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On the Graceful Degradation Performance of Multiple-Device Oscillators

S. SARKAR AND M. C. AGRAWAL

Abstract —**Kurokawa's theory of multiple-device oscillators is extended to an analysis of the graceful degradation performance (GD) of the power-combined oscillators. The analysis shows that the failure of some of the constituent devices of a multiple-device oscillator results in a load-pull effect on the operating devices along with a degradation of power-combining efficiency of the oscillator circuit. A tradeoff exists between power output and circuit improvement of the GD.**

I. INTRODUCTION

In many applications, a number of oscillating devices (such as Gunn's, IMPATT's, etc.) are power combined to generate the required level of microwave power [1], [2]. One of the requirements of such multiple-device oscillators is that the power output degrades gracefully as one or more of its constituent devices fail to operate. The graceful degradation performance (GD) is given by the oscillator power output expressed as a fraction of its no-failure power level. It has been observed [1], [3] that in practice the GD is well below the ideal which corresponds to power reduction by just the amount contributed by the failed devices. Saleh [4] and Kinman *et al.* [5] showed that the deviation of the GD from the ideal is in some way connected with the circuitry involved. In this paper, an attempt has been made to identify the factors which govern the GD of multiple-device oscillators.

Manuscript received April 9, 1984; revised August 20, 1984. This work is a part of a research project supported by the University Grants Commission, India, under the Special Assistance Program.

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II. FACTORS OF THE GD

Typically, a multiple-device oscillator [6] consists of a number N of identical negative conductance devices, each terminated by a conductance G_0 and equally coupled to a power-combining resonator. Fig. 1 shows the coupling between the resonator and one of the devices. Dots signify the existence of the other devices. The device is represented by its negative conductance $-g_D(A_K)$ and susceptance b_D, where A_K is the RF voltage amplitude that the device sees across its terminals $T-T$, when K of devices operate. The resonator is equivalent to a parallel combination of its loss conductance G_C, externally coupled load conductance G_L, a capacitance C, and an inductance L. In Fig. 1, the insert between the device and its terminals $T-T$ shows the effective load conductance $g_L(K)$ and susceptance $b_L(K)$ presented across the device by the entire circuit to the right of $T-T$. Since all the devices are equally coupled to the resonator $(n:1)$ they see the same A_K, $g_L(K)$, and $b_L(K)$.

Assuming that M of the devices belonging to the oscillator described above fail identically and behave as open circuits after failure, it can be shown through Kurokawa's analysis [6], that the GD in decibels is of the form

$$\mathrm{GD} = IDPD + ED + ID, \quad \mathrm{db} \tag{1}$$

where

$$\mathrm{IDPD} = 10\log_{10}\left[\left(\frac{A_{N-M}}{A_N}\right)^2 \frac{G_C + G_L + n^2 G_0 N}{G_C + G_L + n^2 G_0 N(1-M/N)}\right], \quad \mathrm{db} \tag{2}$$

$$\mathrm{ED} = 10\log_{10}\left[\left(1-\frac{M}{N}\right) \frac{G_C + G_L + n^2 G_0 N}{G_C + G_L + n^2 G_0 N(1-M/N)}\right], \quad \mathrm{db} \tag{3}$$

$$\mathrm{ID} = 10\log_{10}(1-M/N), \quad \mathrm{db}. \tag{4}$$

The ratio of load conductance seen by an individual device for $K = N - M$ to that for $K = N$ is [6]

$$\frac{g_L(N-M)}{g_L(N)} = \frac{G_C + G_L + n^2 G_0 N}{G_C + G_L + n^2 G_0 N(1-M/N)}. \tag{5}$$

From (2) and (5) it can be easily seen that the individual diode power degradation (IDPD) represents the effect of device failure on the power output of each individual device. In other words, with device failure, the operating devices experience a load-pull effect. From Kurokawa's analysis [6], it also follows that the efficiency degradation (ED) as given by (3) stands for the effect of device failure on the power-combining efficiency of the oscillator circuit. The ideal power degradation (ID) is given by (4). Thus, the factors of the GD are represented by its three components IDPD, ED, and ID.

