EMI/ESD protection solutions for the CAN bus

J. Lepkowski and B. Wolfe, ON Semiconductor

CAN system designers are being challenged to meet stringent Electromagnetic Interference (EMI) and Electrostatic Discharge (ESD) standards while increasing reliability and reducing the size and cost of their products. To solve this dilemma, noise reduction techniques and bus protection devices can be implemented without significantly adding to the cost and complexity of the transceiver circuit.

Introduction

CAN transceivers must be able to survive the high energy surges produced by transient voltages. Transceivers are available that meet the minimum ISO 7637 specifications; however, a higher immunity level can be achieved using protection circuits. The increased immunity level provides for a more robust communication system.

CAN Hardware

The connection to the CAN bus is implemented with a transceiver IC that uses either a high-speed, fault tolerant or single wire physical layer protocol. Table 1 provides a summary of the key ISO and SAE physical layer specifications, while Figure 1 provides the waveforms.

The ISO 11898_2 [7] high-speed protocol has excellent EMI immunity due to the noise cancellation characteristics of a differential receiver. The ISO 11898_2 bus consists of the CAN_H (high) and CAN_L (low) data lines and a common ground signal. A 120 Ω termination resistor is located at each end of the bus to minimize the reflections and ringing on the waveforms.

The fault tolerant system uses a two wire differential bus; however, the transceivers automatically switch to a single wire mode if either the CAN_H or CAN_L signal lines are shorted to ground or power. There are three different ISO specifications that are used to define the fault tolerant bus. ISO 11992 is widely used in trucks, while the ISO 11519_2 and ISO 11898_3 specifications are popular in automobiles [1].

The single wire bus is defined by SAE J2411 [10] and is typically implemented with an unshielded cable consisting of a signal and a ground wire. The advantages of single wire CAN are simplicity and low cost; however, the noise immunity of a single ended transmission is inherently less than a two-wire differential system.

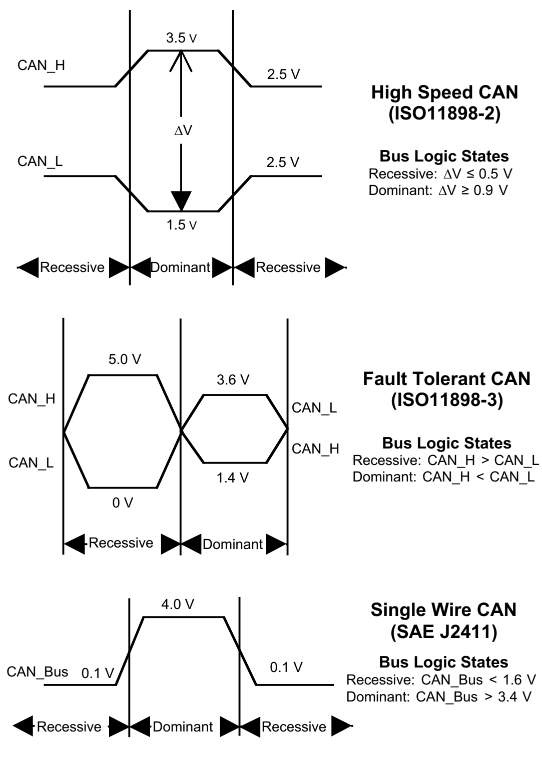

Figure 1: CAN bus waveforms.

