Understanding RS-485 passive fail-safe biasing

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With RS-485 networks, there are periods of time when no driver is actively driving the bus, such as when one driver relinquishes the bus to another driver. During this time, the termination resistors collapse the differential bus voltage to 0V, which is an undefined input level for many RS-485 receivers. Faced with this undefined input, a receiver might output the wrong logic state or worse yet, it might oscillate. The oscillation may be interpreted as an endless stream of message start bits, causing the controller to waste valuable bandwidth trying to service these phantom messages. Fail-safe bus biasing is one way to alleviate this problem.

Passive fail-safe biasing is accomplished through resistor networks of pull-up, termination, and pull-down resistors whose voltage divider action provide a differential dc bus voltage, $V_{\text{AB}}$, when no driver is actively driving the bus (Figure 1).

![Passive fail-safe biasing network for short to medium bus distance](image)

To drive all receiver outputs to the defined idle state of a logic high, $V_{\text{AB}}$ must be higher than the maximum input threshold, $V_{\text{IT-MAX}}$. In addition, sufficient noise margin should be added to allow for operation in harsh industrial environments, thus making $V_{\text{AB}} = V_{\text{IT-MAX}} + V_{\text{Noise}}$. 
This article helps system engineers design successful fail-safe biasing networks by providing equations for calculating the resistor values and the maximum possible bus loading caused by transceivers for single and dual fail-safe terminations. We also present the ISL315x family of high \(V_{OD}\) transceivers, whose common-mode 60 unit loads (ULs) drive capability far exceeds the 32 ULs of standard transceivers.

**Single fail-safe biasing network design**

For short network distances of \(\leq 100\text{m}\) and low- to medium-idle bus voltages of \(0.05\text{V} \leq V_{\text{AB}} \leq 0.3\text{V}\), fail-safe biasing at one bus end will often suffice. For simplification, the network shown in Figure 1 is converted into the lumped equivalent circuit of Figure 2. Note the bias resistors, \(R_B\), and the termination resistors, \(R_{T1}\) and \(R_{T2}\). \(R_{EQ}\) representing the equivalent input resistance of all transceivers connected to the bus.

![Lumped equivalent model of Figure 1 circuit](image)

Prior to deriving the equations for calculating the resistor values, we establish the conditions that must be satisfied for line termination and common-mode loading.

1) The cable end without the biasing network is terminated with \(R_{T1}\), whose value should match the characteristic impedance of the cable, \(Z_0\).

\[
R_{T1} = Z_0 \quad \text{EQ. 1}
\]

2) For line impedance matching during normal operation, the series combination of the two biasing resistors in parallel with the termination resistor, \(R_{T2}\), must match the characteristic cable impedance: \(Z_0 = 2R_{B}||R_{T2}\). Thus, for a given value of \(R_{B}\), \(R_{T2}\) becomes:
3) RS-485 specifies the maximum common-mode load, which a standard compliant transceiver must be able to drive with 32 parallel ULs. One unit load represents a minimum common-mode resistance of around 12kΩ between each signal conductor and ground. Thus, the total common-mode loading of 32 ULs results in a minimum common-mode resistance of \( R_{CM} = 375Ω \).

Because the bias resistors present a common-mode load in addition to the equivalent transceiver input resistance, the parallel combination of \( R_B \) and \( R_{EQ} \) must be greater or equal to \( R_{CM} \): \( R_B \| R_{EQ} \geq R_{CM} \). For a given \( R_B \) value, \( R_{EQ} \) is therefore limited to:

\[
R_{EQ} = \frac{R_B \cdot R_{CM}}{R_B - R_{CM}} \quad \text{EQ. 3}
\]

To find the equation for calculating \( R_{eq} \), we determine the node currents of A and B in Figure 2, and solve for the individual line voltages, \( V_A \) and \( V_B \).

