Comparison of ISO 7637 Transient Waveforms to Real World Automotive Transient Phenomena

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Abstract—**Modern automotive electronic systems must operate as designed while exposed to transient voltages produced on the vehicle's power distribution system via switched inductive loads. ISO 7637-2 presents a number of test pulses that are presumed to simulate the actual transients produced in the vehicle. This paper will compare three of those pulses (Pulses 1, 3a and 3b) to actual transient events which are the result of contact arcing during deactivation of an inductive load. The paper will demonstrate that the Pulses 1, 3a, and 3b are overly simplistic representations of a more complex waveform. This over simplification may impact accurate assessment of system robustness in the presence of actual transient events.**

I. INTRODUCTION

Today's automotive electronic systems are comprised of microprocessor based electronics that control, and/or coexist with switched, inductive electromechanical loads. When these loads are switched, transient voltages are produced on the power distribution system that is also connected to the electronic control unit (ECU). This includes ECU main power circuit in addition to input circuits that sense when power is applied or removed from an inductive load. The ECU must be designed to operate without malfunction during these transients events. Most automotive manufactures have traditionally specified the ECU be tested in accordance with ISO standard 7637-2, which presents a series of test pulses that are suppose to simulate actual transient events. Several test pulses are presented in this standard to simulate a variety of operational conditions.

Although these test pulses have been used for many years, there have been several instances where actual voltage transients, have caused ECU malfunction. Unfortunately the malfunction could not be duplicated when the ECU was exposed to these test pulses. Conversely, many times, application of the ISO test pulses have affected ECU operation, yet the symptoms can not be duplicated when the ECU is installed and operating in the vehicle. Given the potential cost considerations of correcting the issue, it is important that the test pulses properly simulate the vehicle environment.

ISO 7637-2 presents three specific test pulses (Pulse 1, Pulse 3a, and Pulse 3b) that are to represent a transient event that occurs when power is disrupted to an inductive load. Figure 1 illustrates the basic circuit specified by the ISO standard that serves as the basis for these transient pulses. The transients will be impressed on any ECU connected to the same power circuit.

Figures 2 through 4 illustrate the respective open circuit characteristics for these test pulses in addition to their associated thevenin equivalent circuit. ISO 7637-2 states that Test Pulse 1 is due to the supply disconnection from the inductive load. Pulses 3a and 3b are reported to *"occur as the result of the switching process"* and *"are influenced by the distributed capacitance and inductance of the wiring harness"*. Both pulses are impressed on the power supply, which would indicate that they occur between the power supply and the switch. However, ISO 7637-2 provides no specific information.

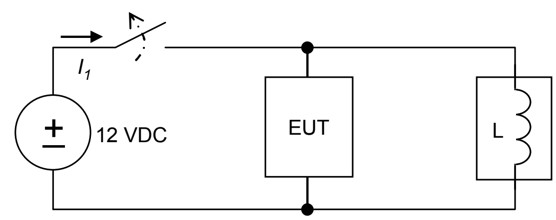
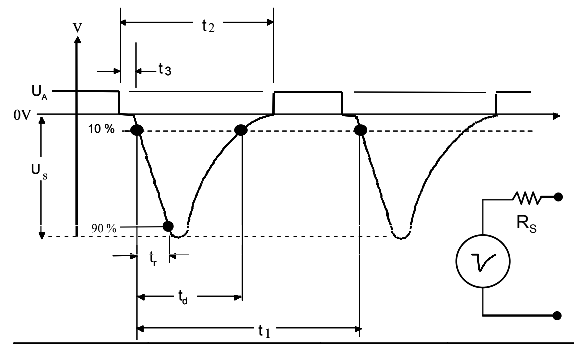


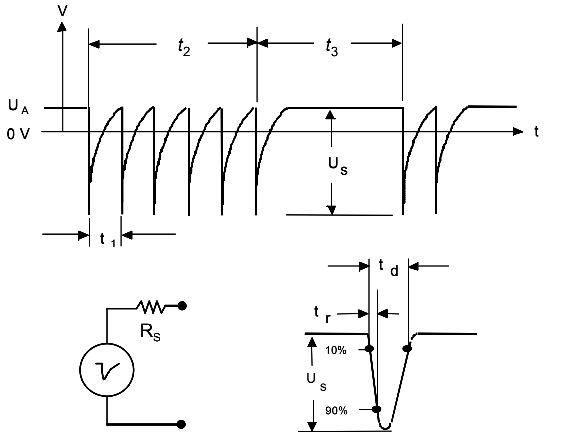
Figure 1 Basic Circuit

Past investigative studies have been executed to characterize and analyze actual automotive transient events [1, 2]. The measured data could not be readily correlated to the ISO pulses depicted in Figures 2-4. The measurements revealed a complex waveform with voltage magnitudes significantly greater than the ISO pulses (~ 350 volts). Given these differences, further investigation was initiated to understand the underlying physics for the observed waveforms.



