

Inductive Load Switching Suppression Methods: Increasing Military and Aerospace Applications Reliability

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ABSTRACT

This paper will illustrate how the increasing electrical demands of military and aerospace applications can successfully be met by high performance electromechanical relays. To meet these higher demands engineering compatibility between the intended application and relay switching performance parameters must be properly understood.

One of the critical parameters are inductive loads which generate transients that can adversely effect relays at the component level and the military or aerospace application at the higher systems levels. In this paper the impact of several methods of inductive suppression are explored.

Diode, zener diode, transient voltage suppressors all provide methods to control polarity and voltage levels generated by collapsing magnetic fields in deenergized inductive devices. Each has strengths and benefits that will be further understood by expanding upon their construction, functionality and electrical performance parameters during implementation in switching inductive relay coils in military and aerospace applications.

INTRODUCTION

With high performance electromechanical relays continuing to play an important part in military aircraft applications it is important for engineers to capture all of the military electrical requirements. A critical area is transient suppression in military aircraft applications. Relays generate transients that can adversely effect circuit performance at the component level and at higher systems levels. In this paper several types of unsuppressed relay coils performance will be examined

and compared with several practical methods of inductive transient suppression and the effects on relay contact life that could effect the reliability in military aircraft applications.

INDUCTIVE LOADS AND CONTACT ARCING

INDUCTANCE DEFINED - Inductance is "The property of a circuit or circuit element that opposes a change in current flow. Inductance thus causes current changes to lag behind voltage changes." [1]. An inductor opposes instantaneous current changes while allowing instantaneous voltage changes. Inductance (L) is measured in Henries (H) and is an indication of an inductor's ability to store energy. In addition a practical inductor has effective resistance (R_L) of the copper wire windings [2], [3]. The combination of the resistance and inductance forms a time constant ($TC=L/R$) that effects the rate of current change upon a change in voltage. After one time constant the current will reach 63% of the final value. Figure 1 indicates that for a 320mH inductor it takes $TC=2.32ms$ to reach the 63% value indicating a total circuit resistance of $L/TC=R$, $320mH/2.32ms = 137.9 \text{ Ohms}$ [4], [5].

INDUCTIVE TRANSIENTS - When current is flowing through a conductor a magnetic field of flux lines is generated around it in a process known as self-inductance. These flux lines link the turns in the coil winding and remain stable as long as current in the inductor remains constant. The transient voltage or electromotive force (emf) when the flux linkages change is generated according to Faraday's Law [6]. To explain by formula the voltage transient is $L[di/dt]$ where the magnitude is directly proportional to the size of the inductor and the rate of current change versus time. The

emf transient polarity is negative due to the opposing magnetic field according to Lenz's Law [7].

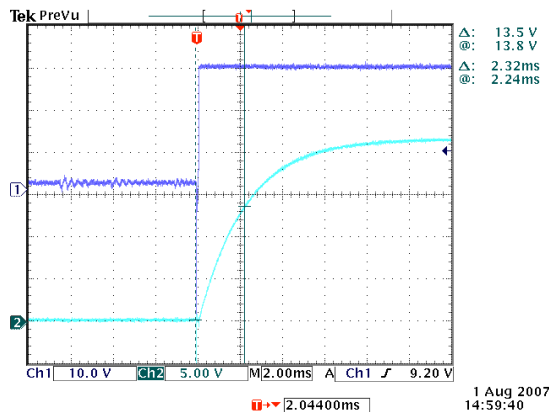


Figure 1 - Inductive Load Time Constant

INDUCTIVE ARCS - The arc during inductive load switching is complex with four stages [8]:

1. Development of molten metal bridge until it ruptures and bridge transfer occurs.
2. An arc of a length shorter than a critical length resulting in material transfer from the anode.
3. Period when material transfer reverses and anode consumes the material previously accumulated on the cathode.
4. An arc that produces net transfer of contact material from the cathode.

