Generalized Class-J Theory

Patrick Roblin
The Ohio State University, Electrical & Comp. Eng.
Columbus, Ohio, USA
roblin.1@osu.edu

Hsiu-Chen Chang
The Ohio State University, Electrical & Comp. Eng.
Columbus, Ohio, USA
chang.1329@osu.edu

Jose-Maria Gomez-Perez
Universidad Nacional Autonoma de Mexico, Dept. of Electr. Eng.
Mexico City 04510, Mexico
josemagomez@comunidad.unam.mx

Jose I. Martinez-Lopez
Universidad Nacional Autonoma de Mexico, Dept. of Electr. Eng.
Mexico City 04510, Mexico
ismartz@unam.mx

***Abstract*—Class J has introduced a new rigorous framework for designing broadband PAs. However, the design of broadband Class-J amplifiers remains challenging, as the fundamental impedance termination is non-Foster when the 2nd harmonic is Foster. In addition the peak instantaneous voltage varies by up to 50% as the frequency changes. In this paper, a generalized Class-J theory is introduced. Then a DC tunable broadband PA with constant instantaneous peak voltage and Foster fundamental and harmonic terminations is proposed.**

***Keywords*—power amplifiers, class-B, class-J, broadband PA**

I. Introduction

With the continuous growth of wireless communication and the use of carrier aggregation to increase capacity, the development of high-efficiency power amplifiers (PA) able to operate over multiple adjacent bands have experienced a surge of attention. Class-J amplifiers have attracted a lot of interest as they theoretically allow maintaining the Class-B output power and high efficiency over a wide range of frequencies while keeping the same DC power supply [1]. This is achieved in Class J by allowing the reactance of the fundamental impedance to vary as the reactance load terminating the 2nd harmonic is departing from an ideal short. Note that the Class-J theory is developed at the current-source reference planes. The impedance terminations required at the package reference planes to sustain Class J at the current-source reference planes can be readily determined by nonlinear embedding [2, 3, 4]. However, the design of Class-J PA is affected by the non-Foster variation of the reactance at the fundamental frequencies if a Foster second harmonic reactance is implemented. In other words, the required fundamental reactance is moving anti-clockwise with frequency as the second harmonic moves clockwise. Such anti-clockwise trajectory can only be approached by a high-order impedance termination [4]. Also at the edge of the bandwidth, the peak instantaneous voltage can increase by up to 50% of the peak voltage at the center frequency. Thus the transistor operation at the center frequency is limited to 2/3 of its maximum operating voltage.

In this paper a generalized theory of Class J is developed to show how the peak instantaneous drain voltage V_{max} can be kept constant over the frequency band of interest. This usually leads to a Foster fundamental and harmonic terminations which greatly simplifies the implementation. However as we shall see these improvements come at a certain cost in terms of efficiency and supply variation. Also the new generalized Class-J design space we explore is only applicable to broadband tunable PAs unless supply modulation is used to handle broadband signals.

II. Theoretical Analysis

Consider a class-J PA at the current-source reference planes as shown in Fig. 1.

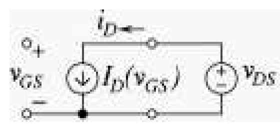

Fig. 1 FET circuit used for class J.

For simplicity, we limit the analysis to the second harmonic for the drain voltage. High drain voltage harmonics are assumed to be perfectly shorted or to have a negligible impact. The drain voltage applied to the device is then of the Class-J form:

$$\begin{aligned} v_{DS}(t) &= V_{DD}-\mathrm{Re}\left\{I_{D1}|Z_L|\exp(j(\omega t+\varphi_1))+jX_2\, I_{D2}\exp(j2\omega t)\right\} \\ &= V_{DD}-I_{D1}\,|Z_L|\; v\,(\theta,\varphi_1) \end{aligned} \tag{1}$$

where we introduce the normalized voltage:

$$v(\theta,\varphi_1)=\cos\theta+R_{21}\cos(2\theta-2\varphi_1+\pi/2) \tag{2}$$

and define the fundamental impedance $Z_L=|Z_L|\exp(j\varphi_1)$. In (1), I_{D1} and I_{D2} are the fundamental and second harmonic components of the drain current i_D whereas I_D is the dc IV:

$$\begin{aligned} i_D &= I_{DC}+I_{D1}\cos(\omega t)\;+I_{D2}\cos(2\omega t)+\;... \\ &= \quad I_D\,[v_{GS}(t),\,v_{DS}(t)] \quad \approx I_D\,[v_{GS}(t)] \end{aligned} \tag{3}$$