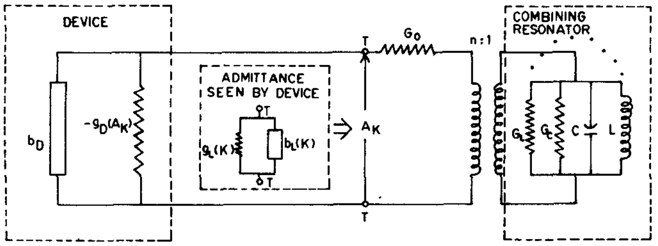

Fig. 1. Coupling between a device and the power-combining resonator of a multiple-device oscillator.

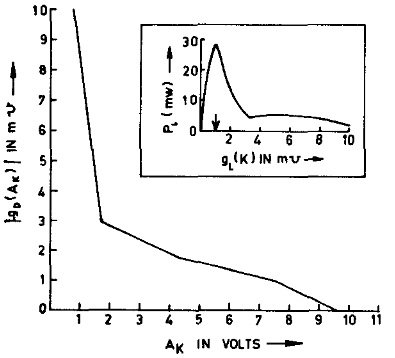

Fig. 2. Device negative conductance as a function of RF voltage amplitude. Insert shows P_t as a function of $g_L(K)$.

The dependence of the GD on the circuit parameters is evident from (2) and (3). The amplitude ratio A_{N-M}/A_N, to some extent, is determined by the inherent parameters of the devices. Its involvement in (2), therefore, implies a dependence of the GD on the behavior of the devices. When $M \ll N$, it is quite in order to assume that $A_N = A_{N-M}$. For such cases, it readily follows from (1)–(4) that

$$\mathrm{GD} \approx 10\log_{10}(1-M/N)^2. \tag{6}$$

Some experimental observations on the GD [1], [3] can be approximated by (6). This means that the GD is independent of circuit and device parameters, as long as the number of failed devices is negligibly small compared with the number of operating ones.

III. Numerical Example

The analysis just presented shows that the factors which determine the GD are the power-generating inability of the failed devices, the load-pull effect experienced by the operating devices, and a fall in the power-combining efficiency of the oscillator circuit. In order to estimate the contributions of these factors towards the GD, a numerical example will now be presented. For this purpose, a multiple-device oscillator consisting of 10 negative conductance devices is considered. It is assumed that the devices are identical and have a negative conductance function, $-g_D(A_K)$, as shown in Fig. 2, which resembles the same for some of the Gunn diodes [7]. The power output P_t of such a device as obtained from the oscillation condition

$$|-g_D(A_K)| = g_L(K) \tag{7}$$

is shown as a function of $g_L(K)$ in Fig. 2 (insert). For a combination of 10 such devices, the GD and its three components have been calculated from (1)–(4), for $G_C = 0.001$ m℧ and various values of the parameters G_0, G_L, n, and M. The plots of GD, IDPD, ED, ID, and $g_L(K)$ as functions of the relative number of failed devices (M/N) are illustrated in Fig. 3. For the sake of concision, only three cases are shown. G_0 and n for all the three cases are 100 m℧ and 0.6, respectively.

