The harmonic components of the voltage and current waveforms are related by the harmonic impedances. The complex amplitudes of a given harmonic component can be represented by

$$V_k = a_{V_k} + jb_{V_k} \tag{3}$$

and

$$I_k = a_{I_k} + jb_{I_k}. \tag{4}$$

The voltage and current components at a given frequency are related by

$$V_k = I_k Z_k. \tag{5}$$

B. Production of Harmonic Components

For theoretical simplicity, it can be assumed that the drain–current waveform is created by the drive and bias applied to the active device. The drain–voltage waveform then follows from interaction of the current components with the harmonic impedances.

In practice, driving the PA to saturation produces the required harmonics with optimum or near-optimum amplitudes through a process similar to that of a saturating class-C PA [16, Sec. 13-2]. Nonlinearities generate the harmonics and the relatively low on-state resistance of the active device during saturation causes them to align to minimize the drain voltage during saturation.

C. Power Output and Efficiency

The effects of the harmonics in a given waveform are manifested in waveform factors [12] that relate the dc component to the fundamental-frequency component and peak as follows:

$$V_{1m} = \gamma_V V_{DD} \tag{6}$$
$$v_{D\,\max} = \delta_V V_{DD} \tag{7}$$
$$I_{om} = \gamma_I I_{\mathrm{dc}} \tag{8}$$
$$i_{D\,\max} = \delta_I I_{\mathrm{dc}}. \tag{9}$$

The output voltage is then related to the waveform factors and load power factor by

$$V_{om} = V_{1m}/\rho = \gamma_V V_{DD}/\rho \tag{10}$$

where

$$\rho = |Z_1|/R_1 = \left(R^2 + X_1^2\right)^{1-2}/R. \tag{11}$$

The power output, dc input, and efficiency are then

$$P_o = \frac{V_{om}^2}{2R_1} = \frac{\gamma_V^2 V_{DD}^2}{2\rho^2 R_1} \tag{12}$$
$$I_{\mathrm{dc}} = \frac{I_{om}}{\gamma_I} = \frac{V_{om}}{\gamma_I R_1} = \frac{\gamma_V V_{DD}}{\rho \gamma_I R_1} \tag{13}$$

and

$$\eta = \frac{P_o}{P_i} = \frac{\gamma_V \gamma_I}{2\rho}. \tag{14}$$

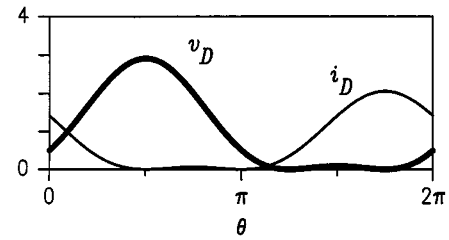

Fig. 3. Waveforms for example second-harmonic class-E PA.

TABLE I
HARMONIC AMPLITUDES AND IMPEDANCES FOR OPTIMUM CLASS E

k	$\lvert V_k \rvert$	$\lvert I_k \rvert$	Z_k for R=1	Z_k for R_1=1
0	1.000	0.5762		
1	1.639	0.8691	1.5260 + j1.1064	1 + j0.725
2	0.8477	0.3120	−j2.7233	−j1.7846
3	0.2222	0.1224	−j1.8155	−j1.1897
4	0.1433	0.1056	−j1.3616	−j0.8923
5	0.08001	0.07344	−j1.0893	−j0.7138
6	0.05907	0.06536	−j0.9038	−j0.5923
7	0.04082	0.05246	−j0.7781	−j0.5099
8	0.03236	0.04774	−j0.6778	−j0.4448
9	0.02470	0.04081	−j0.6052	−j0.3966
10	0.02045	0.03773	−j0.5420	−j0.3552

The power-output capability (output power with $v_{D\,\max} = 1$ V and $i_{D\,\max} = 1$ A) is obtained by dividing power output by peak voltage and current, which yields

$$P_{\max} = \frac{P_o}{v_{D\,\max} i_{D\,\max}} = \frac{\gamma_V \gamma_I}{2\delta_V \delta_I} = \frac{\eta}{\delta_V \delta_I}. \tag{15}$$

D. Solution

The above equations give the performance of an ideal PA with known waveforms. For a given set of harmonic impedances, efficiency is maximized by adjusting the Fourier coefficients and the fundamental-frequency reactance. It is sufficient to vary the Fourier coefficients of one waveform, as those of the second waveform are then given by (5). For simplicity and to provide fundamental PA characteristics, ideal active devices with zero on-state resistances are assumed here.