Table 1: CAN Physical Layer and EMI Specifications

Parameter	High Speed CAN	Fault Tolerant CAN	Single Wire CAN
Physical Layer Spec.	ISO 11898-2	ISO 11519-2, ISO 11992, ISO-11898-3	SAE J2411
Speed	1 Mbits/s @ 40 m 125 kbits/s @ 500 m	125 kbits/s	33.3 / 83.3 kbits/s Normal / Diag. mode
Min. / Max. Supply Voltage	12V System: -3 /16 V 24V System: -3 / 32 V	12V System: -3 /16 V 24V System: -3 / 32 V	12 V System: -3 / 16 V
Common Mode Voltage (V)	min. / nom. / max. CAN_L: -2.0 / 2.5 / _ CAN_H: _ / 2.5 / 7.0	min. / nom. / max. CAN_L: -2.0 / 2.5 / _ CAN_H: _ / 2.5 / 7.0	CAN_Bus offset voltage = 1 V (max.)
Termination Resistance	120 Ω resistors located at each end of the bus	Separate resistors located at each node, value set by number of nodes	Resistor located at each node, value set by number of nodes
Conducted Power line EMI Req.	Recommended tests: ▪ ISO 7637-1 pulse 1, 2, 3a, 3b, 5	Recommended tests: ▪ ISO 7637-1 pulse 1, 2, 3a, 3b, 5	Recommended tests: ▪ ISO 7637-1 pulse 1, 2, 3a, 3b, 5
Conducted Data line EMI Req.	Specified tests: ▪ ISO 7637-3, pulse a, b Recommended tests: ▪ ISO 7637-1, pulse 1, 2	Specified tests: ▪ ISO 7637-3, pulse a, b Recommended tests: ▪ ISO 7637-1, pulse 1, 2	Recommended tests: ▪ ISO 7637-1, pulse 1, 2 ▪ ISO 7637-3, pulse a, b
ESD Req.	Recommended level ▪ ±8 kV (contact) ▪ ±15 kV (air)	Recommended level ▪ ±8 kV (contact) ▪ ±15 kV (air)	Specified level: ▪ ±8 kV (contact) ▪ ±15 kV (air)

*SDS = Honeywell Smart Distribution System

CAN Transceiver Specifications

The critical CAN transceiver specifications that must be evaluated in order to select a protection circuit include:

1. Maximum supply voltage
2. Common mode voltage
3. Maximum transmission speed
4. Coupled electrical disturbance
5. ESD rating

Maximum Supply Voltage

The turn-on voltage of the protection circuit should be greater than the supply voltage, but less than the CAN transceiver's maximum input specification. For example, a TVS device with a breakdown voltage of approximately 30 V should be chosen for a 12 V system. This ensures that a surge voltage will not exceed the maximum input rating of most CAN transceivers. Also, a TVS device with this value will withstand an indefinite short between the power and signal lines, and will provide the ability to jump start a 12 V battery from a 24 V power source.

Common Mode Voltage

A common mode voltage is created when there is a significant difference in the voltage potential between the ground reference of the transmitting and receiving nodes. ISO 11898_2 specifies that the data signal line voltage can be offset by as much as 2.0V above or below their nominal voltage levels.

Maximum Transmission Speed

The transmission speed of the data line signals corresponds to a maximum capacitance specification on the CAN data lines. Minor distortion on the signal lines is acceptable if the capacitance on the CAN_H and CAN_L lines is identical. It is not possible to tightly match discrete capacitors or the capacitance of a TVS device; thus, the data line capacitance should be as small as possible. A design tradeoff exists because the energy absorption rating of a TVS device typically increases with capacitance.

Coupled Electrical Disturbances

A CAN module must be immune to survive the high energy transients that are generated on the power supply lines [2].

Noise is coupled into the data line signals because the power and data lines are often located inside the same wire bundle. The coupled noise produces a surge voltage that can effect the operation and damage the transceiver. The Joffe study correlates the magnitude and source of transients on a bus to the ISO 7637 specification [8].

ESD Rating

An ESD event occurs when a charged object such as a person touches or comes in close proximity to the connector pins or cable. CAN transceivers have a higher ESD rating than a standard IC; however, their ESD levels are typically below the rating of a TVS device. It is recommended that a CAN network should have a contact rating of at least ±8.0kV and a non-contact or air rating of ±15 kV.