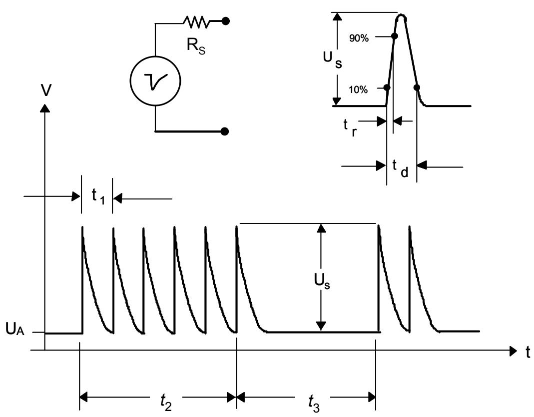
U_A = 13.5 V	U_S = -75 to -100 V	t_r = 1us	t_d = 2 ms
t_1 = 0.5 to 5 s	t_2 = 200 ms	t_3 < 100 us	R_S = 10 Ω

Figure 2 ISO Test Pulse 1



U_A = 13.5 V	U_S = -112 to -150 V	t_r = 5 ns	t_d = 100 ns
t_1 = 100 us	t_2 = 10 ms	t_5 = 90 ms	R_S = 50 Ω

Figure 3 ISO Test Pulse 3a



U_A = 13.5 V	U_S = +75 to +100 V	t_r = 5 ns	t_d = 100 ns
t_1 = 100 us	t_2 = 10 ms	t_5 = 90 ms	R_S = 50 Ω

Figure 4 ISO Test Pulse 3b

Laboratory measurements were performed, using the circuit in Figure 5, to capture transient events and compare those results to the ISO pulses shown in Figures 2 - 4. The switch consisted of a 12 VDC electromagnetic relay (NC contacts), which was selected to represent a typical automotive switch and to achieve reasonable consistency when repeatedly switching the inductive load. The inductive load selected was initially an air conditioner (AC) clutch coil, with a measured inductance, '*L* ' of approximately 100 mH. The measured DC resistance, '*R*' was 7.3 ohms, resulting in a steady state current (switch closed) of 1.7 amperes. The interwinding capacitance 'C_P' was not measured, but was assumed to be approximately 150 pf based on [4] and [7]. The 5uH inductor was used to simulate the series wiring inductance between the switch and the 12.5 VDC automotive battery. Measurements were made across the inductive load (V_L) and between the switch and the 5 uH inductor (V_{PS})

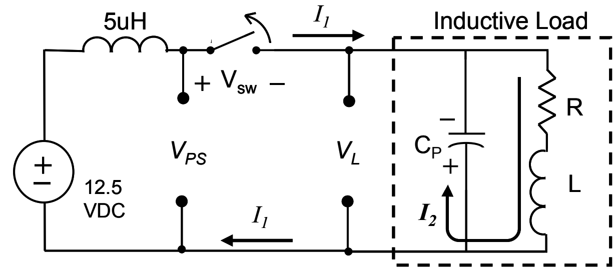


Figure 5 Measurement Test Circuit

Figure 6 shows the typical V-I characteristics of the resultant transient when the switch is opened. The voltage waveform is characterized by an initial drop to zero volts, but then continues negative to approximately -60 volts (see zone A). Note that during this time the current I_1 falls from its initial steady state current to approximately 180 mA. At this point, the current rapidly falls to zero, but the voltage drops significantly to approximately -350 volts (zone B) before decaying to zero. The time base is expanded in Figure 7 to illustrate the details of this pulse. Measurement results were fairly repeatable for consecutive switch openings

Similar measurements were also performed across the coil of a standard automotive relay. The measured coil inductance was similar to the AC clutch coil, but the series resistance was 73 ohms resulting in a steady state current of 162 mA. Measurement results, shown in Figures 8 and 9, show that the transient V-I characteristics for relay coil are significantly different than those for the AC clutch coil. The primary difference is the shorter duration of zone A followed by a high frequency saw-tooth voltage oscillation. Figure 9 illustrates this V-I characteristics of this oscillation. Figure 10 compares the associated waveform (Ch 3) that appears between the switch and the 5 uH inductor, which would represent transients that could appear on power distribution system. Note that consecutive switch openings produce significantly more measurement variability in the relay coil as opposed to the AC clutch coil.

