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Citation: Perreault, David J. "A New Power Combining and Outphasing Modulation System for High-efficiency Power Amplification." 53rd IEEE International Midwest Symposium on Circuits and Systems 2010 (MWSCAS). 441–444. © Copyright 2010 IEEE

As Published: <http://dx.doi.org/10.1109/MWSCAS.2010.5548759>

Publisher: Institute of Electrical and Electronics Engineers (IEEE)

Persistent URL: <http://hdl.handle.net/1721.1/72476>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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A New Power Combining and Outphasing Modulation System for High-Efficiency Power Amplification

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Abstract---This paper describes a new power combining and outphasing system that provides both high efficiency and linear output control. Whereas conventional outphasing systems utilize two power amplifiers, the system introduced here combines power from four or more amplifiers. The proposed technique overcomes the loss and reactive loading problems of previous outphasing systems. It provides ideally lossless power combining, along with nearly resistive loading of the individual power amplifiers over a very wide output power range.

I. Introduction

Radio-frequency (RF) power amplifiers are important in numerous applications, including RF communications, medical imaging, industrial heating and processing, and dc-dc power conversion among many others. Power amplifiers (PAs) are often required to provide *linear* amplification, which encompasses the ability to dynamically control the RF output power over a wide range. It is also often desired to maintain high efficiency across a wide range of output power levels, such that high average efficiency can be achieved for highly modulated output waveforms. Simultaneously achieving both of these requirements – wide-bandwidth linear amplification and high average efficiency – has been a longstanding challenge, and is the goal of this paper.

One concept that has been explored for achieving both linear operation and high efficiency is that of *outphasing*. This technique, which originated in the 1930's [1], is also sometimes referred to as “Linear Amplification with Nonlinear Components” or LINC [2]. In conventional outphasing, a desired output signal is decomposed into two constant-amplitude signals which can be summed to provide the desired output. Because the two signals are of constant amplitude, they can be synthesized with highly-efficient PAs including partially- and fully-switched-mode designs. Combining the two constant-amplitude outputs in a power combining network enables the net output amplitude to be controlled via the relative phase of the two constituent components.

A key consideration with outphasing is how the power combining is done, particularly because many high-efficiency power amplifiers are highly sensitive to load impedance, and their performance and efficiency can heavily degrade due to interactions between the power amplifiers [3-5]. One conventional approach is to use an isolating combiner [6,7]. An isolating combiner provides constant (resistive) loading impedance to each PA independent of the outphasing angle, eliminating any interactions. A consequence of this, however, is that each

PA operates at a constant output power level. Power that is not delivered to the output must instead be delivered elsewhere, usually to an “isolation” resistor, leading to a degradation of efficiency as power is decreased [6,7].

A different conventional approach is to use a lossless combiner, such as a Chireix combiner [1,3,4,6,8-11]. Benefits of the Chireix combining technique, which is non-isolating, include the fact that the combiner is ideally lossless, and that the real components of the effective load admittances seen by the power amplifiers vary with outphasing such that conduction losses can be reduced as power reduces. However, the reactive portions of the effective load admittances are only zero for at most two outphasing angles, and become large outside of a limited power range. This limits efficiency, due both to loss associated with added reactive currents and to degradation of power amplifier performance with (variable) reactive loading [3-5]. It has been observed that the challenges with power combining are a principal reason that outphasing is not a more dominant architecture in RF applications [12].

A goal of the present work is to move beyond the limitations of previous outphasing systems. A new power combining and outphasing modulation system is introduced that overcomes the loss and reactive loading problems of previous outphasing approaches. It provides lossless power combining, along with nearly resistive loading of the power amplifiers over a very wide output power range.

II. THE NEW OUTPHASING SYSTEM

This section describes the proposed new outphasing system. We focus on defining the key system elements and analyzing system behavior. Description of the insights leading to the proposed system and its generalization are deferred to a future paper.

A. System Structure and Control Law

Figure 1 shows an implementation of the proposed system. Whereas conventional outphasing systems utilize two power amplifiers, the system proposed here combines power from four or more amplifiers. (Here we treat the case with four power amplifiers; extensions to more than four amplifiers also exist.) In Fig. 1, the power amplifiers are shown as ideal voltage sources (for analysis purposes only). The power combiner of Fig. 1 has five ports: four connecting to the power amplifiers and one connecting to the load. It is (ideally) lossless, comprising reactive elements having specified reactances at the operating frequency.

We begin by describing how the reactances in the new combiner may be selected. The reactance magnitude X_2 of the combiner is selected close to the load resistance R_L . In particular, we specify a number k equal to or slightly greater than 1 (e.g., $k = 1.05$) and determine X_2 as:

$$X_2 = R_L \frac{2}{k+1} \quad (1)$$

We then select reactance magnitude X_1 in terms of X_2 and k :

$$X_1 = \frac{X_2}{k + \sqrt{k^2 - 1}} \quad (2)$$

Thus, for example, with $R_L = 50 \Omega$, we may choose $X_2 = 48.78 \Omega$ and $X_1 = 35.60 \Omega$ at the operating frequency.