Protection Devices

In most applications a combination of multiple TVS protection devices are required to provide a robust system [9]. The options available to protect from EMI and ESD interference include:

1. Shielded twisted wire pair cables
2. Filters
3. TVS clamping devices

Shielded Twisted Wire Pair Cables

A shielded cable is an effective tool to prevent radiated interference from introducing a noise voltage on the signal wires. Shielded twisted-pair cables minimize the voltage induced on the signal lines. The noise on each wire will be essentially equal, which is the assumption needed for the common mode rejection ratio (CMRR) feature of the CAN receiver's differential amplifier to cancel the interference.

Filters

Filters can be used to provide noise protection by attenuating the magnitude of the noise signal. Resistor-capacitor (RC), inductor-capacitor (LC), common mode chokes, ferrite beads and capacitive feed-through filters are popular filter options. Filters offer the advantage of noise reduction; however, they may not limit the surge voltage to a safe value.

TVS Clamping Devices

An avalanche TVS diode or a Metal-Oxide-Varistor (MOV) can be used to absorb the transient energy of a surge event [3]. These devices have a fast turn-on time of less than 1.0ns and can clamp the transient voltage to a value that will not exceed the transceiver's voltage rating. Low capacitance bidirectional TVS diodes and MOVs minimize the signal distortion and will not clamp the data lines if the signals are offset by the common mode voltage.

TVS diodes are similar to a zener diode; however, they have a larger junction area than a standard zener. They are designed to clamp a short duration transient surge pulse, while a zener is designed to regulate a lower steady state voltage. A bidirectional diode consists of two unidirectional diodes and has a clamping voltage equal to the breakdown voltage of the diode that is reversed biased plus the voltage drop of the second diode that is forward biased.

MOVs function as a nonlinear resistor with electrical characteristics similar to a bidirectional zener diode. The main advantage of MOVs is that they provide clamping protection at a relatively low cost. The main disadvantage is that the clamping voltage is typically higher than a comparable zener diode. Also, the impedance and breakdown voltage of some MOVs decreases over the life of the part.

Protection Circuits

TVS Clamping Circuit

Figure 2 provides an example of a TVS clamping circuit that can be created using either TVS diodes or MOVs. This circuit provides low cost surge protection; however, only minimal noise filtering is achieved due to the inherent capacitance of a diode or MOV. Additional noise filtering can be provided by using RC filters or a common mode choke.

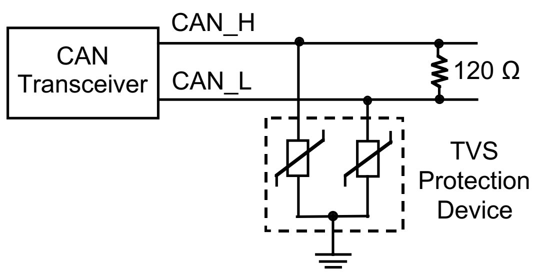

Figure 2: TVS clamping circuit.

Common Mode Choke Circuits

The common mode choke circuit, shown in Figure 3, attenuates the noise that is common to both of the data lines. Chokes function by providing high impedance for common mode signals and low impedance for differential signals, which increases the CMRR of the transceiver. Chokes are an effective device to implement filtering without adding a large amount of distortion on high-speed data lines. TVS devices can be added to a choke to provide clamping protection.

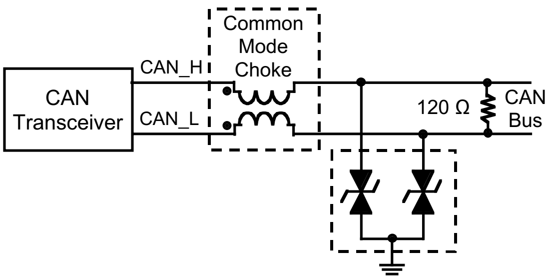

Figure 3: Common mode choke circuit.

Split Termination Circuit

Figure 4 shows a split termination circuit. The termination circuit functions as a low-pass filter and is formed by two equal value resistors and a capacitor. A common mode signal is terminated through a capacitor that shunts the high frequency noise signal to ground. The TVS clamping devices provide the clamping protection.