To find a solution for an ideal PA (zero on-state resistance), it is convenient to set the fundamental-frequency amplitude of one waveform at unity. The minima of the voltage and current waveforms are then calculated, after which the dc components V_{DD} and I_{dc} are adjusted to place the minima at zero. Next, all components are scaled for $V_{DD} = 1$, which gives normalized power output and dc-input current. Finally, the waveform factors γ_V, δ_V, γ_I, and δ_I and the associated efficiency and power-output capability are calculated.

In contrast to class F, it is not possible to optimize the voltage and current waveforms independently when the harmonic terminations can take on arbitrary values. Finding the Fourier coefficients and fundamental-frequency reactance for maximum efficiency must, therefore, generally be accomplished by numerical techniques. In principle, this should be a straightforward process of calculating derivatives of the efficiency and moving the estimates of the parameters accordingly. Alternatively, grid search can be used. In practice, the solution space is often a sharp ridge

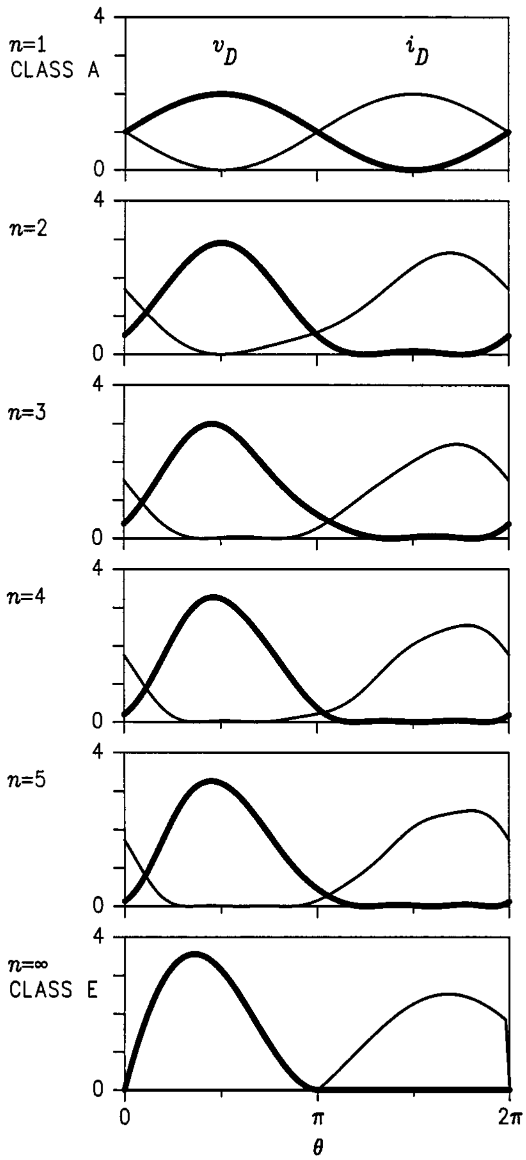

Fig. 4. Waveforms of class E with various numbers of harmonics.