When comparing the ISO pulses to the measurement results, pulses 3a/3b appear to be elements of the composite waveform that occurs between the switch and power supply (ref Figure 10). However, the voltage levels of the measured waveforms are much higher than for either pulse 3a or 3b. No correlation to Pulse 1 was noted. These findings are similar to that reported in [1] and [2].

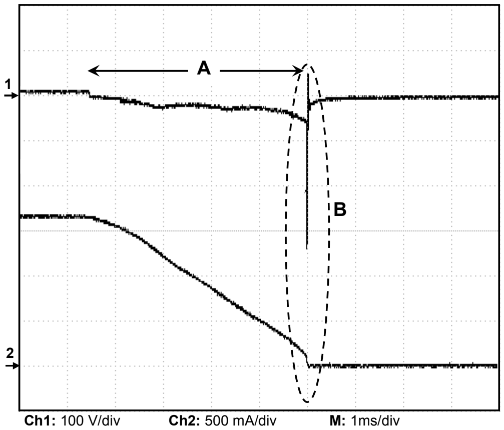


Figure 6 V-I Characteristics (AC Clutch Coil)

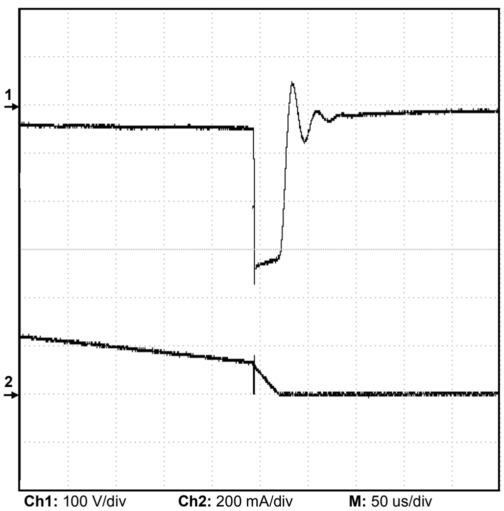


Figure 7 Expanded V-I Characteristics of Zone B

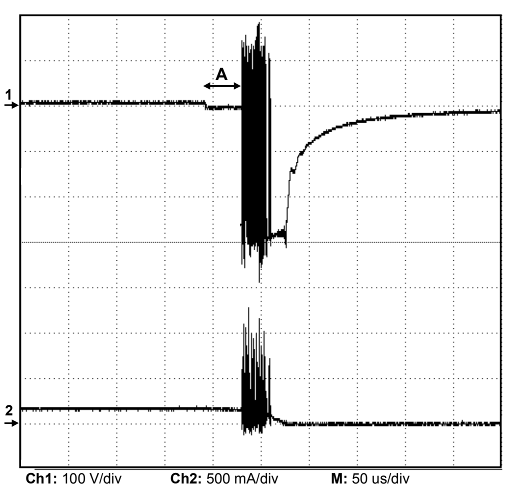


Figure 8 V-I Characteristics (Relay Coil)

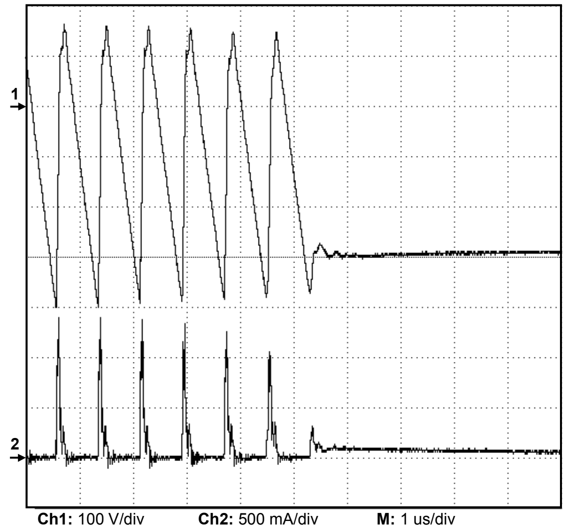


Figure 9 Expanded V-I Characteristics (Relay Coil)