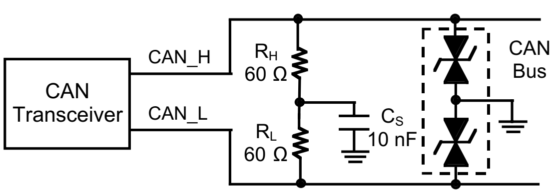

Figure 4: Split termination circuit.

Multiple Suppression Device Circuit

A combination of a common mode choke, capacitors and TVS diodes can be used to solve the most stringent EMI emission and immunity requirements, as shown in Figure 5. Noise entering the CAN node is attenuated by the filters formed by the inductance of the choke filter and capacitors C_{H1} and C_{L1}. In contrast, capacitors C_{H2} and C_{L2} provide a filter to reduce the emissions or noise that exits the transceiver. The TVS diodes are used to clamp the surge to a safe value.

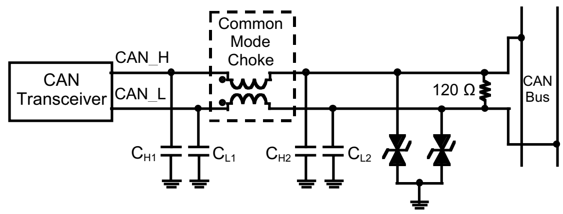

Figure 5: Multiple TVS device circuit.

Single Wire Circuit

Figure 6 shows the single wire protection circuit that is recommended in the SAEJ2411 specification [10]. The circuit consists of a bidirectional TVS diode and a LC filter. The TVS diode provides over-voltage protection, while the LC filter attenuates the emissions exiting the CAN node.

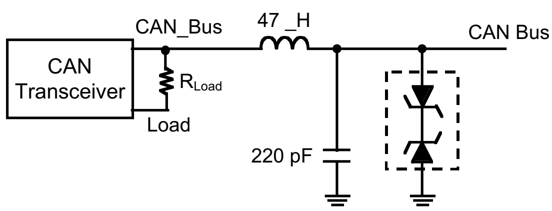

Figure 6: Single wire protection circuit.

EMI Tests

The ISO 7637-1 [5], -2 and -3 [6] specifications can be used to measure a network's immunity to transient noise sources. Also, the reliability of the system can be verified by repeating the surge voltage for an extended period. The power supply line tests are provided by ISO 7637-1 (12V systems) and -2 (24V systems), while the data line tests are given in -3. Other popular tests include the IEC 61000-4-4 Electrical Fast Transient (EFT) [4] and IEC 61000-4-5 surge test. Table 2 provides a summary of the conducted EMI tests and the immunity level provided by the NUP2105L TVS diode.