Node A) \[
\frac{V_A}{R_{EQ}} = \frac{V_S - V_A}{R_B} - \frac{V_{AB}}{R_{T2}} - \frac{V_{AB}}{R_{T1}} \quad \Rightarrow \quad V_A = R_{EQ} \frac{V_S}{R_B} - \frac{V_A}{R_{T2}} - \frac{V_A}{R_{T1}} \left( \frac{1}{R_{T2}} + \frac{1}{R_{T1}} \right)
\]

Node B) \[
\frac{V_B}{R_{EQ}} = \frac{V_{AB}}{R_{T2}} + \frac{V_B}{R_B} + \frac{V_{AB}}{R_{T1}} \quad \Rightarrow \quad V_B = R_{EQ} \frac{V_{AB}}{R_{T2}} + \frac{1}{R_{T2}} + \frac{1}{R_{T1}} \cdot \frac{V_B}{R_B}
\]

Then calculating the difference between the line voltages provides the differential bus voltage:

\[
V_{AB} = R_{EQ} \left\{ \frac{V_S}{R_B} - V_{AB} \cdot \left[ \frac{1}{R_B} + 2\left( \frac{1}{R_{T2}} + \frac{1}{R_{T1}} \right) \right] \right\} \quad \text{EQ. 4}
\]

Inserting Eqs. 1, 2 and 3 into EQ. 4 provides the final equation for the dc-bus idle voltage:
And solving for $R_b$ yields the minimum required bias resistor value:

$$R_b \geq \frac{V_S / V_{AB} + 1}{1/R_{CM} + 4/Z_0}$$ \hspace{1cm} \text{EQ. 6}$$

**Common-mode loading**

Because passive fail-safe biasing presents additional common-mode loading, it is necessary to determine the maximum number of transceiver unit loads, $n_{UL}$, that can load the bus without dropping below $R_{CM} = 375\Omega$.

$n_{UL}$ is the ratio of the common-mode resistance of one unit load to the common-mode resistance of the transceiver unit load: $n_{UL} = 12\, k\Omega / R_{EQ}$, and inserting EQ. 3 for $R_{EQ}$ yields:

$$n_{UL} = \frac{12\, k\Omega}{R_{CM} - \frac{R_{EQ}}{R_b}}$$ \hspace{1cm} \text{EQ. 7}$$

This maximum number of transceiver unit loads can be accomplished using $n \times 1UL$, $2n \times 1/2UL$, $4n \times 1/4UL$, or $8n \times 1/8UL$ transceivers.

**Dual fail-safe biasing**

To maintain a constant $V_{AB}$ over long cable lengths, fail-safe biasing at both bus ends is necessary. Each biasing network compensates for the loss of biasing the other network along the cable run. **Figure 3** shows the lumped equivalent circuit of a bus with dual fail-safe biasing.
The requirements for the termination resistors, $R_T$, are the same as for $R_{T2}$ in the single fail-safe biasing network demanding that $Z_0 = 2R_B||R_T$. Hence, for a given $R_B$, $R_T$ must be:

$$R_T = \frac{2R_B \cdot Z_0}{2R_B - Z_0}.$$  \hspace{1cm} \text{EQ. 8}

However, the condition for common-mode loading changes because each conductor now sees two biasing resistors in parallel to ground. Thus, the parallel combination of $R_B/2$ and $R_{EQ}$ needs to be greater or equal to $R_{CM}$: $R_B/2 \parallel R_{EQ} \geq R_{CM}$. Hence, for a given $R_B$ value, $R_{EQ}$ is limited to:

$$R_{EQ} = \frac{R_B \cdot R_{CM}}{R_B - 2R_{CM}}.$$  \hspace{1cm} \text{EQ. 9}

To find the equation for $R_B$, we determine the node currents into A and B. Because the biasing networks are identical, they drive the same amount of current through $R_{EQ}$. Therefore, we have to establish only one current through $R_{EQ}$ and multiply it by a factor of two to determine $V_{AB}$ in the middle of the bus.

**Node A)** \hspace{1cm} \[ \frac{V_A}{R_{EQ}} = 2 \left( \frac{V_S - V_A}{R_B} - \frac{V_{AB}}{R_T} \right) \]

**Node B)** \hspace{1cm} \[ \frac{V_B}{R_{EQ}} = 2 \left( \frac{V_{AB}}{R_T} - \frac{V_B}{R_B} \right) \]
Solving the node currents for the individual line voltages, $V_A$ and $V_B$, and calculating the difference between them provides the differential bus voltage:

$$V_{AB} = \frac{V_s}{R_B} - V_{AB} \left( \frac{1}{R_B} + \frac{2}{R_T} \right)$$