We now analyze the behavior of the network of Fig. 1, and develop a set of relations for controlling the output by outphasing of the sources. The relationship among the source voltages and input currents of the network of Fig. 1 can be shown to be that of (3) below, where we define $\gamma = R_L/X_1$ and $\beta = X_2/X_1$. In vector notation this becomes:

$$\vec{I} = Y \cdot \vec{V} \quad (4)$$

Here we propose a relative phase relationship among the four sources:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \\ V_D \end{bmatrix} = V_S \begin{bmatrix} e^{-j\phi} e^{-j\theta} \\ e^{j\phi} e^{-j\theta} \\ e^{-j\phi} e^{j\theta} \\ e^{j\phi} e^{j\theta} \end{bmatrix} \quad (5)$$

where V_S is the amplitude of the sources and ϕ and θ are the control angles used for outphasing. (The phases may also be adjusted *together* by an additional angle to control the output phase.) The relationship among the sources is shown graphically in Fig. 2.

$$\begin{bmatrix} I_A \\ I_B \\ I_C \\ I_D \end{bmatrix} = X_1^{-1} \begin{bmatrix} \gamma + j(1-\beta) & -\gamma + j\beta & \gamma & -\gamma \\ -\gamma + j\beta & \gamma - j(\beta+1) & -\gamma & \gamma \\ \gamma & -\gamma & \gamma + j(\beta+1) & -\gamma - j\beta \\ -\gamma & \gamma & -\gamma - j\beta & \gamma + j(\beta-1) \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \\ V_D \end{bmatrix} \quad (3)$$

$$Y_{eff,A} = X_1^{-1} (\gamma - \gamma \cos(2\phi + 2\theta) - \gamma \cos(2\phi) + \gamma \cos(2\theta) - \beta \sin(2\phi)) + jX_1^{-1} (1 - \beta - \gamma \sin(2\phi + 2\theta) - \gamma \sin(2\phi) + \gamma \sin(2\theta) + \beta \cos(2\phi)) \quad (6)$$

$$Y_{eff,B} = X_1^{-1} (\gamma - \gamma \cos(2\theta - 2\phi) - \gamma \cos(2\phi) + \gamma \cos(2\theta) + \beta \sin(2\phi)) + jX_1^{-1} (-1 - \beta - \gamma \sin(2\theta - 2\phi) + \gamma \sin(2\phi) + \gamma \sin(2\theta) + \beta \cos(2\phi)) \quad (7)$$

$$Y_{eff,C} = X_1^{-1} (\gamma - \gamma \cos(2\theta - 2\phi) - \gamma \cos(2\phi) + \gamma \cos(2\theta) + \beta \sin(2\phi)) - jX_1^{-1} (-1 - \beta - \gamma \sin(2\theta - 2\phi) + \gamma \sin(2\phi) + \gamma \sin(2\theta) + \beta \cos(2\phi)) \quad (8)$$

$$Y_{eff,D} = X_1^{-1} (\gamma - \gamma \cos(2\phi + 2\theta) - \gamma \cos(2\phi) + \gamma \cos(2\theta) - \beta \sin(2\phi)) - jX_1^{-1} (1 - \beta - \gamma \sin(2\phi + 2\theta) - \gamma \sin(2\phi) + \gamma \sin(2\theta) + \beta \cos(2\phi)) \quad (9)$$

To characterize system behavior, we find the *effective* admittance seen by each source for the stipulated phase relationships (5). The effective admittance at a combiner input port is the complex ratio of current to voltage at the port *with all sources active*. The effective admittances represent the admittances “seen” by the sources when they are operating under outphasing control. Expressions for the effective admittances at the four combiner input ports can be found as (6), (7), (8), and (9) below.

It is readily observed that the effective admittances seen by sources A and D are complex conjugates, as are those seen by sources B and C. Moreover, the expressions all have many individual terms in common.

We next propose an outphasing control strategy for realizing a desired output power while preserving desirable (nearly resistive) loading of the sources. To synthesize a zero-phase load voltage of amplitude $V_{L,ref}$, or equivalently a “commanded” cycle-average power $P_{cmd} = (V_{L,ref})^2/(2R_L)$, we define an intermediate variable r_o :

$$r_o = \frac{2V_S^2}{P_{cmd}} \quad (10)$$

and pick our control angles θ and ϕ in terms of r_o as follows:

$$\theta = ATAN\left(\frac{2r_o X_2}{r_o^2 + X_1^2}\right) \quad (11)$$

$$\phi = ATAN\left(\frac{X_1}{r_o}\right) \quad (12)$$

As will be seen, this control law provides monotonic output control and desirable loading of the individual power amplifiers over a wide operating range.