Table 2: ISO 7637 and IEC 61000-4 Tests

Test	Pulse	Specifications	NUP2105L Test	Noise Source
ISO 7637-1 12V Power Supply Lines	1	V_s = 0 to -100 V, I_{max} = 10 A Test time = 5000 pulses, R_i = 10 Ω, t_r < 1 μs, $t_{d\_10\%}$ = 2000 μs, t_1 = 2.5 s, t_2 = 200 ms, t_3 = 100 μs	I_{test_max} = 1.75 A V_{oc_test} = 54.8 V $I_{destruct}$ = 4.1 A	DUT in parallel with disconnected inductive load
	2	V_s = 0 to +100 V, I_{max} = 10 A Test time = 5000 pulses, R_i = 10 Ω, t_r < 1 μs, $t_{d\_10\%}$ = 50 μs, t_1 = 2.5 s, t_2 = 200 ms	I_{test_max} = 10.2 A V_{oc_test} = 141.6 V $I_{destruct}$ = 12.1 A	DUT in series with disconnected inductive load
ISO 7637-3 Data Line EFT	a	V_s = -60 V, I_{max} = 1.2 A Test time = 10 minutes, R_i = 50 Ω, t_r = 5 ns, $t_{d\_10\%}$ = 100 ns, t_1 = 100 μs, t_2 = 10 ms, t_3 = 90 ms	I_{test_max} = 50 A V_{oc_test} = 2540 V	Switching noise of inductive loads, relay and switch chatter
	b	V_s = +40 V, I_{max} = 0.8 A parameters same as ‘a’		
IEC 61000-4-4 Data Line EFT	Fig. 12	$V_{open\ circuit}$ = 2 kV, $I_{short\ circuit}$ = 40 A, (Level 4), Test time = 1 minute, R_i = 50 Ω, t_r < 5 ns, $t_{d\_50\%}$ = 50 ns, t_{burst} = 15 ms, f_{burst} = 2 to 5 KHz, t_{repeat} = 300 ms	I_{test_max} = 50 A V_{oc_test} = 2540 V	Switching noise of inductive loads, relay and switch chatter
IEC 61000-4-5	Fig. 10	t_r x $t_{d\ 10\%}$ $V_{open\ circuit}$ = 1.2 x 50 μs, $I_{short\ circuit}$ = 8 x 20 μs, R_i = 42 Ω, I_{max} (Class 2) = 12 A	I_{test_max} = 10 A V_{oc_test} = 461.3 V $I_{destruct}$ = 13.2 A	Lightning, power line and load switching

Notes:
1. DUT = Device Under Test
2. Rise time (t_r) = pulse width from 10% to 90%
3. V_{oc_test} = equivalent open circuit voltage
4. I_{test_max} = peak current used during surge test
5. $I_{destruct}$ = current level that damages TVS device

Non-repetitive Surge Immunity

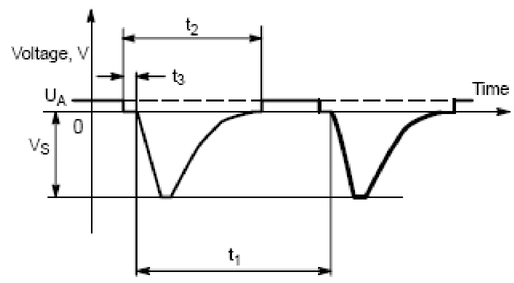

Figure 7: ISO 7637-1, pulse ‘1’

A non-repetitive surge is tested by a transient voltage with a pulse width of typically 20 μs to 2000μs and a repeat rate of usually one pulse per second. These tests are used to test a module’s immunity from transients caused by power switching, sudden load changes or a short circuit fault in the power distribution system. The ISO 7637_1 test pulses ‘1’ and ‘2’ are shown in Figures7 and 8, respectively. Figure 9 shows the ability of a TVS diode to clamp the ISO 7637-1 pulse ‘2’ surge voltage.

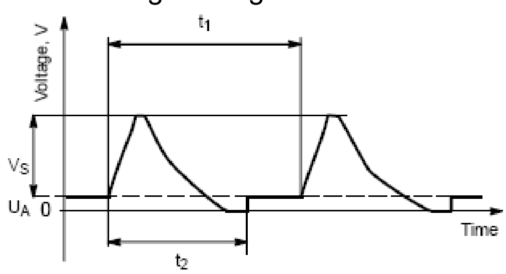

Figure 8: ISO 7637-1, pulse ‘2’

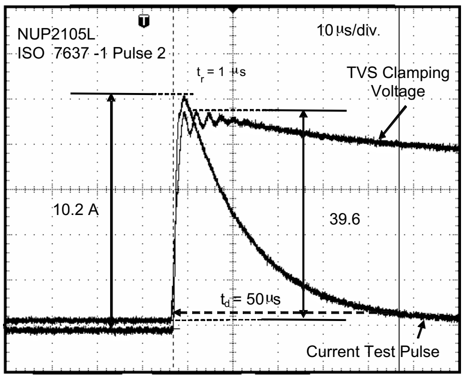

Figure 9: ISO 7637-1, pulse '2' test.