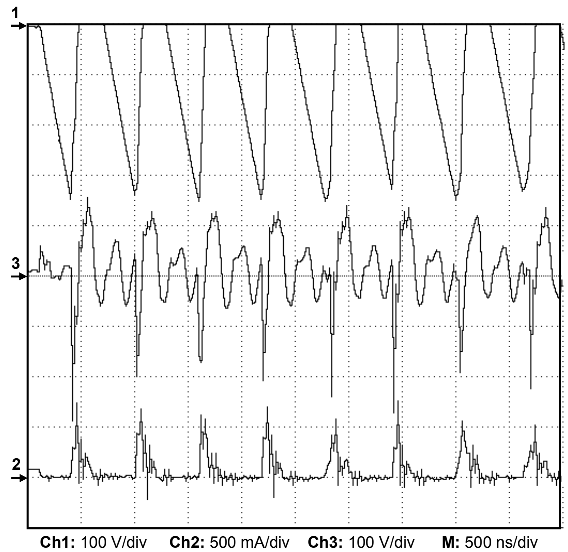


Figure 10 Transients on Between Power Supply and Switch

II. TRANSIENTS DUE TO CONTACT ARCING

The observed affects can be readily explained via understanding of contact arcing phenomena. If an ideal switch were used to disrupt current to the inductor in Figure 5, and the resulting inductive transient would theoretically produce a peak source voltage across the contacts given by [5]:

$$V_P = I_{1(init)}\sqrt{L/C_P} \qquad (1)$$

Where $I_{1(init)}$ is the initial circuit current prior to contact opening, L is the inductance and C_P is the inductor's interwinding capacitance plus the capacitance from the external circuit. Note that the equation neglects the resistance R, and assumes that all the energy stored in the inductor, is transferred to the capacitor. The initial rate of change in the source voltage across the contacts is the ratio of initial circuit current to the circuit capacitance ($I_{1(init)}$ / C_P) [4]. For the test circuit in Figure 5, assuming a C_P = 150 pf, V_P would greater than 43 KV!

However, Curtis and Wagnar [3,4] show that when real switch contacts initially open, the electric field between the contacts, is sufficient to cause metal vaporization of cathode or anode. This action will result in initiation of an arc discharge, which will be sustained if the contact voltage exceeds a minimum arcing voltage V_A (~12 volts), and the current, I_l exceeds the minimum arcing current I_A (30 – 400 mA). If either condition is not met, the arc discharge will extinguish. When arc discharge is initiated, I_l begins to reduce. This is due to increase in the "arc resistance" [7], which increases as the contacts separate. Eventually I_l falls below I_A,, at which point the arc is extinguished. The time it takes for I_l to fall below I_A is directly proportional to the product of the inductance and the initial current prior to opening the contacts (i.e. L*$I_{l(init)}$) [7].

When the arc extinguishes, any remaining energy in the inductance charges C_P via $I_{2\ as}$ shown in Figure 5. This causes V_{SW} to increase to the point where a momentary arc is generated. The arc may be formed by either a field (~10^8 V/m) induced emission from the cathode causing metal vaporization or by ionization of air molecules between the contacts, which is called the *Townsend breakdown region.* The avalanche process ultimately leads to contact vaporization. The two phenomena are referred to respectively as a *short arc* and *long arc* respectively [4]. The minimum contact voltages to achieve short and long arc are:

$$V_{B(arc)} = E_B ut \quad \textit{(short arc)} \tag{2}$$

$$V_{B(gas)} = 320 + 7x10^6 ut \quad \textit{(long arc)} \tag{3}$$

Note that the short arc predominately occurs when the contacts initially open and are closely spaced but under some conditions, can also occur at wider contact separations. Under either condition, the momentary arc causes rapid discharge of C_P causing an impulsive current I_l, whose initial magnitude is dependent on the power supply voltage, V_A and the wiring impedance [4]. If the wiring impedance between the switch and the power supply is zero, V_{SW} rapidly falls to V_A and remains there until the impulsive arc current falls below I_A, which causes the arc to extinguish. Note that if there is any series inductance between the switch and the power supply, V_{SW} will fall below V_A. Repeated charging and discharging of C_P may continue as long as the energy in the inductor is sufficient to charge C_P to $V_{B(gas)}$. This phenomenon is referred to as *arc-controlled showering* [4] or more commonly "*showering arc"*. The phenomena will continue until the inductive source voltage falls below the minimum voltage required to initiate either a short or long arc.

