### Abstract

As general purpose components, logic devices are used at different frequencies and power supply voltages in many different varieties of applications. This large diversity has produced the need to express a single parameter that can be used in determining the power dissipation of a device in a given application. This application note describes different components of power dissipation and how they may be calculated.
1. Introduction

As general purpose components, logic devices are used at different frequencies and power supply voltages in many different varieties of applications. This large diversity has produced the need to express a single parameter that can be used in determining the power dissipation of a device in a given application.

This application note describes different components of power dissipation and how they may be calculated.

2. Static considerations

2.1. CMOS

When a CMOS device is not switching and the input levels are GND or $V_{CC}$, the p-channel and n-channel transistors do not conduct at the same time; no direct MOS transistor channel path exists between $V_{CC}$ and GND. In practice however, thermally generated minority carriers, which are present in all reverse biased diode junctions, allow a very small leakage current to flow between $V_{CC}$ and GND. As this leakage current is typically a few nA, quiescent CMOS power dissipation is extremely low. Maximum quiescent power dissipation for the above conditions is calculated as:

$$P_D = V_{CC} \times I_{CC}$$  \hspace{1cm} (1)

where:

$I_{CC}$ is specified in the device data sheet.

2.2. BiCMOS

In the case of BiCMOS devices; the current in the output bipolar stage is different when the output is set high or low. This results in two data sheet specifications for quiescent current $I_{CCL}$ and $I_{CH}$. Quiescent power dissipation for input levels of GND or $V_{CC}$ is calculated as:

$$P_D = V_{CC} \times \left( n_1 I_{CCL} + n_2 I_{CH} \right) / (n_1 + n_2)$$  \hspace{1cm} (2)

where:

$n_1$ is the number of outputs LOW
$n_2$ is the number of outputs HIGH

2.3. Input stage current due to $GND < V_I < V_{CC}$

In the case where the input levels of the device are not held at GND or $V_{CC}$, a direct MOS transistor current path can exist between $V_{CC}$ and GND; this leads to additional supply current through the input buffer stage of both CMOS and BiCMOS devices, and additional power dissipation. In device data sheets this is represented as $\Delta I_{CC}$, the additional current due to an input level other than $V_{CC}$ or GND. In the case of 5.5 V logic families this parameter is generally measured at an input voltage of $V_{CC} - 2.1$ V; in the case of 3.3 V logic families it's measured at an input voltage of $V_{CC} - 0.6$ V. Static power dissipation is then calculated as:

$$P_D = V_{CC} \times \left[ (n_1 I_{CCL} + n_2 I_{CH}) / (n_1 + n_2) + n \Delta I_{CC} \right]$$  \hspace{1cm} (3)

where:

$n$ is the number of inputs at the intermediate level.

Note: For CMOS $I_{CCL} = I_{CH} = I_{CC}$, simplifying Equation (3). Table 1 and Table 2 show comparisons of $I_{CC}$ and $\Delta I_{CC}$ for the '244 function of several logic families.
Power considerations when using CMOS and BiCMOS logic devices

### Table 1. Specified \( I_{CC} \) and \( \Delta I_{CC} \) for CMOS families

<table>
<thead>
<tr>
<th>Device</th>
<th>Voltage</th>
<th>( I_{CCQ} )</th>
<th>( V_{I} )</th>
<th>( \Delta I_{CC} )</th>
<th>Units</th>
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<tbody>
<tr>
<td>74HC244</td>
<td>6 V</td>
<td>80</td>
<td>( V_{CC} - 2.1 ) V</td>
<td>450</td>
<td>( \mu A )</td>
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<tr>
<td>74AHC244</td>
<td>5.5 V</td>
<td>40</td>
<td>( V_{CC} - 2.1 ) V</td>
<td>1500</td>
<td>( \mu A )</td>
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<tr>
<td>74LV244</td>
<td>5.5 V</td>
<td>20</td>
<td>( V_{CC} - 0.6 ) V</td>
<td>500</td>
<td>( \mu A )</td>
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<td>74LVC24</td>
<td>3.6 V</td>
<td>10</td>
<td>( V_{CC} - 0.6 ) V</td>
<td>500</td>
<td>( \mu A )</td>
</tr>
<tr>
<td>74ALVC244</td>
<td>3.6 V</td>
<td>10</td>
<td>( V_{CC} - 0.6 ) V</td>
<td>750</td>
<td>( \mu A )</td>
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### Table 2. Specified \( I_{CC} \) and \( \Delta I_{CC} \) for BiCMOS families