The ISO 61000_4_5 specification serves as a standard test to verify the immunity of a system to a non-repetitive surge. The surge voltage waveform, shown in Figure 10, is defined by a double exponential pulse with a specified rise time (t_r) of 8 µs and a duration (t_d) of 20µs. The 8 µs x 20µs test is also often used to quantify the power rating of a TVS device.

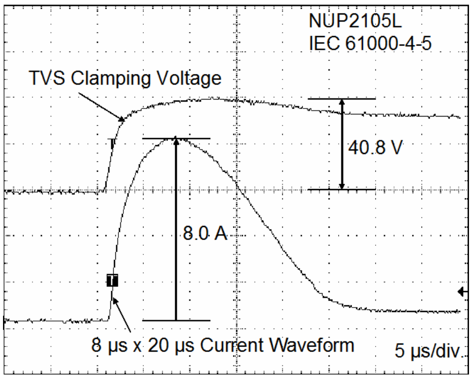

Figure 10: IEC 61000-4-5 test results.

Repetitive Surge Immunity

Repetitive surges are represented by 50 ns transient pulses in bursts of 15 to 300 ms long. These tests are used to test a module's immunity from noise sources such as inductive load switching, relay contact chatter and ignition system noise. Repetitive switching transients are coupled into the data line cables because of the parasitic capacitance and inductance inherent in the wiring harness.

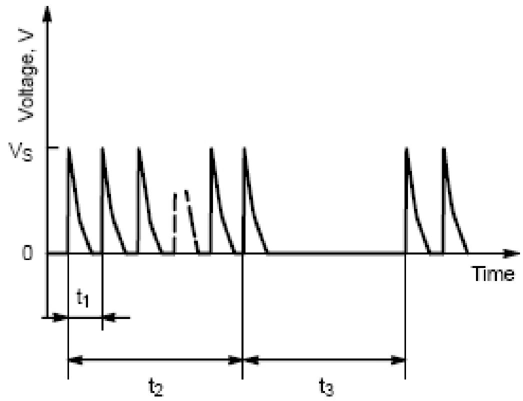

Figure 11: ISO 7637-3 pulse 'b' test.

The ISO7637_3 test pulses 'a' and 'b', along with the IEC 61000_4_4 specification can be used to define the repetitive surge immunity of the system. Repetitive surges are also identified as the electrical fast transients (EFT) and are modeled by a recurring pattern of a burst of high voltage spikes. Figures 11 shows the ISO7637_3 pulse 'b' test waveform. The ISO 7637-1 pulse '3a' and '3b', and ISO 7637-3 'a' and 'b' tests are similar, except that the ISO7637-1 test waveforms are offset by the battery voltage. The IEC 61000-4-4 test waveform is shown in Figure 12.

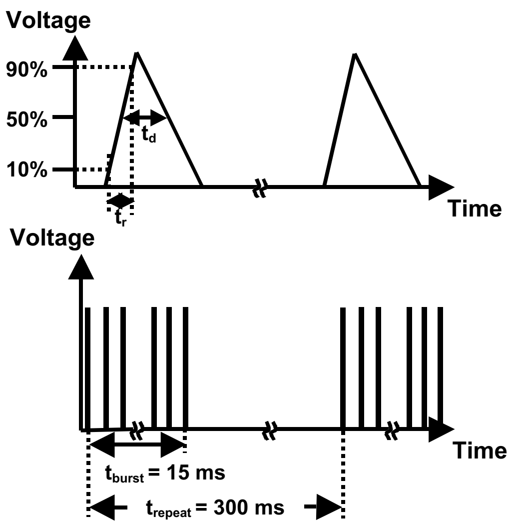

Figure 12: IEC 61000-4-4 EFT test

ESD Tests

The ESD immunity level can be specified by several different tests. The human body model (HBM) test is typically listed on IC datasheets, while the IEC 61000-4-2 specification is often used for system level tests. Both ESD specifications are designed to simulate the direct contact of a person to an object such as the I/O pin of a connector. ESD can produce gradual changes to the impedance of an I/O circuit that can be difficult to quantify. Often, the circuit may continue to operate and the complete failure may not show up until after an extended time. The NUP2105L TVS diode has an IEC contact rating of 30kV, a level which will improve the reliability of the system.