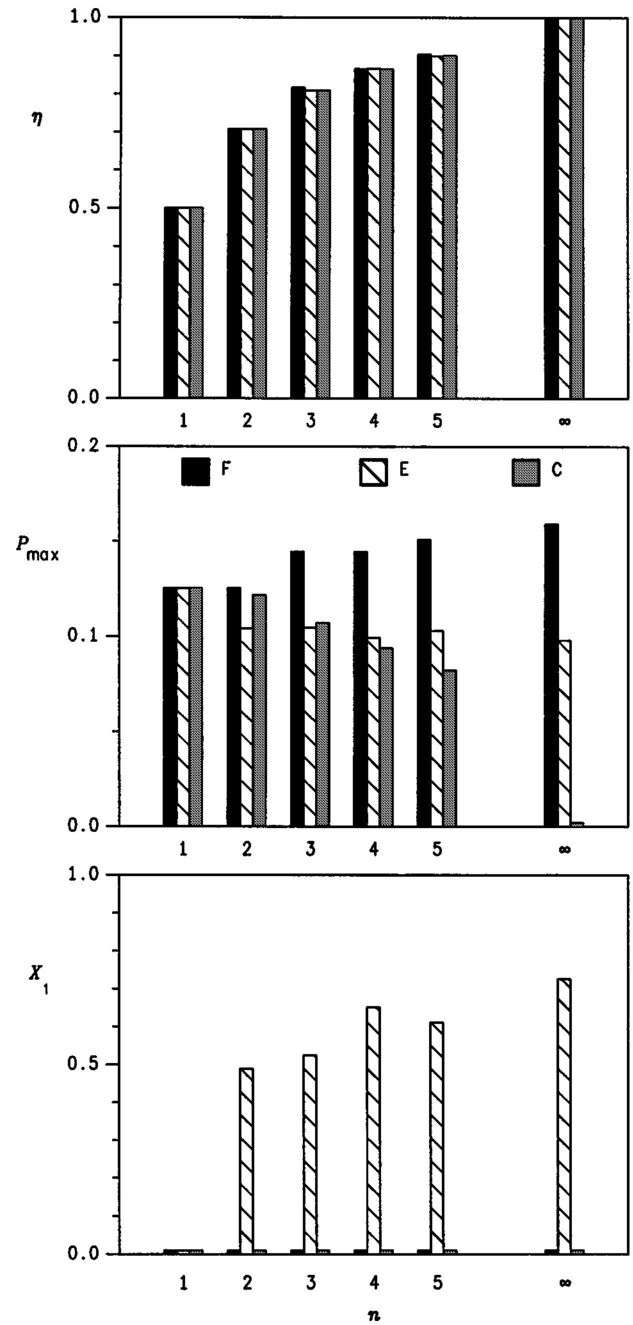

Fig. 5. Performance of ideal PAs with various numbers of harmonics.

with different slopes on either side of the peak and significantly different slopes for different parameters. This results in a long and tedious process that is difficult to automate.

IV. Finite-Harmonic Class E

Frequency-domain analysis of the class-E PA is most readily illustrated by a simple example, after which the characteristics of the class-E PA are determined as a function of the number of harmonics.

A. Second-Harmonic Class E

The basic principles of approximating class-E operation with a finite number of harmonics are illustrated by a simple example in which both voltage and current waveforms are composed of dc, fundamental-frequency, and second-harmonic components. Maximum output is obtained by selecting the maximum-power "second-harmonic-peaking" waveform [13, Fig. 3] for both voltage and current. From [13]

$$\gamma_V = \gamma_I = 1.414 \tag{16}$$

and

$$\delta_V = \delta_I = 2.912. \tag{17}$$

To prevent generation of power at the second harmonic, the second-harmonic components must be in phase quadrature (90°). This requires the fundamental-frequency components to differ in phase by 45°, hence, $Z_1 = R_1 + jR$ and $\rho = 1.414$. To maintain the same relative level of second harmonic to fundamental in the current waveform as in the voltage waveform, $X_2 = -j1.414\,R_1$.

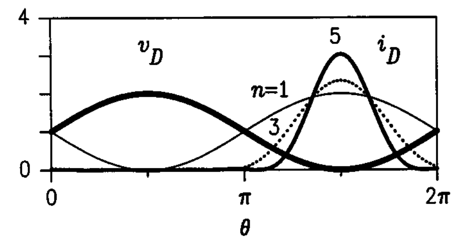

Fig. 6. Waveforms of class C with various numbers of harmonics.

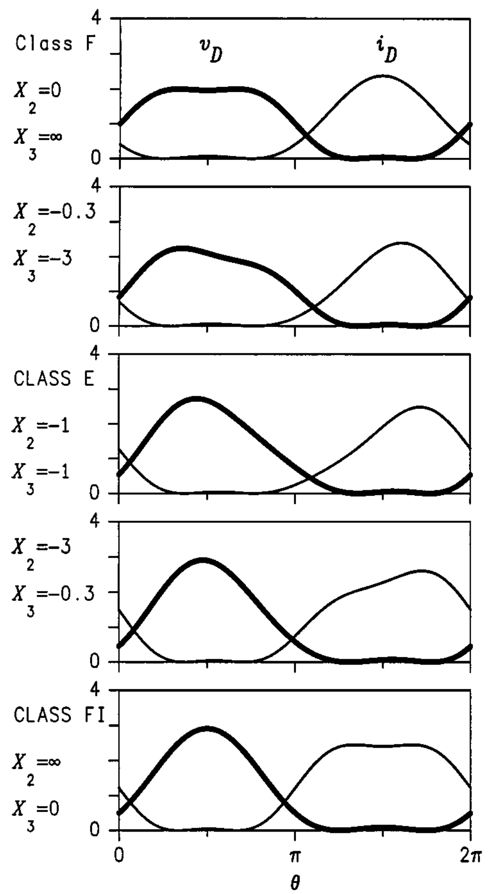

Fig. 7. Waveforms for transition from class F to E to inverse F.

