Comparing Simulated Impact of Single Frequency and Multitone EMI for an Integrated Circuit

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Abstract—Electromagnetic immunity performance characteristics for integrated circuits are currently verified using tests involving single-frequency continuous wave disturbances. In real operational environments, however, systems may be exposed to simultaneous interference sources at multiple frequencies. Simulation results obtained for the electromagnetic susceptibility of a simple voltage-controlled oscillator to randomly generated multitone interference are compared with corresponding data obtained for single frequencies. The results obtained are used to assess the validity of the current approach of testing circuit designs for immunity using single frequency noise source. Notable differences in the output response of the circuit to single and multitone interference, which could possibly lead to system malfunctions, are illustrated.

Keywords—Electromagnetic interference, multitone immunity, single frequency, electromagnetic immunity, integrated circuits.

I. INTRODUCTION

Integrated circuits (ICs) are present within the electronic components of most complex systems (e.g., road vehicles, medical and military equipment etc.), often providing safety, mission and/or security critical functions. Increases in the proportion of electrical and electronic components within such systems may lead to higher levels of intra-system emissions, while increasing use of radiocommunications also creates increasingly complex external environments. These internal and external electromagnetic disturbances may lead to system malfunctions due to electromagnetic interference (EMI). Currently, immunity verification testing of IC designs are carried out with reference to BS EN 62132 [1]. The guidelines provided in this standard include testing the ICs with amplitude modulated single frequency continuous wave (CW) disturbances. However, several studies in the literature ([2]–[7]) also discuss the need to demonstrate immunity to multiple frequency (multitone) CW disturbances. The main reason for this is the non-linear behaviour of the electronic systems and the resulting intermodulation products for multitone noise sources, as discussed in [3], [7], [8].

In practice, a comprehensive analysis of immunity to multiple sources is impracticable due to the cost and time required to evaluate the potentially infinite range of possible combinations of frequencies, amplitudes, polarizations and waveform modulations. Nonetheless, more limited multitone testing is possible [9] and has also been identified as a possible approach in at least one immunity test standard [10].

More typically, system components at different hierarchical levels are tested with single frequency noise sources with an amplitude equivalent to, or higher than, the net amplitude of multiple noise sources that are reasonably foreseeable in the expected system EM environment [6]. As an example, if the system environment consists of two co-existing noise sources with frequencies \( f_1 \) and \( f_2 \), and corresponding amplitudes \( a_1 \) and \( a_2 \), then the immunity test verification of the component under test is carried out using CW at frequencies \( f_1 \) and \( f_2 \) individually, each with an amplitude \( a_1 + a_2 \) (due to the uncertainty regarding the operational environment). However, for complex systems with many internal and external noise sources this approach becomes impracticable and could potentially lead to over-engineering whilst providing no knowledge as to its true effectiveness.

Prior to immunity testing, simulation tools like Cadence Spectre can be used to predict the susceptibility of IC designs [11]. Simulation has therefore been used to compare the effectiveness of single frequency and multitone interference for a representative IC design. In this study the multitone EMI noise sources are also randomly distributed in frequency, in order to limit the computational burden. In addition, knowledge of the operational electromagnetic (EM) environment could be also be used to further minimise the computational costs.

Section II provides a functional description of the sample IC, a current starved voltage controlled oscillator (VCO), as well as the steps to generate the single and random multitone noise samples for the EMI simulations. In section III, the EMI impact metrics for this test case are defined and the probability of EMI impact causing deviations from the expected operation of the VCO are discussed, for both single and multitone noise samples. The results are summarised in tables to indicate the safety margin that could be achieved by the current immunity testing approach. The conclusions of this analysis, as well as

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plans for future work, are then outlined in the final section of the paper.