<table>
<thead>
<tr>
<th>Device</th>
<th>Voltage</th>
<th>( I_{CCZ} )</th>
<th>( I_{CCL} )</th>
<th>( I_{CCH} )</th>
<th>( V_{I} )</th>
<th>( \Delta I_{CC} )</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>74ABT244</td>
<td>5.5 V</td>
<td>0.25</td>
<td>30</td>
<td>0.25</td>
<td>( V_{CC} - 2.1 ) V</td>
<td>1.5</td>
<td>mA</td>
</tr>
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<td>74LVT244</td>
<td>3.6 V</td>
<td>0.19</td>
<td>12</td>
<td>0.19</td>
<td>( V_{CC} - 0.6 ) V</td>
<td>0.2</td>
<td>mA</td>
</tr>
</tbody>
</table>

### 3. Dynamic considerations

When a device is clocked, power is dissipated through the charging and discharging of on-chip parasitic and load capacitances. Power is also dissipated at the moment the output switches when both the p-channel and the n-channel transistors are partially conducting. This transient energy loss is typically only 10% of that due to parasitic capacitance.

The total dynamic power dissipation per device is:

\[
P_D = \sum (C_{PD} \cdot V_{CC}^2 \cdot f_I) + \sum (C_L \cdot V_{CC}^2 \cdot f_O)
\]  

(4)

where:

- \( C_{PD} \) is the power dissipation capacitance per buffer
- \( f_I \) is the input frequency
- \( f_O \) is the output frequency
- \( C_L \) is the total external load capacitance per output.

It should be noted from the Equation (4), that \( C_{PD} \) is a useful parameter for determining power dissipation in any device for which power dissipation is a linear function of frequency. Fig. 1 shows \( I_{CC} \) as a function of frequency for the devices listed in Table 1 and Table 2. From this we can conclude that for all of Nexperia’s CMOS and BiCMOS logic families \( C_{PD} \) can be used in order to determine the worst case power consumption of a device in a given application.

Fig. 1. Power dissipation as a function of frequency
3.1. Duty cycle considerations with unbalanced outputs

In the case of unbalanced output drive, such as is found in BiCMOS, the output duty cycle could also be considered. Fig. 2 shows the effect of duty cycle on the power dissipation of the 74LVT244. It can be concluded from these measurements that the duty cycle has little effect on the total power dissipation. This is due to the switching currents within BiCMOS products being more dominant than steady state currents.

![Fig. 2. Effect of duty cycle on Average current versus frequency](image)

3.2. Power dissipation due to slow input rise/fall times

When an output stage switches, there is a brief period when both output transistors conduct. The resulting through-current is additional to the normal supply current and causes power dissipation to increase linearly with the input rise or fall time. As long as the input voltage is less than the n-channel transistor threshold voltage, or is higher than V_{CC} minus the p-channel transistor threshold voltage, one of the input transistors is always off and there is no through-current. When the input voltage equals the n-channel transistor threshold voltage (typ. 0.7 V), the n-channel transistor starts to conduct and through-current flows, reaching a maximum at V_{I} = 0.5 V_{CC}. For devices with CMOS inputs, the maximum current is determined by the geometry of the input transistors. When Schmitt triggers are used to square pulses with long rise/fall times, through-current at the Schmitt-trigger inputs will increase the power dissipation (see Schmitt-trigger data sheets).
4. Power dissipation capacitance

$C_{PD}$ is specified in the CMOS device data sheets, the published values being calculated from the results of tests described in this section. The test set-up is shown in Fig. 3. The worst-case operating conditions for $C_{PD}$ are always chosen and the maximum number of internal and output circuits are toggled simultaneously, within the constraints listed in the data sheet. Appendix 1 gives the pin status for devices during a $C_{PD}$ test. Devices that can be separated into independent sections are measured per section, the others are measured per device.