Surge Protection Test Specifications

Test Setup
System level surge tests typically use a coupling clamp and the Input/Output (I/O) cable is placed between two parallel metal plates. The test voltage is applied to the plates, which induces a surge voltage on the wires. In contrast, CAN transceivers use a capacitor or resistor to couple the noise signal to the IC pins, while TVS devices are connected directly to the signal generator. Figure 13 shows that the IC and TVS device test setups remove the cable as a test variable; however, the results of the test must be carefully analyzed.

The impedance of the coupling capacitor has an effect on the transceiver's surge specification. All capacitors block DC; however, the equivalent series resistance (ESR) and inductance (ESL), and the magnitude of the capacitor may limit the transfer of the high frequency energy of a surge pulse. The impedance of a capacitor (Z_c) can be calculated from the equation listed below, which assumes that the ESR and ESL terms are negligible.

$$Z_C \cong \frac{1}{\omega * C} \cong \frac{1}{2\pi * f * C}$$

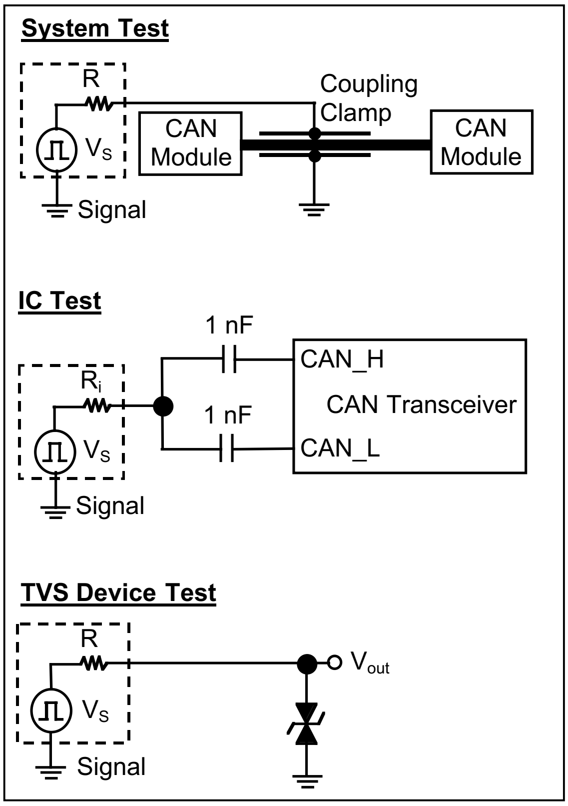

Figure 13: Surge test configurations.

The frequency of a surge waveform can be estimated from the rise time (t_r) of the pulse as shown below.

$$EMI \quad Frequency \cong \frac{1}{\pi * t_r}$$

The ISO 7637-1 pulse '1' and '2' tests have a rise time of 1μs, which corresponds to a frequency of 318 kHz, while the 5 ns rise time of the ISO 7637-3 pulse 'a' and 'b' tests has a frequency of 63.7 MHz. If a 1 nF capacitor is used to couple the surge, the capacitor's impedance will equal 500 Ω at 318 kHz and 50 Ω at 63.7 MHz. The capacitor impedance must be added to the voltage generator's source impedance (R_i) to determine the maximum current.

Internal Transceiver Protection Circuits
Many of the CAN transceivers are built with a BiCMOS process. Bipolar transistors (BJTs) typically have a higher breakdown voltage than a CMOS device; thus, the BJTs are used in the circuits that connect to the I/O pins. The BJT's provide protection by having a breakdown voltage that exceeds the amplitude of some transients, such as the high energy, long duration test pulses. The negative of using

the breakdown voltage as the protection method is that the amplitude of the short duration pulses often will exceed the BJT's specification.