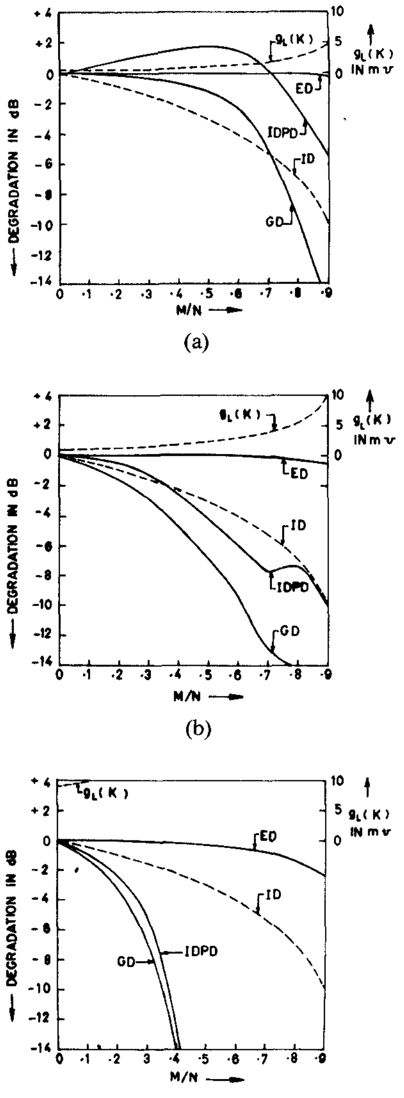

Fig. 3. $g_L(K)$, GD, and its components as function of M/N. (a) $G_L = 1.81$ m℧, $g_L(N) < g_{\mathrm{opt}}$, (b) $G_L = 4.0$ m℧, $g_L(N) = g_{\mathrm{opt}}$, (c) $G_L = 35$ m℧, $g_L(N) > g_{\mathrm{opt}}$.

Fig. 3 shows that the major factor responsible for the deviation of the GD from the ideal (ID) is the load-pull effect represented by IDPD. Interestingly, the IDPD by itself does not necessarily mean degradation. For example, when G_L is 1.81 m℧ (Fig. 3(a)) over a wide range of M/N, the IDPD compensates for the power degradation caused by the power-generating inability of the failed devices (ID) and the fall in power-combining efficiency (ED). The power compensating effect, however, ceases when M/N exceeds 0.71. For $M/N >$ 0.71, the IDPD, like the other two components of the GD, represents degradation. The mechanism, which results in the power compensation and subsequent power degradation as indicated by IDPD in Fig. 3(a), can be understood from a consideration of the influence of M/N on $g_L(K)$. For a G_L of 1.81 m℧, the no-failure terminal load conductance $g_L(N)$ seen by each device is 0.5 m . This is less than the optimum terminal conductance g_{opt}, which is 1.11 m℧ as indicated by an arrow head in Fig. 2 (insert). With the failure of one or more of the devices, $g_L(K)$ first approaches g_{opt} from its initial value of $g_L(N)$. As a result, until $g_L(K)$ is equal to g_{opt},

P_t improves with the increase in the number of failed devices. When $g_L(K)$ equals g_{opt}, P_t reaches its peak. At this stage, maximum power compensation occurs. A further increase in the number of failed devices pulls $g_L(K)$ above g_{opt}, and P_t falls towards its no-failure level (P_N). For a certain M/N, P_t equals P_N and power compensation ceases. If M/N exceeds this limit, P_t falls below P_N and the IDPD makes a negative contribution towards the GD.

A comparison of the IDPD versus M/N plots in Fig. 3(b) and (c) with that in Fig. 3(a) shows that power compensation due to the load-pull effect occurs only when $g_L(N) < g_{\text{opt}}$. For $g_L(N) \geqslant g_{\text{opt}}$, $g_L(K)$ only recedes away from g_{opt} as M/N increases. Consequently, in such cases, power compensation never takes place and P_t degrades as one or more of the devices fail. This is implied by the negative IDPD, over the entire range of M/N in Fig. 3(b) and (c). The illustrations in Fig. 3 also demonstrate that the rate of change of the IDPD with M/N is different for different $g_L(N)$. Depending upon $g_L(N)$, it may even undergo drastic variations as M/N increases (Fig. 3(b)). These deviations in the rate of change of the IDPD arises out of the fact that the P_t variation with $g_L(K)$ is not uniform (Fig. 2) Actually, much depends upon the $g_L(N)$ and P_t variations over the $g_L(K)$ pulling range. The dependence of P_t on $g_L(K)$ is an inherent property of an individual device. Thus, the IDPD variation with M/N is device dependent. The IDPD being one of the major components of the GD, the device dependence of the former strongly reflects on the latter. A better GD will result if the IDPD variation with M/N can be made slower. As (2) shows, this is achieved if the devices used have $g_D(A_K)$ functions of steeper slopes and the product n^2G_0 is small enough to make $g_L(K)$ a slowly varying function of M/N. By meeting the first requirement, GD improvement can be effected by device level considerations. As will be shown subsequently, the second requirement is in opposition to the circuit requirements for high power output, with all the devices operating.