Stages 1 and 2 are almost identical to the arc and material transfer of resistive switching explained later in greater details. Stages 3 and 4 are unique to inductive load switching. As the energy stored in an inductor is dissipated a point will be reached where molten material transfer cannot be continued. The low voltage drop of the opening contacts from this arc ceases and the contacts go much above the minimum arcing voltage to a high voltage condition controlled by the contact spacing and switching atmosphere. An example can be seen in Figure 4 where a 320mH, 200mA, inductive load is interrupted with the emf waveform reaching -368V magnitude. This is much lower than the MGAD relay's dielectric rating prior to arc initiation of 500Vdc peak and the -553Vdc potential transient from Equation 2 calculations [9].

This can be explained by what is known as glow discharge during the later stages of the arc. This is a function of low cathode temperature and low current density in the arc [10], [11]. The electrical breakdown (V_s) of gas in the contact gap is what starts and continues the glow discharge based on Paschen's Law. It states the breakdown potential between two electrodes is a function of the gas present, the product of the gas density (p_s) and gap width. The Paschen curve shows V_s of 330V at p_s of 7×10^{-4} atm cm [12].

INDUCTIVE LOADS - The energy stored in an inductor is measured in terms of potential rate of flow in Watts-seconds or Joules using Equation 1, $0.5LI^2$ [13]. The inductive load utilized a 320mH inductor at 200mA steady state current resulting in 6.4 mJ of stored energy. The unit of measure Henry (H) is stated mathematically: "A coil has an inductance of 1H if a current change (di/dt) of 1A/s induces an emf of 1 volt in the coil.". Substitution yields the usable formula $L(A/s)$ [14]. Using Equation 2 provides an estimated emf transient voltage of -553Vdc could be generated.

Equation 1 - Stored Inductive Energy

$$0.5(LI^2) = \text{energy}$$

$$(0.5)(320\text{mH})(200\text{mA})^2 = 6.4\text{mJ or mW-s}$$

Equation 2 - Inductive Transient Voltage

$$L(A/s)$$

$$(320\text{mH})[(-2.90\text{Vdc}/21.5\text{Vdc})/200\text{mA}]/15.6\mu\text{s}]$$

$$(320\text{mH})(-26.98\text{mA}/15.6\mu\text{s}) = -553\text{Vdc}$$

INDUCTIVE LOAD SUPPRESSION

TRANSIENT VOLTAGE REDUCTION - Most methods to reduce transient voltages take advantage of the polarity reversal generated by the inductive emf voltage to place polarity sensitive components in parallel with the inductor. The components used to reduce inductive transients are most often diodes, zener diodes and unidirectional or bidirectional transient voltage suppressors (TVS). To better understand how these devices work Figure 2 illustrates how they function when there is forward or reverse bias voltage applied. The diode conducts only in the forward direction while zener diodes and TVS devices conduct in both forward and reverse directions. The reverse conduction occurs at a controlled breakdown or avalanche voltage point [15].

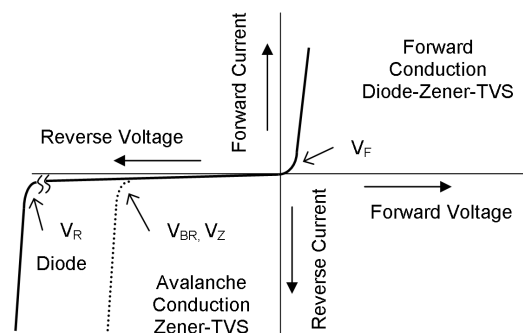


Figure 2 - Diode-Zener-TVS-VI Curve

POPULAR SUPPRESSION DEVICES - Diode - A diode is a semiconductor device that functions electrically as a one-way conductor of electrical current. When the diode is forward biased it is in the forward conduction mode. In the forward conduction mode the diode has a small forward voltage drop V_F that can act as a suppression or clipping device to an inductive transient. When reverse biased, as shown in Figure 3, it will not conduct electrical current at any voltage level below its reverse blocking voltage limit, which is often several hundred volts.

The diode used in the testing was a 1N4005 device. It has a forward voltage (V_F) of 1Vdc at 1 Amp average forward current (I_F) and a maximum reverse blocking voltage (V_R) of 600Vdc. The 1N4005 provides steady state power dissipation (P_D) rating of 1 Watt and peak power dissipation (P_{PK}) of 30 Watts [16].