B. System Attributes and Demonstration

Here we demonstrate the attributes of the proposed system. As an example we consider a system having $V_s = 1$ V, $R_L = 50 \Omega$ and a design value $k = 1.05$ (resulting in $X_2 = 48.78 \Omega$ and $X_1 = 35.60 \Omega$). Figure 3 shows actual output power vs. commanded power. As can be seen, the actual power increases monotonically from zero with commanded power, and matches the commanded power well over the range shown. (At higher commanded power levels the actual power achieved saturates at approximately 0.31 W.) Because the output power is a smooth, monotonic function of command down to zero power, the nonlinearity can be readily addressed through predistortion or other means. This result demonstrates that the new outphasing scheme can smoothly control output power over a wide range down to zero power.

Also of practical importance are the effective impedances seen by the individual power amplifiers across the control range. Figure 4 shows the real and imaginary components of the effective impedances at the four combiner input ports as a function of the commanded cycle-average output power P_{cmd} (as per (6) – (9)). (Simulation of the system supports these results.) This plot illustrates key characteristics of the system. First, it can be seen that the input admittance at each port is highly conductive over a wide range of power commands, and that the susceptive component of the admittance is never large on an absolute scale. This represents a nearly-ideal loading characteristic for many kinds of power amplifiers: the susceptive portions of the effective admittances loading the power amplifiers are small and the conductive components of the admittances are closely matched and scale up with desired power delivery. At very low commanded powers (below the range illustrated), the admittances do increase and become susceptive (becoming entirely susceptive at zero commanded power). However, as the source currents and power drawn in this range are small, this nonideality will be tolerable in many applications. These results demonstrate that the proposed power combiner and outphasing system can meet the goal of providing wide-range power control at high efficiency while preserving desirable loading characteristics of the individual power amplifiers.

A key advantage of the new system is that the susceptive portion of admittance loading the power amplifiers is substantially smaller than with conventional Chireix combining, as illustrated in Fig. 5. One can achieve smaller susceptive loading over a specified power range with the proposed outphasing system than one can with a Chireix combiner. Likewise, for a specified allowable magnitude of susceptive loading one can operate over a greater power range with the proposed system than one can with a Chireix combiner.

V. CONCLUSION

This paper describes a new power combining and outphasing system that provides greatly improved performance characteristics. Whereas conventional outphasing systems utilize two power amplifiers, the system introduced here combines power from four or more

amplifiers. The proposed technique overcomes the loss and reactive loading problems of previous outphasing systems. It provides ideally lossless power combining, along with nearly resistive loading of the individual power amplifiers over a very wide output power range.

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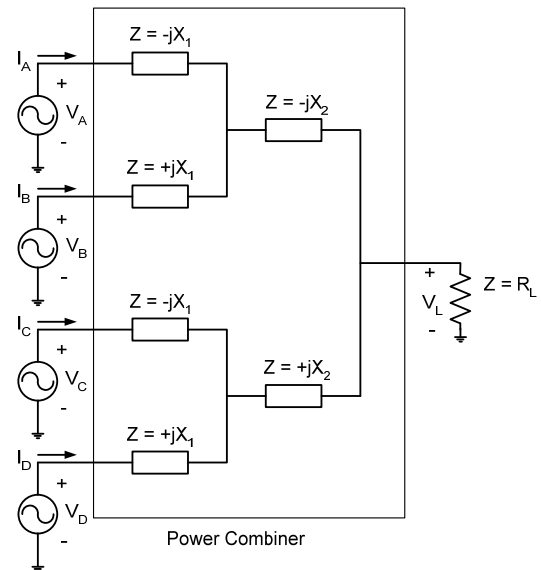


Figure 1 An implementation of the proposed outphasing architecture. This implementation employs four power amplifiers (as compared to two in conventional outphasing). The power combiner comprises reactive elements with specified impedances at the operating frequency.

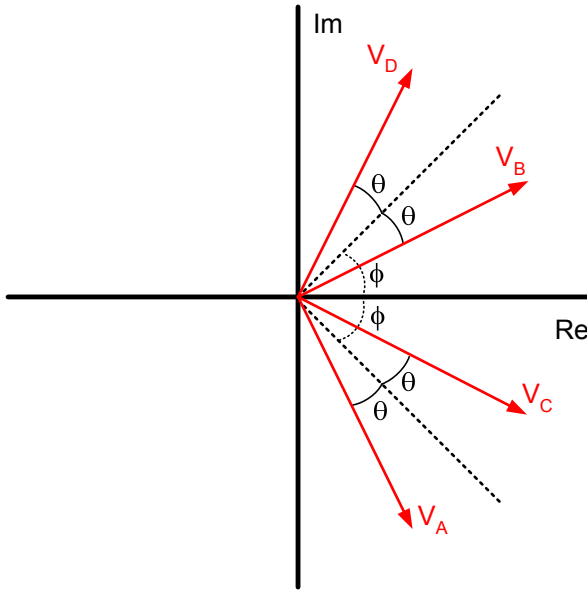


Figure 2 Phasor diagram showing the relationship among the phase voltages. The outphasing control angles ϕ and θ are used to regulate output power while maintaining desirable loading of the sources.