Many times, the avalanche process described above may become self sustaining, however at a lower breakdown voltage which remains relatively constant over about two decades of current. This leads to the third condition referred to as *Glow Discharge* and is strongly dependent on the contact materials. For silver contacts:

$$V_G = 280 + 1000ut \tag{4}$$

Note that under some conditions described in [4], further increases in current causes joule heating of the cathode and increases the voltage. This is referenced as *Abnormal Glow*.

Equations 2 -4 are plotted in Figure 9 using a contact velocity of 379 mm/sec, which is based on empirical measurements of the relay switch used in Figure 5. Also shown is an example of the inductive source voltage (ideal switching of inductive load) along with waveform characteristics corresponding to arc-controlled showering and glow discharge. Note that the waveform presented serves only as a qualitative example to provide directional information regarding the effects of contact arcing on transient voltage behavior. Since the timing characteristics of actual transients can vary over six orders of magnitude, it is difficult to illustrate this on a single plot.

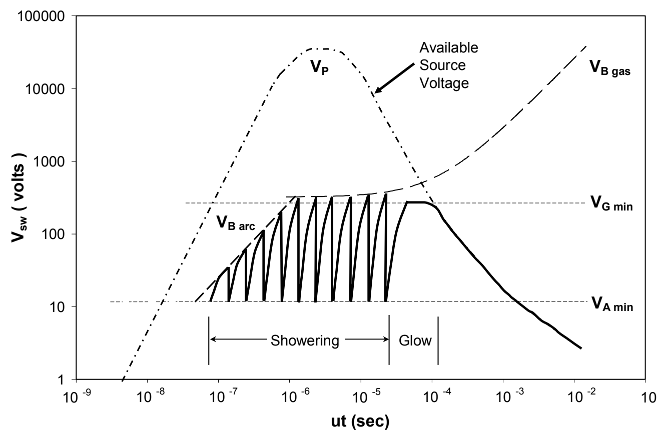


Figure 11 Transient due to Showering Arc and Glow Discharge

Application of the concepts presented for contact arcing help explain the measured results illustrated in Figures 6-10. The measured voltages across the inductive load are related to V_{SW} by:

$$V_L = V_{PS} - V_{SW} \tag{5}$$

where V_{PS} is the supply voltage. Zone A of Figures 6 and 8 is due to arc discharge. The arc duration is shorter in Figure 8 because the initial current for the relay coil is closer to the minimum arcing current I_A as compared to the AC clutch coil. Zone B (ref Figures 6, 7) illustrates an example of abnormal glow. Figure 8 and 9 illustrate arc controlled showering transitioning to glow discharge. Note that the positive going part of the showering arc is due to the step change in current, I_l through the 5 uH inductor when either a short or long arc occurs. Figure 10 illustrates the same characteristic. Note that voltage transients only occur between the battery and the switch during an arcing event.

Based on the information presented, transient characteristics in air are affected by the physical switch characteristics (e.g.

contact opening speed, contact material) and the external circuit parameters. Equation (1) shows that the inductive source voltage is directly affected by both the initial circuit current and the parasitic capacitance. The circuit shown in ISO 7637-2 (ref Figure 1) neglects the effect of other electronic loads being connected in parallel across the inductor. Since many of these loads (e.g. other modules) present additional resistance and capacitance across the inductor, the resulting affect on the inductive source voltage should impact the transient characteristics.

Figures 12 and 13 show measurement results when resistance is added in parallel across the AC clutch coil and relay coil. In Figure 12, placing a 220 resistor across the clutch coil has minimal affect on the duration of the arc discharge, but does substantially reduce the pulse which was due to abnormal glow. By contrast, an 1100 resistor placed across the relay coil reduces the voltage to below $V_{B(gas)}$ (3) thus eliminating the showering arc. The resulting waveform is substantially different than for the open circuit condition.