Zener Diode - Long a favored device to limit transients zener diodes offer the advantages of polarity sensitivity and selectable voltages. Zener diodes are devices that are intended to operate in the reverse biased or avalanche conduction region. The disadvantage to a zener diode is limited power dissipating capability which factors into proper selection of the device based upon the stored inductive energy to be dissipated.

The zener diode used in the testing was a 1N4749A rated at a nominal zener voltage (V_Z) of 24VDC at a current (I_{ZT}) of 10.5mA current with a forward voltage (V_F) of 1Vdc. The 1N4749A provides steady state power dissipation (P_D) rating of 1 Watt and peak power dissipation (P_{PK}) of 5 Watts [17].

To use a zener diode for transient suppression a standard diode has to be placed in series opposition as seen in Figure 3 for polarity protection. Without the diode in the circuit the zener diode would initiate forward conduction at 1Vdc when the 28Vdc supply voltage was applied.

Transient Voltage Suppressor - These components are avalanche conduction devices like zener diodes with the added capabilities of extremely fast operating time and higher surge current and power ratings. Transient Voltage Suppressors (TVS) are either unidirectional for polarity sensitive applications or bidirectional for circuits where transients are generated of either polarity.

The transient voltage suppressors used in the load testing were unidirectional P6KE27A and P6KE36A devices rated at nominal breakdown voltages of (V_{BR}) 27Vdc and 36Vdc respectively at a current (I_{BRT}) of 1mA and less than 1ns response time. The P6KE27A and P6KE36A provide steady state power dissipation (P_D) rating of 5 Watts and much higher peak power dissipation (P_{PK}) of 600 Watts [18].

To use a TVS for transient suppression another TVS with a 36Vdc rating, which is much higher than the 28Vdc supply voltage, was placed in series opposition as seen in Figure 3 for polarity protection. Without the

other TVS in the circuit the 27Vdc TVS would initiate forward conduction at 1Vdc when the 28Vdc supply voltage was applied.

TESTING SUPPRESSION DEVICES

LOAD TESTS CONFIGURATIONS - The test consisted of a JMGAPD-26M relay connected to a M39016/18 nominal 320mH inductive, 200mA, 28Vdc rated load configuration. For this particular test only the normally open (NO) contacts were used to switch the load. Four individual transient suppression configurations were tested. They were unsuppressed and suppressed with diode, zener/diode or TVS/TVS devices placed across the inductive load.

TESTING PROCEDURE - Prior to initiation of the test, new JMGAPD-26M relays were produced and tested with ATE parameters recorded. The test was performed at 25C ambient temperature with the relay contacts monitored for proper operation within specified limits. At the start of the test each suppression circuit configuration had the voltage and current waveforms recorded during several phases of the contact closure and opening. The tests were performed until approximately 50,000 operations, or half the rated lifespan, were switched by the relay contacts. At the conclusion of the tests the same ATE parameters testing was repeated for comparison and all relays passed. The individual relays were then delidded and the normally open and moveable contacts that switched the inductive load photographed and examined for wear.

INDIVIDUAL RELAY TESTING – Unsuppressed Load Test - Load Testing Configuration - The circuit in Figure 3 illustrates the unsuppressed inductive load switched by the normally open relay contacts. The circuit values measured indicated an inductor of 333mH with an internal inductor resistance of 31 Ohms. This was in

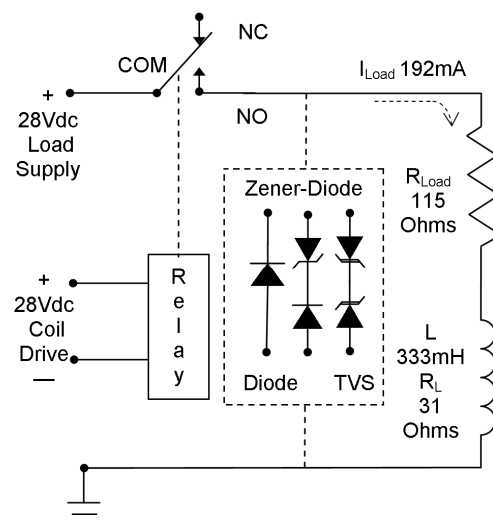


Figure 3 – Inductive Load Test Schematic

series with a 115 Ohms resistor for the nominal 200mA current load at 28Vdc. The actual current load was 192mA during the test.