In the normalized voltage (2), the harmonic to fundamental ratio R_{21} and the radial phase θ are defined as follows:

$$R_{21}(\omega)=\frac{I_{D2}X_2(\omega)}{I_{D1}\left|Z_L(\omega)\right|},\ \text{and}\ \theta=\omega t+\varphi_1. \tag{4}$$

Note that it is assumed that I_{D1} and I_{D2} are both pure real numbers, which is verified if the IV is only controlled by v_{GS}. This usually holds well if the minimum instantaneous drain voltage is larger than the knee voltage V_{on}.

Let us define $\theta_{\min}$ and $\theta_{\max}$ as the angles for which the normalized drain voltage $v(\theta)$ reaches its minimum v_{min} and maximum v_{max} respectively. They are obtained from the solution of $dv(\theta,\varphi_1)/d\theta=0$ which leads to the identity:

$$R_{21}(\theta_{\min/\max},\varphi_1) = -\frac{\sin(\theta_{\min/\max})}{2\sin(2\theta_{\min/\max} - 2\varphi_1 + \pi/2)}.$$

It results that for each impedance angle φ_1 we can easily build a look up table (LUT) to identify the pairs of solutions $[\theta_{min},\theta_{max}]$ which share the same harmonic voltage ratio $R_{21}(\theta_{min},\varphi_1)=R_{21}(\theta_{max},\varphi_1)$. This provides the possible $\theta_{min}(R_{21},\varphi_1)$ and $\theta_{max}(R_{21},\varphi_1)$. The desired drain voltage boundary conditions can then be formed for each impedance angle φ_1 and possible harmonic voltage ratio R_{21}:

$$V_{\text{on}} = v_{DS}(\theta_{\max}) = V_{DD} - |Z_L| I_{D1} v_{\max},$$
$$V_{\max} = v_{DS}(\theta_{\min}) = V_{DD} - |Z_L| I_{D1} v_{\min}.$$

In these equations the phase definition is such that $I_{D1}>0$ and V_{on} is the minimum instantaneous drain voltage set at the IV knee voltage V_{on} and V_{max} the maximum instantaneous drain voltage attained. In the normal Class-J solution, the DC bias V_{DD} is assumed to be constant and V_{max} varies as the reactance X_2 changes with frequency. In the tunable Class-J solution we shall allow V_{DD} to be tuned for different frequencies of operation while keeping constant the peak instantaneous voltage V_{max} for all frequencies of operation. In this case the required biased $V_{DD}(\omega)$ and load impedance amplitude $|Z_L(\omega)|$ at each radial frequency is given for each reactance $X_2(\omega)$ by:

$$V_{DD} = \frac{v_{\min}V_{on} - v_{\max}V_{\max}}{v_{\min} - v_{\max}},$$
$$|Z_L| I_{D1} = \frac{V_{\max} - V_{on}}{v_{\max} - v_{\min}}. \qquad (5)$$

Envelope tracking is an alternative solution if an instantaneous broadband operation is desired instead of a broadband DC tunable PA. This would require the calculation of the instantaneous frequency as the signal amplitude and phase is modulated. For the case of the DC tunable PA, a continuum of solution is also possible if we allow for a partial variation of both V_{DD} and V_{max} as well as I_{max} the maximum peak current as the frequency changes. We shall refer to this continuum of solutions as *generalized Class J*. As we shall see, a simultaneous Foster implementation of both the fundamental and 2nd harmonic termination may become possible under such generalized operating conditions which extend the design space.

III NUMERICAL SIMULATIONS

In the analytic analysis of the previous section it was seen that there was a continuum of solutions for $\theta_{min}(R_{21},\varphi_1)$ and $\theta_{max}(R_{21},\varphi_1)$ in terms of the harmonic voltage ratio R_{21} for each impedance angle φ_1. To finalize the design we need to select the optimal $R_{21}(\varphi_1)$ ratio which yields the best targeted figure of merit as φ_1 varies. We investigate now the case of the maximization of the drain efficiency.