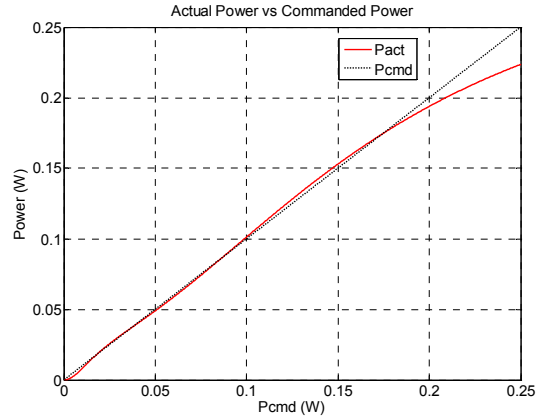


Figure 3 Actual output power vs. commanded power for the example system ($V_s = 1$ V, $R_L = 50$ Ω , $X_2 = 48.78$ Ω and $X_1 = 35.60$ Ω). The actual power increases monotonically from zero with commanded power, and matches the commanded power well over the range shown. At higher commanded power levels the actual power achieved saturates at approximately 0.31 W.

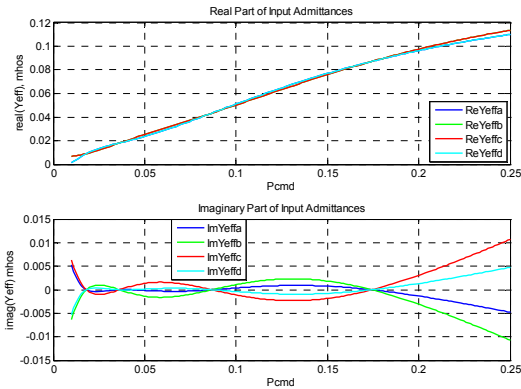


Figure 4 Real and imaginary components of the effective admittances at the four power combiner input ports plotted as a function of the power command P_{cmd} . The plots are shown for the example $R_L = 50$ Ω , $X_2 = 48.78$ Ω and $X_1 = 35.60$ Ω over a commanded power range of [0.01,0.25] W. It can be seen that the imaginary components are small compared to the real components over a wide range (i.e., highly conductive input admittances). Below the range shown, as commanded power goes to zero, the real parts of the admittances go to zero, while the imaginary parts go to ± 0.028 Mhos. (The real parts of $Y_{eff,A}$ and $Y_{eff,D}$ briefly go negative for $P_{cmd} < \sim 0.00875$ W, with a minimum negative real component of ~ -0.0026 Mhos. This indicates power transfer from sources B and C to A and D over this range.) As P_{cmd} is increased above the range shown, real components of the admittances saturate at values in the range 0.15 – 0.16 Mhos, with imaginary parts saturating to values in the range of [-0.075, 0.075] Mhos.

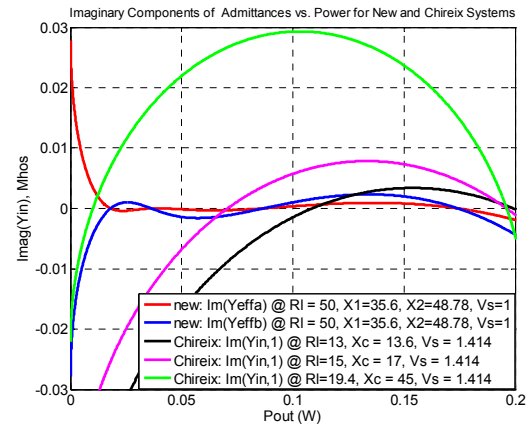


Figure 5 This figure compares the imaginary components of admittances of the new power combiner and outphasing system to that of a Chireix system as a function of total output power. Three example designs of the Chireix system are shown. The Chireix systems are shown for a factor of $\sqrt{2}$ higher input voltage to account for the fact that a Chireix system only has two PAs. With this normalization, the same total power is achieved in the two systems with each PA seeing similar real components of admittance. It can be seen that the new power combining and outphasing system yields much smaller reactive loading than the Chireix combiner over a wide power range. (For reference, the real part of the admittances for $P_{out} = 0.2$ W are each approximately 0.1 Mho.)