Load Profile - The waveform profiles in Figure 4 were captured at the start of the inductive load test. They were measured by placing probes across the inductive load to capture the voltage waveform and across the series load resistor to capture the current waveform. The waveforms were captured during the opening of the inductive load by the normally open relay contacts. The results indicate that a maximum inductive transient of -368Vdc occurred 44us after interrupting the load. The bulk of the transient subsided by 566us after contact opening.

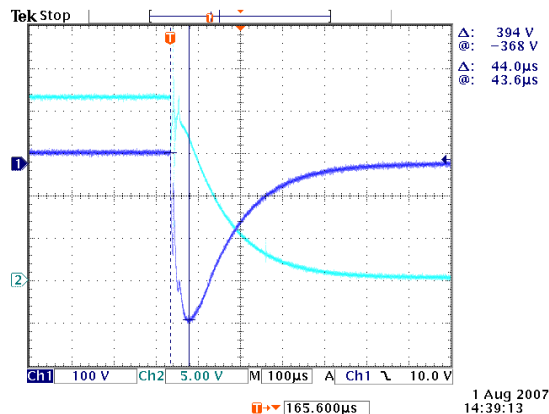


Figure 4 - Unsuppressed Load Profile

Diode Suppressed Load Test - Load Testing Configuration - The test circuit in Figure 3 placed the 1N4005 diode across the inductive load and the relay switched the normally open contacts. The balance of the circuit was the same as the unsuppressed load configuration.

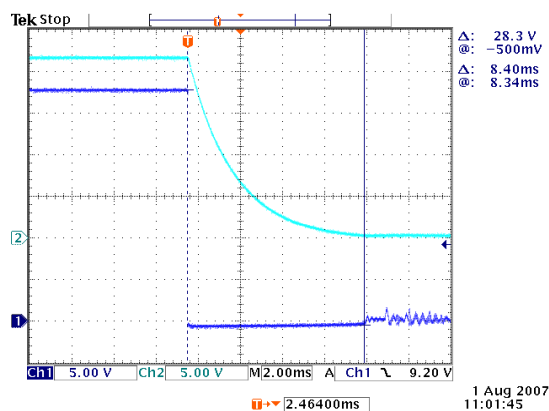


Figure 5 - Diode Suppressed Load Profile

Load Profile - The waveform profiles in Figure 5 were captured in the same manner as for the unsuppressed inductive load profile. The results indicate that a

maximum inductive transient of -0.5Vdc occurred that was 8.400ms in duration. The transient voltage waveform profile approximated a square wave as compared to the exponentially rising and falling pulse waveform that occurred during the unsuppressed load testing.

Zener Diode Suppressed Load Test - Load Testing Configuration - The test circuit in Figure 3 placed the 1N4749A zener diode, in series with the 1N4005 diode, across the inductive load and the relay switched the normally open contacts. The balance of the circuit is the same as the unsuppressed load configuration.

Load Profile - The waveform profiles in Figure 6 were captured in the same manner as for the unsuppressed inductive load profile. The results indicate that a maximum inductive transient of -24.0Vdc occurred that was 1.480ms in duration. The transient voltage waveform profile approximated a square wave with a higher voltage magnitude and shorter time duration as compared to the waveform that occurred during the diode suppressed load testing.