The recommended test frequency for determining $C_{PD}$ is 10 MHz, 50% duty cycle. Loading the switched outputs gives a more realistic value of $C_{PD}$, because it prevents transient through-current in the output stages.

The values of $C_{PD}$ provided in data sheets have been calculated using:

$$C_{PD} = \frac{(I_{CC(ave)} \times V_{CC}) - \left[ (C_L \times V_{CC}^2 \times f_o) + V_{CC} \times I_{STAT} \right]}{V_{CC}^2 \times f_i}$$

(5)

where:

- $C_{PD}$ = power dissipation capacitance (per buffer)
- $I_{CC(ave)}$ = supply current
- $V_{CC}$ = supply voltage
- $C_L$ = output load capacitance
- $f_o$ = output frequency
- $f_i$ = input frequency.
- $I_{STAT}$ = supply current at dc (approx. zero for CMOS).

4.1. Example $C_{PD}$ calculations

**CMOS:**

In the case of 74LVC244, $I_{STAT}$ is negligible and can be considered as zero for the purpose of $C_{PD}$ calculation. The test set-up for the '244 as indicated in Appendix 1 was used, with the load shown in Fig. 3. At $V_{CC} = 3.6$ V, $f_i = 10$ MHz; $I_{CC(ave)}$ was found to be 2.24 mA.

Using Equation (5):

$$C_{PD} = \frac{(2.4 \text{ mA} \times 3.6 \text{ V}) - \left[ (50 \text{ pF} \times 3.6 \text{ V}^2 \times 10 \text{ MHz} ) + 0 \text{ mW} \right]}{3.6 \text{ V}^2 \times 10 \text{ MHz}}$$

$$C_{PD} = 12.2 \text{ pF}$$
BiCMOS:
In the case of 74LVT244, $I_{\text{STAT}}$ cannot be considered as negligible at low frequency. As a result, a higher frequency is recommended for modeling its $C_{\text{PD}}$. The test set-up for the '244 as indicated in Appendix 1 was used to perform a measurement, with the same load shown in Fig. 3, however at a frequency of 30 MHz, $I_{\text{CC(ave)}}$ was found to be 11.53 mA. We then apply Equation (5) with the assumption that $I_{\text{STAT}}$ is negligible.

Using Equation (5):

$$C_{\text{PD}} = \frac{(11.53 \text{ mA} \times 3.6 \text{ V}) - (50 \text{ pF} \times 3.6 \text{ V}^2 \times 30 \text{ MHz})}{3.6 \text{ V}^2 \times 30 \text{ MHz}}$$

$$C_{\text{PD}} = 56.8 \text{ pF}$$

5. Using $C_{\text{PD}}$ to calculate power dissipation

5.1. CMOS device calculation
Consider a 3.6 V application in which every 40 ms a 74LVC244A device is used to buffer four 40 MHz, 75% positive duty cycle signals and two 80 MHz, 75% positive duty cycle signals, for a duration of 25 ms. The unused inputs are tied to 3.6 V, the outputs drive 30 pF loads, and when not buffering, four inputs are held at 3.0 V and two inputs held at GND.

In calculating the average power dissipation we need to consider both the power dissipation for the 15 ms when the device is not buffering, and the power dissipation for the 25 ms when the buffers are active.