The resultant waveforms (Fig. 3) somewhat resemble those of ideal class E. From the equations of the previous section

$$\eta = 2/2^{1/2} = 0.707 \tag{18}$$

$$P_{\max} = 0.0832. \tag{19}$$

The power-output capability is close to the 0.0981 of an ideal class-E PA. The efficiency is the same as that of a maximum-efficiency second-harmonic class-F PA.

B. Harmonic Impedances of Optimum Class E

The harmonic structure of the drain–voltage waveform of an optimum class-E PA is determined in [3]. Fourier components of voltage and current waveforms are given in Table I.

Optimum operation of an ideal class-E PA [8], [16] requires a series load reactance of $(1 + j1.1525)R$ and a drain shunt susceptance of $0.1836/R$. Combining these produces the fundamental-frequency drain–load impedance

$$Z_1 = (1.526 + j1.1064) \quad R = (1 + j0.725)R_1. \tag{20}$$

The harmonic terminations are from (18), and are ideally pure reactances of

$$X_k = \frac{1 + \pi^2/4}{2k} \quad R = -\frac{3.5692}{k} R_1. \tag{21}$$

In frequency-domain analysis, it is most convenient to relate performance to the fundamental-frequency drain resistance R_1, which is normalized to unity in subsequent waveform diagrams.

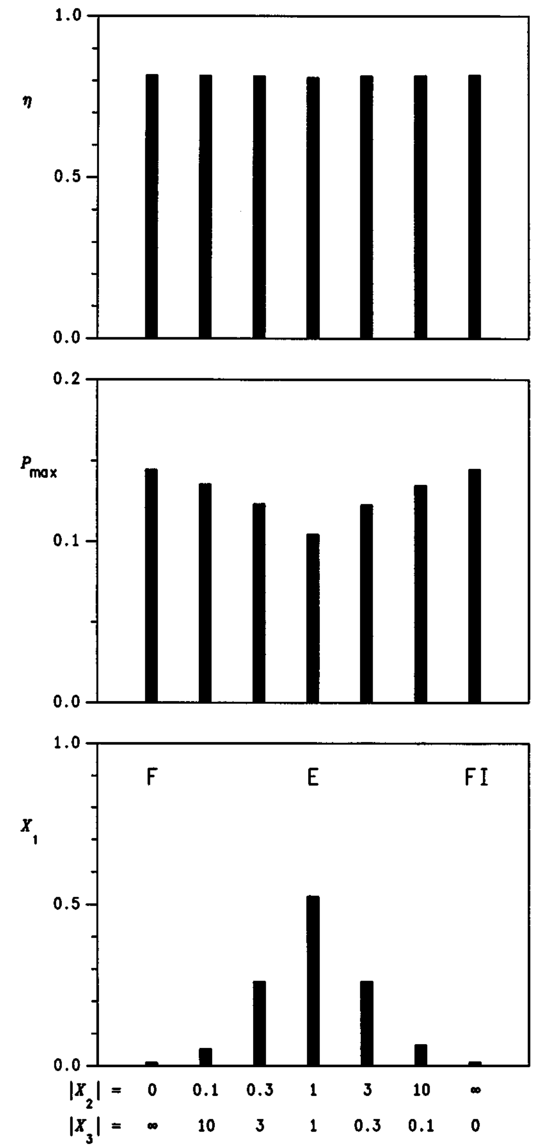

Fig. 8. Performance of three-harmonic PA in F–E–FI transition.