First to illustrate the procedure, the conventional Class-J conditions are reproduced. As shown in Fig. 2 for the line with purple squares, if the black marker face color is assigned to the highest frequency, a non-Foster variation is observed for the fundamental load for a Foster variation of the 2nd harmonic.

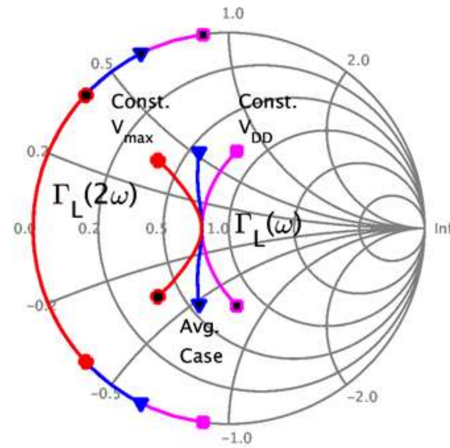

Fig. 2 Fundamental and 2nd harmonic for various Class J.

Fig. 3 (purple line with squares) shows the corresponding variation of the maximum instantaneous drain voltage V_{max} as φ_1 varies.

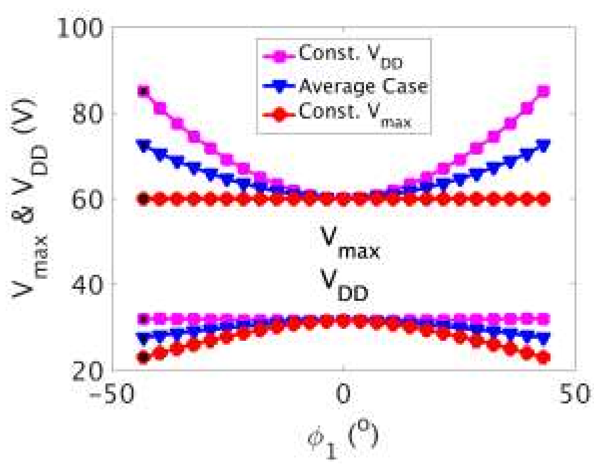

Fig.3 Variation of V_{max} and V_{DD} for various Class J.

We turn now to the case where V_{max} is kept constant and V_{DD} is solved for using (5). The variation of V_{DD} with φ_1 is shown in Fig. 3 (red line & circles). The resulting fundamental and 2nd harmonic reflections coefficients are both observed to be Foster on Fig. 2 (red line & circles). The efficiency only slightly degrades with φ_1 in Fig. 4.

This work was supported by the NSF grant # 60060512.

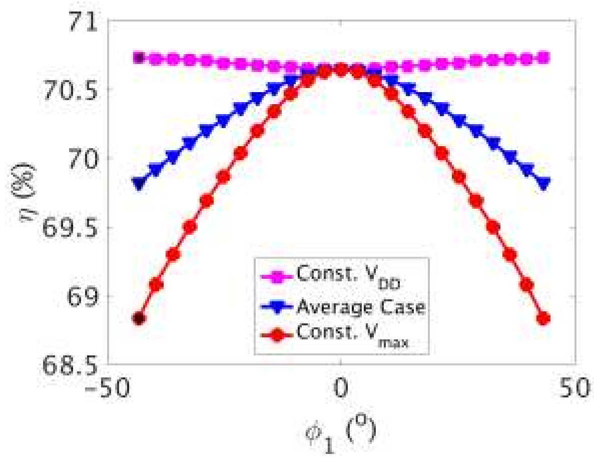

Fig. 4 Variation of the drain efficiency η with φ_1.

The loadlines associated with constant-V_{max} Class J are shown on Fig. 5. Their features are similar to Class J except that the maximum current and I_{D1} varies with φ_1.