In the first 15 ms the device is static and power dissipation is calculated using Equation (2). In this case we have four inputs that are connected to $V_{\text{CC}} - 0.6$ V.

$$P_{D1} = 33.6 \times 10 \mu\text{A} + 4 \times 3.6 \times 500 \mu\text{A}$$

$$P_{D1} = 7.24 \text{ mW}$$

In the second 25 ms the total power dissipation can be estimated as the combination of static the dynamic dissipation due to the four buffers and outputs switching at 40 MHz, and dynamic dissipation due to the two buffers and outputs switching at 80 MHz.

$$P_{D2} = 4 \times (C_{\text{PD}} + C_{\text{L}}) \times 3.6^2 \times 40 \text{ MHz} + 2 \times (C_{\text{PD}} + C_{\text{L}}) \times 3.6^2 \times 80 \text{ MHz}$$

$$P_{D2} = 87.1 \text{ mW} + 87.1 \text{ mW}$$

$$P_{D2} = 174.2 \text{ mW}$$

The average power dissipation is then:

$$P_{D(\text{ave})} = (15 \times 7.24 \text{ mW} + 25 \times 174.2 \text{ mW}) / 40$$

$$P_{D(\text{ave})} = 111.6 \text{ mW}$$

5.2. BiCMOS device calculation
Consider the LVT244 in the same application.

In the case of BiCMOS devices, the duty cycle must be taken into consideration because $I_{\text{CCCL}}$ and $I_{\text{CCCH}}$ are not identical. In the first 15 ms of the application the static power dissipation is calculated using Equation (2) to determine quiescent power dissipation and adding the power dissipation caused by the four inputs that are connected to $V_{\text{CC}} - 0.6$ V.

$$P_{D1} = 3.6 \times (6 \times I_{\text{CCCH}} + 2 \times I_{\text{CCCL}}) / 8 + 4 \times 3.6 \times \Delta I_{\text{CC}}$$

$$P_{D1} = 11.3 \text{ mW} + 2.9 \text{ mW}$$

$$P_{D1} = 14.2 \text{ mW}$$

The power dissipation in the next 25 ms contains in addition to those of the 74LVC244A case the component $I_{\text{STAT}}$. $P_{D1}$ can be used to approximate $I_{\text{STAT}}$. 

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Power considerations when using CMOS and BiCMOS logic devices

\[ P_{D2} = 4 \times (C_{PD} + C_L) \times 3.6^2 \times 40 \text{ MHz} + 2 \times (C_{PD} + C_L) \times 3.62 \times 80 \text{ MHz} + 3.6 \times I_{STAT} \]

\[ P_{D2} = 180 \text{ mW} + 180 \text{ mW} + 14.2 \text{ mW} \]

\[ P_{D2} = 374.2 \text{ mW} \]

It should be noted that in using Equation (3) to determine our dynamic dissipation components we are assuming a rail to rail output swing. As BiCMOS outputs don’t swing rail to rail this will produce a worse case approximation.

The calculated average power dissipation is then:

\[ P_{D(ave)} = (15 \times 14.2 \text{ mW} + 25 \times 374.2 \text{ mW}) / 40 \]

\[ P_{D(ave)} = 239 \text{ mW} \]

6. Results and conclusion

<table>
<thead>
<tr>
<th>Device</th>
<th>Static 15 ms</th>
<th>Dynamic 25 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(I_{CC(ave)}) (mA)</td>
<td>(P_{D1}) (mW)</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
<td>Calculated</td>
</tr>
<tr>
<td>74LCV244A</td>
<td>0.008</td>
<td>0.028</td>
</tr>
<tr>
<td>74LVT244</td>
<td>2.5</td>
<td>9</td>
</tr>
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</table>

Determination of power dissipation is an essential part of system design. By understanding the static and dynamic components of power dissipation, and how they can be modeled; a system designer is able to estimate the worse case power dissipation of an application.

Table 3 shows the comparison of the measured results to those calculated. The values of static and dynamic current that were calculated are within 10% of the measured values. Importantly the calculated values are higher than the measured values. This is due to the calculations being made with worse case data sheet limits. This is considered advantageous in system level power calculations, as it provides extra power budget margin in the application. It can be concluded, from the examples presented, that any device that has a linear relationship between supply current and frequency can be modeled as a single power dissipation capacitance \(C_{PD}\) for the purpose of power dissipation calculations of that device used in any application.

7. References

- Nexperia HCMOS users guide
- Nexperia AN241: Thermal Considerations for Advanced Logic Families
8. Appendix 1: Conditions for $C_{PD}$ tests

**Gates.** All inputs except one are held at either $V_{CC}$ or GND, depending on which state causes the output to toggle. The remaining input is toggled at a known frequency. $C_{PD}$ is specified per-gate.