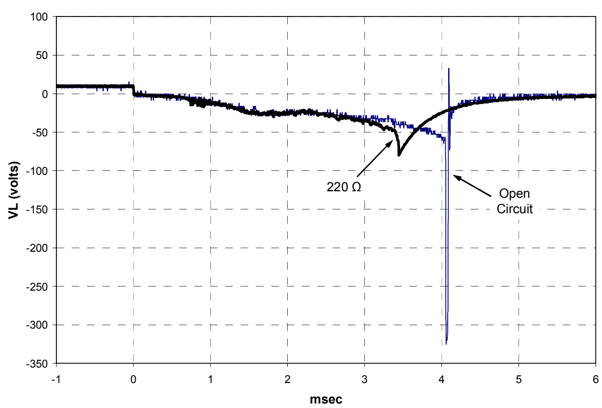


Figure 12 Affect of Parallel Resistive Load (AC Clutch Coil)

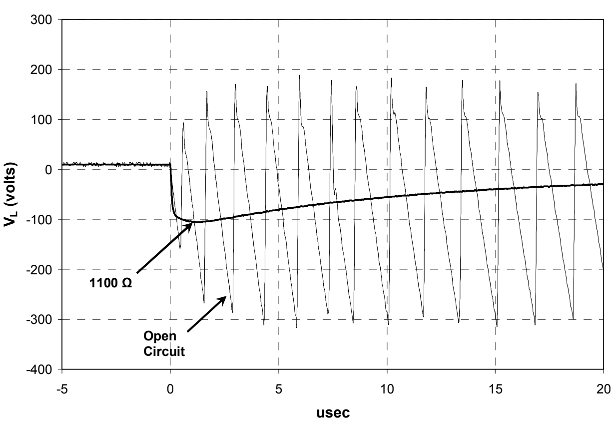


Figure 13 of Parallel Resistive Load (Relay Coil)

Figures 14 and 15 illustrate the added effect of placing both resistance and capacitance across the inductor. In Figure 11 the RC load reduces or eliminates the arc discharge, which is due to the arcing current I_l being reduced by the available charge from the additional capacitance. Note that under these conditions, the resulting waveform now resembles ISO Pulse 1! Addition of the 0.1 uF capacitor across the relay coil (ref Figure 12) eliminates showering arc by reducing the voltage below $V_{B(gas)}$ (3), but oscillation is present in absence of any resistance. The oscillation and the voltage are reduced by addition of resistance across the coil.

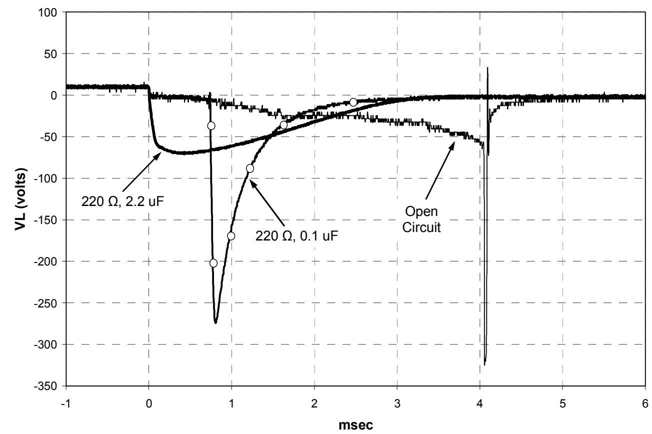


Figure 14 Affect of Parallel RC Loading (AC Clutch Coil)

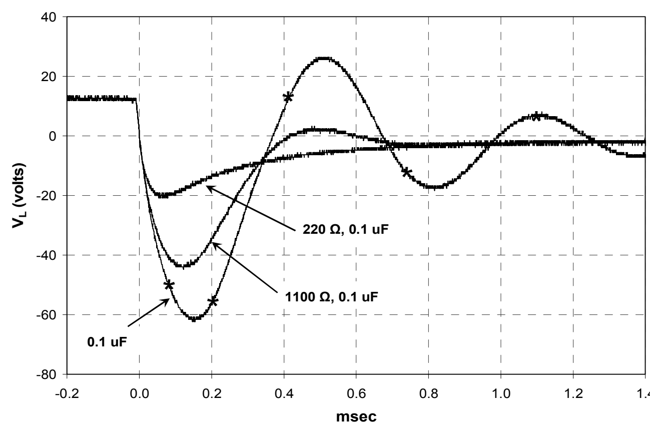


Figure 15 Affect of Parallel RC Loading (Relay Coil)

Note that ISO 7637-2 specifies a simple thevenin equivalent circuit for Pulse 1, 3a, and 3b with a resistive source impedance of 10 ohms (Pulse 1) and 50 ohms (Pulse 3a, 3b). Resistive loading of this circuit reduces the amplitude via simple voltage division. Per ISO 7637-2, pulse timing for Pulse 3a/3b is identical for either open circuit or matched load conditions. The pulse width for Pulse 1, under matched load conditions, may not reduce more than 25% (2 msec – 1.5 msec).