**EQ. 10**

Inserting EQs. 8 and 9 into EQ. 10 provides the final equation for $V_{AB}$:

$$V_{AB} = \frac{V_s}{R_B} \left( \frac{1}{R_{CM} + 4/Z_0} \right) - 1$$

**EQ. 11**

And solving for $R_B$ yields the minimum required bias resistor value:

$$R_B \geq \frac{2(V_s/V_{AB} + 1)}{1/R_{CM} + 4/Z_0}$$

**EQ. 12**

With $R_B$ in place, the maximum number of transceiver unit loads can now be calculated via:

$$n_{UL} = 12k\Omega \cdot \left( \frac{1}{R_{CM}} - \frac{2}{R_B} \right)$$

**EQ. 13**

Note, because the $R_B$ value for dual failsafe biasing is twice the $R_B$ value for single fail-safe biasing, $n_{UL}$ remains the same for both applications.

**Calculation examples**

In the following examples, we calculate the resistor values for the single and dual fail-safe biasing networks of a short and a long data link assuming a characteristic impedance of $Z_0 = 120\Omega$. The ISL8487E bus transceiver is used in this example. This device is a 1/8 UL transceiver with a minimum supply of $V_s = 4.75V$. Its maximum receiver input threshold is 200mV which, assuming a 100mV noise margin, requires an idle bus voltage of $V_{AB} = 300mV$. 
### Single Fail-safe Network

1) Make \( R_{11} = Z_0 = 120 \Omega \)
2) Calculate \( R_E \) with Eq. 6
   \[
   R_E \geq \frac{4.75V/0.3V + 1}{1/375\Omega + 4/120\Omega} = 467.6\Omega
   \]
   Choose \( R_E = 470\Omega \) from E-96 series of standard resistors.
3) Calculate \( R_{12} \) with Eq. 2
   \[
   R_{12} = \frac{2 \cdot 470\Omega - 120\Omega}{2 \cdot 470\Omega - 120\Omega} = 137.6\Omega
   \]
   Choose \( R_{12} = 138\Omega \) from E-96 series.
4) Calculate \( n_{UL} \) with Eq. 7
   \[
   n_{UL} = 12\,k\Omega \cdot \left( \frac{1}{375\Omega} - \frac{1}{470\Omega} \right) = 6.4UL
   \]

The maximum number of 1/8UL transceivers is 6.4UL / 1/8UL = 51.

### Dual Fail-safe Network

1) Calculate \( R_E \) with Eq. 12
   \[
   R_E \geq \frac{2(4.75V/0.3V + 1)}{1/375\Omega + 4/120\Omega} = 935.2\Omega
   \]
   Choose \( R_E = 942\Omega \) from E-96 series.
2) Calculate \( R_{12} \) with Eq. 2
   \[
   R_{12} = \frac{2 \cdot 942\Omega - 120\Omega}{2 \cdot 942\Omega - 120\Omega} = 128.2\Omega
   \]
   Choose \( R_{12} = 129\Omega \) from E-96 series.
3) Calculate \( n_{UL} \) with Eq. 13
   \[
   n_{UL} = 12\,k\Omega \cdot \left( \frac{1}{375\Omega} - \frac{2}{942\Omega} \right) = 6.5UL
   \]

Here the maximum number of 1/8UL transceivers is 6.5UL / 1/8UL = 52.

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**Transceiver selection**

Selecting the best transceiver to address noise immunity and output drive capability is important for robust network design for two reasons.

1. During times when the bus is not actively driven, there should be sufficient noise margin to prevent a receiver from false triggering, even in very noisy environments.
2. During normal data transmission, the active driver must be able to drive the added common-mode load created by fail-safe biasing and still provide a signal with sufficient noise margin to remote transceivers.

For example, the first-generation ISL8487E device has a positive receiver input threshold of \( V_{IT\text{-max}} = 200\text{mV} \). Adding just a small noise margin of 50mV makes \( V_{AB} = 200\text{mV} + 50\text{mV} = 250\text{mV} \).

Compare this to a second-generation transceiver, such as the ISL83082E with full fail-safe capability. Its receiver output turns high whether the receiver inputs are floating (bus open) or shorted (bus short or idle).