**Decoders.** One input is toggled, causing the outputs to toggle at the same rate (normally one of the address-select pins is switched while the decoder is enabled). All other inputs are tied to $V_{CC}$ or GND, whichever enables operation. $C_{PD}$ is specified per-independent-decoder.

**Multiplexers.** One data input is tied HIGH and the other is tied LOW. The address-select and enable inputs are configured such that toggling one address input selects the two data inputs alternately, causing the outputs to toggle. With 3-State multiplexers, $C_{PD}$ is specified per output function for enabled outputs.

**Bilateral switches.** The switch inputs and outputs are open-circuit. With the enable input active, one of the select inputs is toggled, the others are tied HIGH or LOW. $C_{PD}$ is specified per switch.

**3-State buffers and transceivers.** $C_{PD}$ is specified per buffer with the outputs enabled. Measurement is as for simple gates.

**Latches.** The device is clocked and data is toggled on alternate clock pulses. Other preset or clear inputs are held so that output toggling is enabled. If the device has common-locking latches, one latch is toggled by the clock. 3-State latches are measured with their outputs enabled. $C_{PD}$ is specified per-latch.

**Flip-flops.** Measurement is performed as for latches. The inputs to the device are toggled and any preset or clear inputs are held inactive.

**Shift registers.** The register is clocked and the serial data input is toggled at alternate clock pulses (as described for latches). Clear and load inputs are held inactive and parallel data are held at $V_{CC}$ or GND. 3-State devices are measured with outputs enabled. If the device is for parallel loading only, it is loaded with 101010..., clocked to shift the data out and then reloaded.

**Counters.** A signal is applied to the clock input but other clear or load inputs are held inactive. Separate values for $C_{PD}$ are given for each counter in the device.

**Arithmetic circuits.** Adders, magnitude comparators, encoders, parity generators, ALUs and miscellaneous circuits are exercised to obtain the maximum number of simultaneously toggling outputs when toggling only one or two inputs.

**Display drivers.** $C_{PD}$ is not normally required for LED drivers because LEDs consume so much power as to make the effect of $C_{PD}$ negligible. Moreover, when blanked, the drivers are rarely driven at significant speeds. When it is needed, $C_{PD}$ is measured with outputs enabled and disabled while toggling between lamp test and blank (if provided), or between a display of numbers 6 and 7.

LCD drivers are tested by toggling the phase inputs that control the segment and backplane waveforms outputs. If either type of driver (LCD or LED) has latched inputs, then the latches are set to a flow-through mode.

**One-shot circuits.** In some cases, when the device $I_{CC}$ is significant, $C_{PD}$ is not specified. When it is specified, $C_{PD}$ is measured by toggling one trigger input to make the output a square wave. The timing resistor is tied to a separate supply (equal to $V_{CC}$) to eliminate its power contribution.
8.1. Pin conditions for $C_{PD}$ tests; devices with 14 to 28 pins

Table 4. Pin conditions for $C_{PD}$ tests

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<thead>
<tr>
<th>Function</th>
<th>Pin number</th>
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</thead>
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<tr>
<td>00</td>
<td>P H C D D O G O D D O D D V -- -- -- -- -- -- -- --</td>
</tr>
<tr>
<td>02</td>
<td>C P L O D D G D D O D D O V -- -- -- -- -- -- -- --</td>
</tr>
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<td>03</td>
<td>P H B D D O G O D D O D D V -- -- -- -- -- -- -- --</td>
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<td>04</td>
<td>P C D O D O G O D O D O D V -- -- -- -- -- -- -- --</td>
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<td>U04</td>
<td>P C D O D O G O D O D O D V -- -- -- -- -- -- -- --</td>
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<td>08</td>
<td>P H C D D O G O D D O D D V -- -- -- -- -- -- -- --</td>
</tr>
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<td>10</td>
<td>P H D D D O G O D D D C H V -- -- -- -- -- -- -- --</td>
</tr>
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<td>11</td>
<td>P H D D D O G O D D D C H V -- -- -- -- -- -- -- --</td>
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## Power considerations when using CMOS and BiCMOS logic devices