ED, the degradation in power-combining efficiency resulting from device failure, is the least significant component of the GD (Fig. 3). Although small compared with ID and IDPD, ED may, however, be appreciable if a major fraction of the constituent devices fail. Like the IDPD, ED is also dependent on $g_L(N)$ and it is lower in magnitude for lower $g_L(N)$. Thus, circuit improvement of the GD lies in lowering $G_L(N)$. Fig. 3 shows that $g_L(N)$ can be improved by decreasing g_L. The same can be achieved by decreasing G_0 and increasing n [6]. Similarly, simultaneous adjustment of the circuit parameters G_L, G_0, and n can therefore improve the GD. Unfortunately, one cannot take much liberty in such a process. The most important requirement of a multiple-device oscillator is high power output. For maximum power output of such an oscillator there are optimum values for G_L and n. Any deviation of G_L and n from their respective optimum values reduces the oscillator power output. Moreover, for high power-combining efficiency, G_0 should be large [6]. Thus, the GD improvement requirements of low $g_L(N)$ and n^2G_0 do not quite match with the requirements for high power output. Fig. 4(a) and (b) shows that circuit improvement of the GD through G_L and n control can be achieved at the expense of the power output. Fig. 4(c), on the other hand, indicates that the parameter G_0, which should normally be high, loses control over both the GD and the power output if it exceeds a certain limit. Below this limit, a decrease in G_0 improves the GD at the expense of power output. It is thus evident that a tradeoff exists between the circuit improvements of the GD and the power output of a multiple-device oscillator.

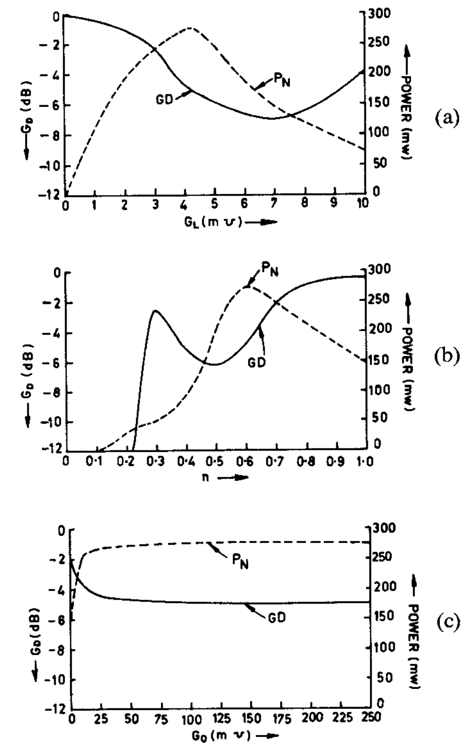

Fig. 4. GD and P_N as functions of (a) G_L for $M/N = 0.4$, $n = 0.6$, $G_0 = 100$ m℧, (b) n for $M/N = 0.4$, $G_L = 4.0$ m℧, $G_0 = 100$ m℧, and (c) G_0 for $M/N = 0.4$, $G_L = 4.0$ m℧, $n = 0.6$.

IV. Conclusions

Based on Kurokawa's theory of multiple-device oscillators [6], the factors which determine the GD of such oscillators are identified. It is found that, with the failure of one or more of the devices belonging to a multiple-device oscillator, the power output of the operating ones undergo an appreciable change due to the load-pull effect. This change in power depends on the circuit and device parameters. The power variation of the operating devices is accompanied by a degradation of the power-combining efficiency of the oscillator circuit. Combining efficiency degradation is also circuit dependent. These two factors, along with the power-generating inability of the failed devices, determine GD. The analysis shows that possibilities of improving the GD by circuit- and device-level considerations exist. The circuit-level improvement of the GD can, however, be achieved only at the expense of the power output of the oscillator.

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