Internal zener diodes and clamping diodes can be used to provide surge protection. The zeners will clamp the surge voltage; however, they are relatively large and increase the die size. A diode array can be used to connect the I/O pin to the power supply (V_{DD}) and ground (V_{SS}) pins through a diode. The diode clamp limits a surge voltage to a voltage that is equal to the diode's forward voltage drop above V_{DD} or below V_{SS}. The power energy absorption capability of zeners and clamping diodes is directly proportional to size; therefore, it usually is not practical to have an integrated device that can absorb the energy of the ISO 7637 pulses.

PCB Layout Recommendations

The PCB layout is critical to maximize the effectiveness of the CAN protection circuit. The following PCB guidelines are recommended:

1. Locate the protection devices close to the I/O connector. This allows the devices to absorb the energy of the transient voltage before it can be coupled into the adjacent traces on the PCB.
2. Minimize the loop area for the high-speed data lines, as well as the power and ground lines to reduce the radiated emissions and the susceptibility to RF noise.
3. Use ground planes to reduce the parasitic capacitance and inductance of the PCB.

Conclusion

Many CAN transceivers have transient voltage ratings that exceed the ISO 7637 specifications; however, external protection circuit still should be used. The maximum voltage of an IC is specified at the destructive point and latent damage may occur at a level well below the IC's transient rating. The surge capability of an IC is determined by both voltage and current, and most data sheets provide limited information on the maximum current rating. Also, the transceiver transient ratings are typically specified for a single transient event, while protection circuits provide immunity for an indefinite amount of surges.

A combination of filters and TVS clamping devices will provide noise attenuation and clamp a surge voltage to a safe level. Filter circuits help prevent failed transmissions due to noise, while the TVS devices protect against damaging transient surge voltages. These protection circuits are relatively inexpensive and provide for a simple solution that supplements the immunity level of a CAN transceiver.

References

[1] "Application Hints – Fault-tolerant CAN Transceiver, Version 3.1", Philips Semiconductors, 2001.

[2] Cherniak, S., "AN843 – A Review of Transients and Their Means of Suppression", ON Semiconductor, 1982.

[3] Durham, M., Durham, K. and Durham, R., "A Performance Evaluation of Transient Voltage Suppression Devices", *IEEE Industry Applications Magazine*, Sept. / Oct., 2002.

[4] "IEC 61000-4-4, EMC - Part 4-4: Testing and Measurement Techniques – Electrical Fast Transient/Burst Immunity Test", International Electromechanical Commission (IEC), 2004.

[5] "ISO 7637-1, Electrical Disturbance by Conduction and Coupling - Passenger Cars and Light Commercial Vehicles with Nominal 12 V Supply Voltage – Electrical Transient Conduction along Supply Lines Only", International Standard Organization (ISO), 2002.

[6] "ISO 7637-3, Electrical Disturbance by Conduction and Coupling – Electrical Transient Transmission by

Capacitive and Inductive Coupling via Lines Other Than Supply Lines", ISO, 1995.
[7] "ISO 11898-2, Road Vehicles – Controller Area Network (CAN), Part 2: High-Speed Medium Access Unit", ISO, 2003
[8] Joffe, E., "Power Line Transients on a Bus due to the Operation of the Electrical Systems", International Symposium on EMC, pages 758-761, 1999
[9] Lepkowski, J., "AND8169 - EMI/ESD Protection Solutions for the CAN Bus", ON Semiconductor, 2004.
[10] "SAE J2411, Single Wire CAN Network for Vehicle Applications", February 2002.

Jim Lepkowski
ON Semiconductor
5005 East McDowell Road
Phoenix, AZ 85008
(602) 244 - 5473
jim.lepkowski@onsemi.com

Brandon Wolfe
ON Semiconductor
5005 East McDowell Road
Phoenix, AZ 85008
(602) 244 - 3280
brandon.wolfe@onsemi.com