C. Effect of Number of Harmonics

The waveforms for class-E PAs based upon different numbers of harmonics are shown in Fig. 4. The efficiency, power-output capability, and fundamental-frequency reactance for maximum efficiency are shown in Fig. 5. A given value of n means that

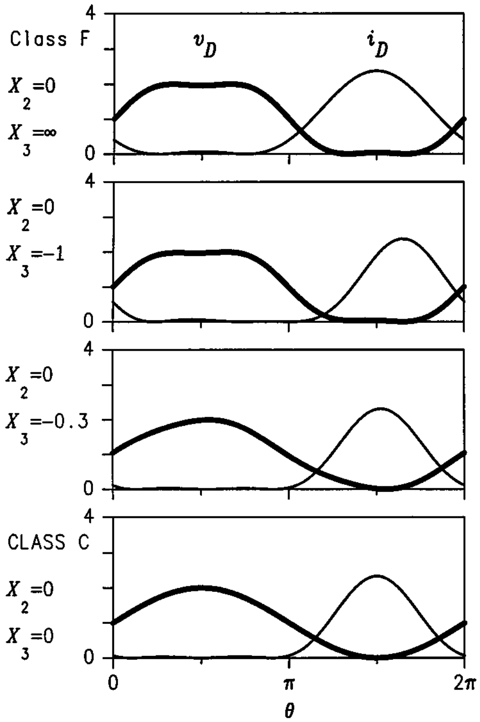

Fig. 9. Waveforms for transition from class F to class C.

all harmonics through n are used. The harmonic reactances are those of the optimum all-harmonic class-E PA (Table I).

For $n = 1$, there are no harmonics and the amplifier operates in class A. For $n = 2$, the voltage waveform has maximum-power characteristics; the current waveform is somewhat flattened at the bottom and is skewed rightward. The efficiency is the same as that of the example of Fig. 2, although the waveforms are different. For $n = 3$, both voltage and current waveforms begin to look like class-E waveforms and the phase shift between them becomes visible. Additional harmonics continue shaping the waveforms toward those of class E, but it is apparent that this is a slow process.

The efficiency of the finite-harmonic class-E PAs are (within numerical error) identical to those of a maximum-power class-F PA with the same number of harmonics. The power-output capability drops quickly (although not monotonically) and for $n \geq 4$ is too close to the 0.0981 of an all-harmonic class-E PA. The required fundamental-frequency reactance immediately jumps to about 0.49 and then slowly and not necessarily monotonically increases toward the 0.725 of an all-harmonic class-E PA. Output power (not shown) immediately jumps from the 0.5 of a class-A PA to 0.81 and then climbs irregularly toward the 0.88 of an ideal class-E PA ($V_{DD} = R_1 = 1$).

V. Finite-Harmonic Class C

The waveforms for class-C PAs are shown in Fig. 6. The efficiency, power-output capability, and fundamental-frequency reactance for maximum efficiency are shown in Fig. 5.

In class C, all harmonics are shorted, hence, the drain voltage is always sinusoidal. As the number of harmonics is increased, the current waveform transitions from the raised sinusoid of class A to a progressively narrower pulse. The efficiency increases with the number of harmonics and is again identical to that of a maximum-power class-F PA with the same number of harmonics. Just as in a conventional class-C PA, the power-output capability decreases with increases in efficiency. The value of $P_{\max}$ is comparable or better than that of class E for $n = 2$ and 3, but drops below that of class E for $n \geq 5$. Any fundamental-frequency reactance alters the alignment of the current maximum with the voltage minimum, hence, $X_1 = 0$ for maximum efficiency.