II. CASE-STUDY

A. Circuit Function

The VCO circuit model used for the case-study, is assumed as a black-box, with an input supply voltage of 5V direct current (DC) (Vdd), a biasing voltage (Vin) of 1.6 V (to tune the o/p frequency), and the output alternative current (AC) with amplitude, $A_0 = 2.5$ V and frequency, $F_0 = 277$ MHz, as shown in Fig. 1. Immunity of IC-level designs are usually verified by direct power injection (DPI) using conducted EMI at sensitive input pins of the circuit [12]. The incident power level of the single frequency EMI used for DPI tests are generally varied according to ranges provided by EMC standards for ICs [1]. For the simulations carried out in this work, only the impact of EMI coupled into the power supply (Vdd) is considered. The input Vin is assumed to be isolated from any EMI effects. The input supply voltage when exceeding 5.5 V is assumed to be eliminated due to surge protection circuits.

B. Single and Multitone Noise Generation

For the susceptibility analysis of the VCO circuit, several single and multiple EMI sources were simulated. To reduce the computational time, the frequency of all EMI cases (single and multitone) were chosen from within the range 1–10 MHz, 10–100 MHz and 100–300 MHz. The frequencies of all of the single frequency noise sources were chosen to be within any of the frequency sub-domains, denoted $D_1$ (1–10 MHz), $D_2$ (10–100 MHz) and $D_3$ (100–300 MHz). The frequencies of all the single frequency EMI samples were chosen to be within any of the frequency sub-domains. Depending on the selected sub-domain, the single frequency samples are simply categorized as belonging to the sets $\{100\}$, $\{010\}$ or $\{001\}$, which indicate whether the single frequency noise is from the $D_1$, $D_2$ or $D_3$ sub-domains, respectively. The single frequency noise sources were sinusoidal noise waveforms, each with a fixed amplitude of 0.5 V and a zero initial phase. The frequency of each noise sample was uniformly distributed with a fixed increment. For the case-study, 20 noise samples were taken for each sub-domain.

The multitone noise samples were generated by superposition of multiple sinusoidal waveforms (at most three for the case-study), each with a frequency randomly selected uniformly within each sub-domain, assuming that not more than one source can occur in any of the three sub-domains considered. This leads to three possible categories for two-tone sources, denoted by the sets $\{011\}$, $\{110\}$ and $\{101\}$, as well as one combination for three, denoted by $\{111\}$.

The individual EMI signals $i$ for each of the categories $\{a_i, b_i, c_i\}$, where $a_i, b_i, c_i \in \{0,1\}$, are of the form:

$$EMI_i(t) = \frac{0.5}{a_i + b_i + c_i} \sum_{k=1}^{a_i + b_i + c_i} \sin(2\pi f_{ik}t)$$  \hspace{1cm} (1)

where $a_i + b_i + c_i \in \{1,2,3\}$ and the terms $f_{ik}$ for $k \in \{1,2,3\}$ represent the frequency components of the interference.

Using (1) and ensures that the net amplitude (for any number of noise sources considered) is limited to 0.5 V. It should be noted that, the random multitone noise samples generated could be further randomized by taking random amplitude values for each noise source, such that the total amplitude sum is 0.5 V.

III. SIMULATION RESULTS

A. EMI Impact Metrics

The o/p parameters of the VCO circuit that were used to determine the susceptibility due to single and multitone EMI impact are:

- the deviation from the expected output frequency (i.e., $F_0 = 277$ MHz); and
- the deviation from the desired amplitude (i.e., $A_0 = 2.5$ V) at $F_0$.

For each EMI simulation of the VCO circuit design using the Spectre simulation platform in Cadence, the VCO output voltage was recorded for a time-period of 1 $\mu$s. To determine the deviations in frequency $\Delta F_i$, the $SKILL$ mode function of the Cadence software was used. Based on the VCO output voltage this function determines the frequency over every 4 ns of the simulated 1 $\mu$s time-interval as a time-series (see Fig. 2). The output voltage time-series was also converted to frequency-domain by Fourier transform in order to obtain the amplitude corresponding to each frequency component within the data (see Fig. 3).