Full fail-safe capability is accomplished by offsetting the maximum input threshold to a slightly negative level, in this case -50mV. To provide the same 50 mV noise margin, a \( V_{AB} \) of 0V is sufficient for eliminating the need for external fail-safe biasing. Without a biasing network, all 32 unit loads are available to the bus transceivers.

In modern industrial applications with high electrical noise pollution, industrial networks, such as PROFIBUS, use dual fail-safe biasing with idle bus voltages of 0.6V and more. \( V_{AB} \) levels that high require the bias resistors to be of such low resistance that their combined value drops far below the
minimum common-mode resistance of 375Ω. When this happens, the calculation of $n_{UL}$ will result in negative values. In fact, it is possible to calculate the maximum $V_{AB}$ \((\text{when } n_{UL} = 0)\) by making $R_w/2 = R_{CM}$ in EQ. 12 and solving for $V_{AB}$:

$$
V_{AB} = \frac{V_s \cdot Z_0}{4R_{CM}} = \frac{4.75V \cdot 120\Omega}{4 \cdot 375\Omega} = 0.38V
$$

Hence, networks requiring high $V_{AB}$ levels need dedicated transceivers that provide much higher differential and common-mode drive capability than standard compliant transceivers.

One transceiver series able to meet these demands is Intersil’s ISL315x family of large $V_{OD}$ transceivers. These devices are capable of driving up to eight 120Ω terminations in parallel at a minimum differential output of $V_{OD-MIN} = 1.5V$, (Figure 4) and more than 60 dc-unit loads over a common-mode voltage range from -7V to +12V at a minimum $V_{OD}$ of 2.4V (Figure 5).

Figure 4 Differential output drive capability, ISL315x vs standard RS-485 transceivers
Figure 5 Common-mode output drive capability, ISL315x vs standard RS-485 transceivers

The ISL315x’s superior output drive capability provides enhanced noise immunity even to the most remote bus transceiver, while enabling twice the common-mode loading compared to standard RS-485 transceivers.

Table 1 lists the resistor values for single and dual fail-safe biasing networks and compares the available transceiver unit loads for two standard transceivers, ISL8487 and ISL83082, and the high-$V_{os}$ transceiver, ISL3152, as a function of noise margin.

Table 1 Resistor values and unit loads for standard and high $V_{os}$ transceivers as a function of noise margin
Transceivers with 200mV input threshold, such as the ISL8487, only allow for low idle-bus noise margins of up to 100mV. Beyond that, the required rise in $V_{AB}$ demands the bias resistor values to be so low that the resulting numbers in transceiver unit loads turns negative.

Full fail-safe transceivers, such as the ISL83082, require much lower $V_{AB}$ values due to their negative input threshold of -50mV. This allows for much higher bias resistor values and consequently higher numbers of required bus transceivers. Both transceiver types however have standard drive capability of up to 32 unit loads, which limits their use in noisy environments to networks with standard noise margins and low transceiver counts.

In strong contrast, the ISL3152, with its high $V_{OD}$, easily drives more than twice the transceiver count at medium noise levels and still manages to support up to 100 transceivers at 600mV noise margin. To accomplish even higher noise margins, an increase in the characteristic cable impedance is necessary. This is done in PROFIBUS where $Z_0 = 150\Omega$, thus necessitating higher values for $R_T$ and $R_S$ to lower common-mode loading of the biasing networks.

**Conclusion**

Creating a fail-safe biasing network ensures stable network node operation during periods of time when the bus is not actively driven. In addition, the common-mode loading caused by the bias resistors must be driven by an active driver during normal data transmission. The high noise margins required in industrial networks demand low bias resistor values whose common-mode load can overburden the drive capability of standard RS-485 transceivers. This problem can be alleviated with the ISL315x family of large output voltage-swing transceivers, capable of driving up to eight 120\(\Omega\) terminations and more than 60 dc-unit loads. In combination with the equations provided in this article, these transceivers ease and accelerate the design of fail-safe biasing networks.

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References

- Download the ISL3159E and ISL3179E datasheets
- Order free ISL3159E samples and ISL3179E samples
- Learn more about Intersil’s RS-485 solutions
- Search for RS-485 transceivers using parametric search

Also see:

- High-speed connections require RS-485
- The RS-485 Design Guide
- A troubleshooting guide for RS-485