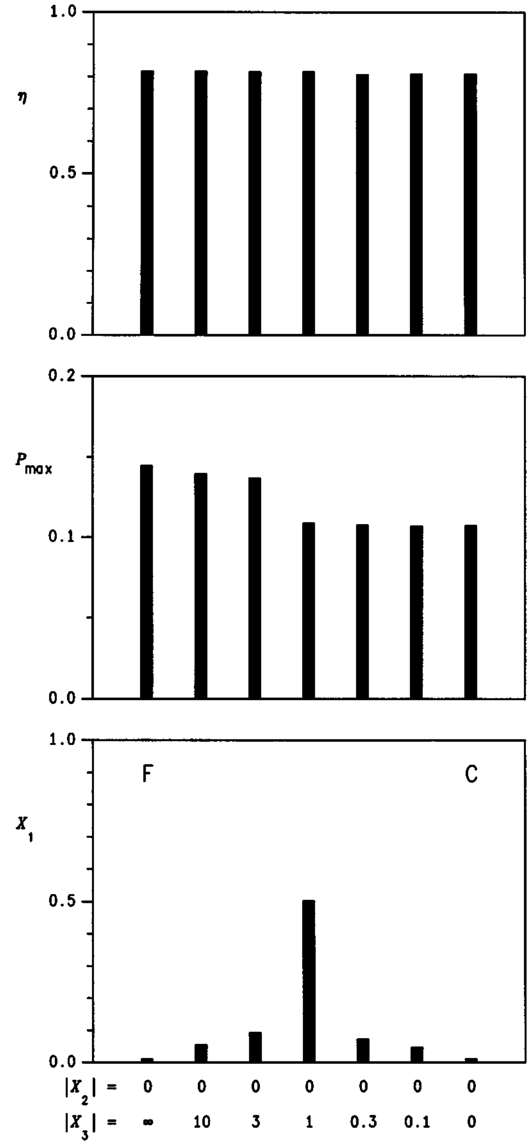

Fig. 10. Performance of three-harmonic PA in F–C transition.

TABLE II
Maximum Attainable Efficiencies

n	η
1	$1/2 = 0.500$
2	$(1/2)^{1/2} = 0.7071$
3	$(2/3)^{1/2} = 0.8165$
4	0.8656
5	0.9045
∞	1

VI. Transitional PAs

This section illustrates how PAs behave as the harmonic impedances change from those of one class to those of another. The two examples are based upon PAs with second and third harmonics.

A. Transition from Class F to E to Inverse F

This transition moves diagonally in Fig. 2 by progressively increasing X_2 from zero to ∞ while decreasing X_3 from ∞ to zero so that $X_3 = 1/X_2$. In ideal class F ($X_2 = 0$, $X_3 = \infty$), the voltage is a third harmonic maximum-power waveform (Fig. 7), while the current is a second harmonic maximum-power waveform. For $X_2 = -0.1$ and $X_3 = -10$, a slight tilt is visible in the voltage waveform and the power-output capability is decreased slightly. For $X_2 = -0.3$ and $X_3 = -3$, the tilt in the voltage waveform is more pronounced and a phase shift is visible in the current waveform. For $X_2 = X_3 = -1$, the voltage waveform leans leftward and the current waveform leans rightward, and resemblance to the all-harmonic class-E waveforms is apparent. The fundamental-frequency reactance reaches a maximum value of 0.53, and the power-output capability reaches a minimum of 0.104 (Fig. 8). As X_2 continues to increase and X_3 continues to decrease, the voltage waveform transitions to a second harmonic maximum-power waveform. The current waveform first develops a tilt (on the right-hand side) and transitions to a third harmonic maximum-power waveform. Finally, when $X_2 = \infty$ and $X_3 = 0$, the amplifier operates in inverse class F. The same efficiency (0.816) is achieved within numerical error for all harmonic reactances.

B. Transition from Class F to C

This transition moves down the left-hand side of Fig. 2 by setting X_2 at zero and progressively decreasing X_3 from ∞ to zero. It is less dramatic and more abrupt than the F–E–FI transition. The waveforms (Fig. 9) remain almost unchanged for $X_3 \leq -3$. At $X_3 = -1$, the current waveform narrows and shifts in phase. At $X_3 = -0.3$, the current waveform remains narrow, but largely shifts back to zero phase. The voltage waveform is mostly sinusoidal by $X_3 = -0.1$. The power-output capability (Fig. 10) remains relatively constant for $X_3 \leq -3$, then abruptly drops to 0.108. The fundamental-frequency reactance for maximum efficiency is relatively low, except near $X_3 = -1$. The same efficiency is again achieved within numerical error for all harmonic reactances.

VII. Conclusions

This paper has presented a method for analysis of class-E, class-C, and transitional-class PAs implemented with a finite number of harmonics. It has also provided a means of determining the effects of less than ideal harmonic reactances in class-F PAs. The question of what harmonic impedances optimize the efficiency of a class-E PA has been rendered moot.

The results presented here demonstrate a new and fundamental generally applicable principle for ideal PAs based upon a finite number of harmonics.

1) For the use of all harmonics through a given highest order, there is a maximum attainable efficiency (Table II).
2) For a given fundamental-frequency load resistance and set of harmonic reactances, there is a set of waveforms (Fourier coefficients) and fundamental-frequency reactance that yields the maximum attainable efficiency.
3) When efficiency is maximized, the power-output capability varies with the harmonic reactances. It is lowest for harmonic reactances that are comparable to the load resistance and highest for class-F harmonic reactances.

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