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<thead>
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<th>Function</th>
<th>Pin number</th>
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## Power considerations when using CMOS and BiCMOS logic devices

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Power considerations when using CMOS and BiCMOS logic devices

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### Power considerations when using CMOS and BiCMOS logic devices

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# Power considerations when using CMOS and BiCMOS logic devices

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### 8.2. Pin conditions for \(C_{PD}\) tests; devices with > 28 pins

#### Table 5. Pin conditions for \(C_{PD}\) tests

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### Power considerations when using CMOS and BiCMOS logic devices

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## Power considerations when using CMOS and BiCMOS logic devices

### Pin definition

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8.3. Pin conditions for $C_{PD}$ tests; notes and key

**Note:** For 32-bit devices, the $C_{PD}$ set-up of control pins is identical to those of the 16-bit equivalent. The extra inputs are set as D, the extra outputs as O.

**Key**

- $V = V_{CC}$ (in the case of level translators $V1 = 5.5\, V$, $V2 = 3.6\, V$).
- $G =$ ground.
- $H =$ logic 1 ($V_{CC}$).
- $L =$ logic 0 (ground).
- $D =$ don’t care (input either H or L but not switching).
- $C =$ 50 pF load to ground.
- $O =$ an open pin (50 pF to ground is allowed).
- $P =$ input pulse (see Fig. 4)
- $Q =$ half frequency pulse (see Fig. 4)
- $R =$ 1 kW pull-up resistor to an additional supply (not $V_{CC}$)
- $B =$ both $R$ and $C$

![Fig. 4. Input pulse (P) and half frequency pulse (Q)](image)

9. Revision history

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<th>Revision number</th>
<th>Date</th>
<th>Description</th>
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<td>3.0</td>
<td>2023-02-07</td>
<td>Updated to latest Nexperia document standards.</td>
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<tr>
<td>2.0</td>
<td>2002-03-02</td>
<td>Initial version.</td>
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<tr>
<td>1.0</td>
<td>2002-03-01</td>
<td>Pre-publication version.</td>
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List of Tables

Table 1. Specified ICC and δICC for CMOS families........3
Table 2. Specified ICC and δICC for BiCMOS families........3
Table 3. Comparison of measured and calculated results....7
Table 4. Pin conditions for CPD tests.............................9
Table 5. Pin conditions for CPD tests............................15
Table 6. Revision history............................................20
List of Figures

Fig. 1. Power dissipation as a function of frequency............3
Fig. 2. Effect of duty cycle on Average current versus frequency.................................................................4
Fig. 3. Test set-up for CPD determination...............................5
Fig. 4. Input pulse (P) and half frequency pulse (Q)........... 20
Contents

1. Introduction...................................................................2
2. Static considerations...................................................2
  2.1. CMOS.................................................................2
  2.2. BiCMOS............................................................2
  2.3. Input stage current due to GND < \( V_i < V_{CC} \).........2
3. Dynamic considerations..............................................3
  3.1. Duty cycle considerations with unbalanced outputs.....4
  3.2. Power dissipation due to slow input rise/fall times......4
4. Power dissipation capacitance...................................5
  4.1. Example \( C_{PD} \) calculations.................................5
5. Using \( C_{PD} \) to calculate power dissipation.............6
  5.1. CMOS device calculation.......................................6
  5.2. BiCMOS device calculation...................................6
6. Results and conclusion..............................................7
7. References....................................................................7
8. Appendix 1: Conditions for \( C_{PD} \) tests..................8
  8.1. Pin conditions for \( C_{PD} \) tests; devices with 14 to 28 pins.........................................................9
  8.2. Pin conditions for \( C_{PD} \) tests; devices with > 28 pins...15
  8.3. Pin conditions for \( C_{PD} \) tests; notes and key...........20
9. Revision history..........................................................20
10. Legal information........................................................21

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24 / 24