The relative deviations due to EMI sample $i$, in output frequency over time, $\Delta F_i(t)$, and voltage amplitude at $F_0$, $\Delta A_i(F_0)$, were calculated as follows:

$$\Delta F_i(t) = 100 \left( \frac{(F_0 - F_i(t))}{F_0} \right) \text{(MHz)}$$  \hspace{1cm} (2)

$$\Delta A_i(F_0) = 100 \left( \frac{(A_0 - A_i(F_0))}{A_0} \right) \text{(V)}$$  \hspace{1cm} (3)

The examples shown in Figs. 2–3, correspond to the frequency and amplitude deviations (respectively) caused by two-tone EMI with frequencies of 10.8 MHz and 110.25 MHz, both with amplitudes of 0.25 V.

In general for VCO circuits, deviations of $\pm 5\%$ in the expected output frequency (i.e., 277 $\pm$ 13.85 MHz), and $\pm 10\%$ in the output voltage amplitude at 277 MHz (i.e., 2.5 $\pm$ 0.25 V) are considered to be tolerable. Any EMI impacts exceeding the tolerable limits for either of the two output parameters would be considered to be VCO malfunctions.

B. Single Frequency EMI Impact

Cumulative probability distributions (CPDs) for $\Delta F_i$ and $\Delta A_i$ due to single frequency EMI are shown in Fig. 4 and...

![Fig. 1. Input and output specifications of the VCO model considered for the case-study.](image-url)
Fig. 5, respectively. The CPDs for the VCO output frequency are noticeably smoother than those for the output voltage amplitude. This is because the output frequency data comprises 275 discrete time samples for each of the 20 single frequency EMI cases spread over each of the three frequency bands ($D_1$, $D_2$ and $D_3$).

The lower frequency EMI cases (from sets {100} and {010}) have relatively higher probability of malfunction due to deviation in output frequency, when compared to the higher frequency EMI cases (in {001}), as illustrated in Table I below.

The EMI cases from set {001}, with frequencies in band $D_3$ (100–300 MHz), are found to have a relatively low probability of unacceptable frequency deviation (25%). Output frequency deviations beyond the tolerable range of ±13 MHz were observed for cases taken in all the three sets for single frequency EMI, with probabilities of 74% for class {100}, 69% for class {010}, and 25% for class {001}.

Furthermore, from the analysis done to determine the probability of VCO malfunction due to deviations in output voltage amplitude it is found that the impact of single frequency noise at lower frequencies (in sub-domains $D_1$ and $D_2$) always causes the output voltage amplitude to be unacceptable. As shown in Fig. 4, for all noise cases within sets {100} and {010}, the amplitude of the output voltage amplitude at $F_0$ is less than 2.25 V. For the noise samples in

<table>
<thead>
<tr>
<th>No. of Tones</th>
<th>Noise Class</th>
<th>$P(\Delta F_i &lt; -5%)$</th>
<th>$P(-5% \leq \Delta F_i \leq 5%)$</th>
<th>$P(\Delta F_i &gt; 5%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>0.38</td>
<td>0.26</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>010</td>
<td>0.34</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>001</td>
<td>0.14</td>
<td>0.74</td>
<td>0.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of Tones</th>
<th>Noise Class</th>
<th>$P(\Delta A_i &lt; -10%)$</th>
<th>$P(-10% \leq \Delta A_i \leq 10%)$</th>
<th>$P(\Delta A_i &gt; 10%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>010</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>001</td>
<td>0.29</td>
<td>0.71</td>
<td>0.00</td>
</tr>
</tbody>
</table>
multitone noise samples from set \{110\}, with a total malfunction due to frequency deviation corresponds to \(\Delta F\). 

Increasing the probability of VCO malfunction, for both low frequency contributions from range inference for single frequency EMI impact, the presence of CPDs for \(C\). 

1-100 MHz, than for the band 100-300 MHz. 

susceptible to single frequency EMI at frequencies in the band 

voltage amplitude for the single frequency EMI cases. 

output voltage is always the malfunction mode for output voltage amplitude, i.e. \(P(\Delta F)\). 

noted that, for all single frequency EMI cases simulated, the probability of \(\Delta A\) is zero. Thus insufficient 

output voltage is always the malfunction mode for output 

voltage amplitude for the single frequency EMI cases. 

These results indicate that, the VCO circuit design is more susceptible to single frequency EMI at frequencies in the band 1-100 MHz, than for the band 100-300 MHz. 