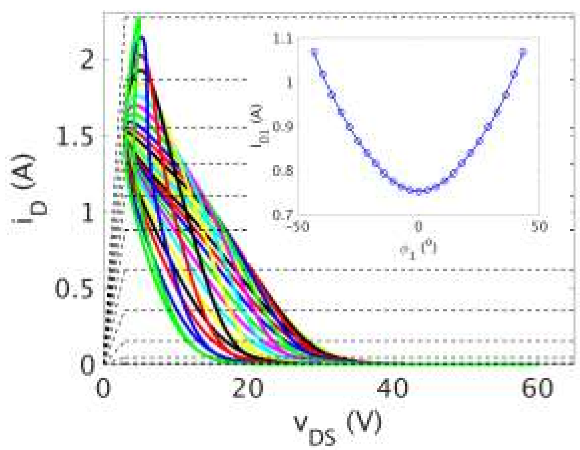

Fig. 5 Loadlines for constant-V_{max} Class J.

In all the three Class-J designs, the output power was kept constant (10.7 W). In the constant-V_{max} Class J, the maximum drain current I_{D1} needs to vary from 0.75 to 1.1 A to maintain a constant output power. Meanwhile as is shown on Fig. 6 the maximum instantaneous drain voltage V_{max} remains at 60 V. To illustrate the continuum of Class-J design, an average case is presented in Fig. 2, 3 and 4 using blue lines and triangles.

So far the generalized Class J was presented at the current-source reference planes. Using the Angelov embedding model reported in [3] it is demonstrated in Fig. 7 that, after projection to the package reference planes, the constant-V_{max} Class J still yields a Foster design for both the ω and 2ω terminations when φ_1 is selected to vary from -43° to 43° in the frequency range [1.8, 2.2] GHz.

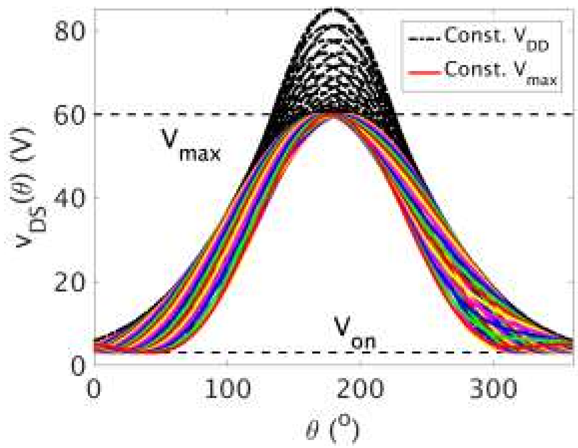

Fig. 6 Drain voltage waveforms for const. V_{DD} and V_{max}.

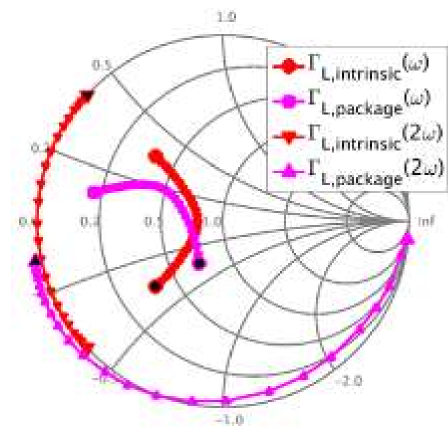

Fig. 7 Projection to package reference planes.

IV. Conclusion

In this paper, the class-J theory was extended for the case where the DC drain supply voltage is allowed to vary with the frequency of operation while keeping a constant maximum instantaneous drain voltage V_{max}. A Foster realization of the fundamental impedance then becomes possible. To keep the output power constant, the maximum drain current and thus the input power must also be varied. The resulting generalized Class J provides the opportunity to realize DC tunable broadband PAs. Supply modulation is only required for broadband signals.

V. References

[1] S. C. Cripps, et al., *IEEE, Microw. Wireless Compon. Lett.*, Vol. 19, No. 10, pp. 665-667, 2009.

[2] A. Raffo, et al., *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 7, pp. 1743–1752, 2009.

[3] H. Jang, et al., *IEEE Trans. Microw. Theory and Techn.*, Vol. 62, No. 9, pp.1986-2002, 2014.

[4] S. Saxena, et al., *IEEE Trans. on Circuits and Systems II: Express Briefs* Vol. 64, No. 7, pp. 837-841, 2016.