Inspection of Figures 12 -15 clearly demonstrate that external circuit conditions will have a significant impact on open circuit waveforms with respect to both voltage and timing. Figures 16 and 17 further exemplify the effect of loading on the transient voltage. Figure 16 compares the expected peak negative transient levels for ISO Pulse 1, due to resistive loading, with measured values across the AC clutch coil with both resistive and resistive/capacitive loading. The data shows that the expected voltage levels for ISO Pulse 1 do not correlate well with the measured results except, when the capacitance is approximately 2 uf. Its important to note that when only a 0.1 capacitor is placed across the AC clutch coil, the magnitude of the voltage transient is in excess of 1KV. This occurs because the capacitance reduces the initial rate of change of the inductive source voltage, which increases the time before the source voltage exceeds the minimum arcing voltage V_A. The increased time allows the further separation in the switch contacts, which, per (3), increases the air breakdown voltage.

Figure 17 presents similar comparisons between Pulse 3a and measured values across the AC clutch coil with both resistive and resistive/capacitive loading. The measurements show that for resistance values less than 2K , showering arc will not occur, which is consistent with (3). In absence of arcing, voltage transients between the switch and the battery are eliminated.

Based on the data presented, the source characteristics defined by ISO 7637 do not appear to accurately account for external circuit variations.

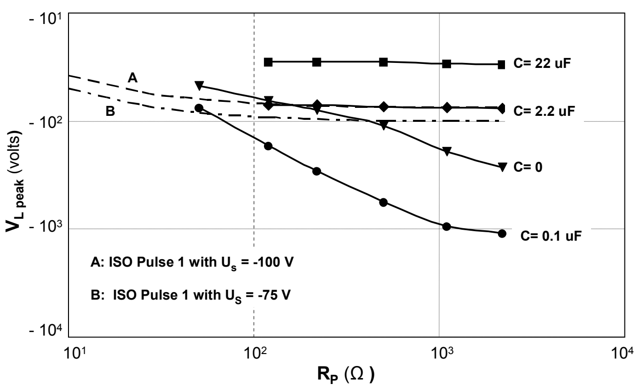


Figure 16 AC Clutch Coil Peak Transient Voltage vs Load (R_P)

III. CONCLUSION

Transient behavior in switched inductive loads can be explained via underlying principles for contact arcing. These principles show that transient V-I characteristics are largely affected by the physical switch characteristics and by the external circuit conditions. It is interesting to note that ISO 7637-2 specifies different amplitudes for Pulse 1, 3a, and 3b for 12 and 24 volt systems. The data presented shows that the voltage is actually dependent on the contact gap and contact opening velocity. Similar results have been reported in [6] and [7] for 42 VDC applications. This may have been an assumption when ISO 7637 was initially conceived, but this information is not provided to the reader.

The data demonstrates that Pulse 1 is based on assumptions about the external circuit loading, but unfortunately this information is not present in ISO 7637-2. Pulses 3a and 3b are overly simple representations of components of a more complex waveform that only exists if contact arcing is present. The product designer must be aware of these aspects so as to design the circuit to tolerate the potentially different pulse characteristics.

Recent analytical work has been performed that verifies the empirical data presented and will be the subject of a future paper.

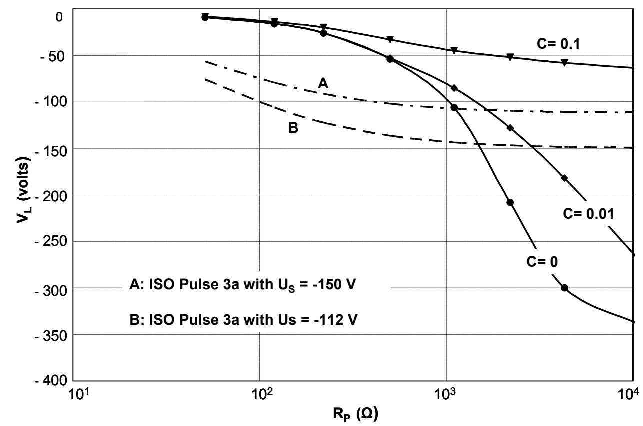


Figure 17 Relay Coil Peak Transient Voltage vs Load (R_P)

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