C. Multitone EMI Impact 

For the multitone EMI cases, Fig. 6 and Fig. 7 provide the CPDs for \(\Delta F\) and \(\Delta A\) respectively. Similar to the previous inference for single frequency EMI impact, the presence of low frequency contributions from range \(D1\) is found to increase the probability of VCO malfunction, for both \(\Delta F\) and \(\Delta A\), in the multitone cases. 

From Table III, the highest probability of VCO malfunction due to frequency deviation corresponds to multitone noise samples from set \{110\}, with a total probability of 44\% for frequency deviations exceeding the acceptable tolerance of \pm 5\%. Comparing the EMI impact due to two- and three-tone EMI cases, it can be seen that increasing the number of EMI frequencies (which also increases the number of intermodulation products) does not show any significant increase in the probability of malfunction. 

Comparison of the simulation results for single and multitone EMI shows that, the probability of VCO malfunction due to single frequency EMI is much higher than for multitone EMI combinations of the types studied here. 

However, with a tighter tolerance limit on the VCO output voltage amplitude, the probability of multitone EMI causing malfunctions would be higher than for the single frequency EMI cases. This can be observed by comparing the CPD curves of Fig. 5 and Fig. 7, where the multitone noise cases from sets \{011\} and \{110\} are associated with higher VCO output voltage amplitudes. 

IV. CONCLUSION AND FUTURE WORK 

With uncertainty due to limited knowledge of the target system and operational environment, ICs are currently tested with single frequency disturbances at relatively high threat levels, with the aim of ensuring that immunity to multiple frequency threats can be achieved. However, this rule-based approach, could potentially lead to overengineering of EMC designs without the awareness of residual risk of EMI. 

The simulation results obtained for the case study illustrated here show that the studied VCO circuit design has a higher probability of malfunction due to single frequency EMI in comparison to the impact of the multitone EMI cases. Hence its immunity to single frequency EMI disturbances indicates that it also can be expected to have adequate immunity to multitone disturbances that may in practice be encountered in its operational environment.

Nonetheless, the statistical characteristics of the single frequency and multitone results are very different, with the implication that different tolerances on the required performance metrics could potentially result in very different conclusions. 

**TABLE III. PROBABILITY OF FREQUENCY DEVIATION DUE TO MULTITONE EMI** 

<table>
<thead>
<tr>
<th>No. of Tones</th>
<th>Noise Class</th>
<th>(P(\Delta F &lt; -5%))</th>
<th>(P(\Delta F &lt; 5%))</th>
<th>(P(\Delta F &gt; 5%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>011</td>
<td>0.20</td>
<td>0.69</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>101</td>
<td>0.23</td>
<td>0.66</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>0.24</td>
<td>0.56</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td>111</td>
<td>0.18</td>
<td>0.72</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**TABLE IV. PROBABILITY OF AMPLITUDE DEVIATION DUE TO MULTITONE EMI** 

<table>
<thead>
<tr>
<th>No. of Tones</th>
<th>Noise Class</th>
<th>(P(\Delta A &lt; -10%))</th>
<th>(P(\Delta A &lt; -5%))</th>
<th>(P(\Delta A &gt; 10%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>011</td>
<td>0.15</td>
<td>0.85</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>101</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>0.95</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>111</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Fig. 6. CPDs for deviation from the expected VCO output frequency (i.e. 277 MHz) due to the impact of multitone EMI.**

**Fig. 7. CPD for the deviation from the expected VCO output voltage amplitude (i.e. 2.5 V) due to the impact of multitone EMI.**
The simulations leading to this conclusion assume that the amplitude used for the single frequency EMI to be equal to the net amplitude that can be coupled into the circuit (due to surge protection measures), which may not always be the case. Furthermore, the number and range of frequencies investigated is somewhat limited.

As a part of the ongoing research for developing risk-based approaches to EMC engineering, the impact of single frequency and multitone EMI for a more complex circuit design will be undertaken, along with experimental verification of the results using standard immunity measurement techniques.

REFERENCES