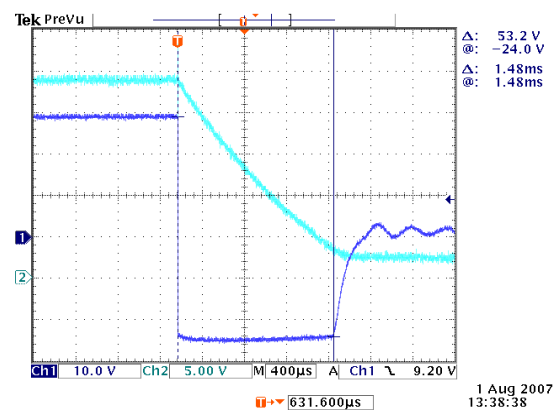


Figure 6 - Zener Suppressed Load Profile

TVS Suppressed Load Test - Load Testing Configuration - The test circuit in Figure 3 placed the P6KE27A TVS, in series with a P6KE36A TVS, across the inductive load and the relay switched the normally open contacts. The balance of the circuit is the same as the unsuppressed load configuration.

Load Profile - The waveform profiles in Figure 7 were captured in the same manner as for the unsuppressed inductive load profile. The results indicate that a maximum inductive transient of -27.2Vdc occurred that was 1.340 ms in duration. The transient voltage waveform profile approximated a square wave very similar to the zener diode suppression testing.

Load Test Summary - From Table 1 it is seen that any type of suppression device greatly lessens the transient voltage the relay contacts must switch when interrupting an inductive load. The added bonus is much reduced contact material erosion, which enhances the lifespan

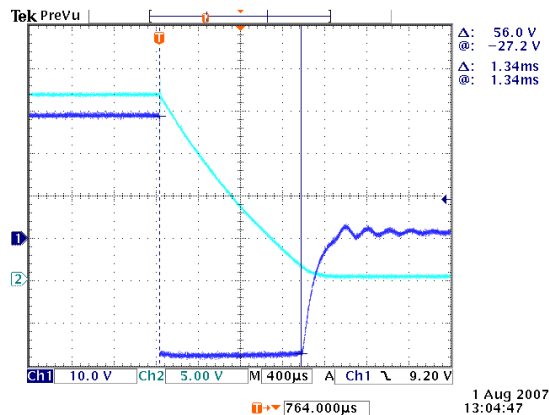


Figure 7 - TVS Suppressed Load Profile

and contact resistance performance of the switching relay. As current ratings increase from smaller to larger relays the suppression devices function the same. The key difference is selecting the power rating of the particular suppression device so that the levels of stored energy indicated by Equation 1 can be safely dissipated.

Suppression Device	Maximum Transient (Vdc)	Transient Duration (ms)
Diode	-0.5	8.400
TVS/TVS	-27.2	1.340
Diode/Zener	-24.0	1.480
Unsuppressed	-368.0	0.566

Table 1 - Transient Voltage and Duration

The most basic suppression device is the diode that practically eliminates the transient in the circuit with the penalty of an extended decay time for the inductive energy pulse. If this is not a desirable effect then use of a zener diode or TVS device properly rated near the 28Vdc contact load voltage rating of the relay contacts is recommended. The net effect is a transient voltage that is limited to the voltage ratings of the relay contacts with a transient duration time of less than 2 milliseconds which produced few negative effects on the inductive circuit.

Effects on Relay Contacts - With inductive loads the arcing takes place when the contacts open and the voltage generated is often several orders of magnitude greater than the supply voltage. When relay contacts switch loads above 100V the arcing becomes more severe accelerating contact material disturbance and erosion.

Unsuppressed Rated Load - After the inductive load tests the relays were delidded and the normally open contacts realigned from normal positioning so the mating surfaces that switched the inductive load could be

positioned side by side. It was observed that substantial base material beneath the gold plated surface had been eroded and redeposited on both the flat moveable and round stationary normally open contacts. Slight discoloration of the gold plating around the eroded base material can be seen indicating that significant energy or power levels were switched during the test. Even with this level of erosion the contacts had not visibly or electrically reached end of usable life as substantiated by the post life data.

Transient Suppression-Rated Load - The results were very similar for the diode, zener-diode and TVS suppressed rated load contacts. Compared with the unsuppressed load it was observed that an extremely small amount of base contact material transfer occurred. There was also very little discoloration of the gold plating on the stationary contact indicating low energy or power levels were switched during the test. These contacts showed little indication of being near their end of usable life as substantiated by the post life data.

Insufficient TVS Suppression-Overloaded - As a comparison with a properly TVS suppressed inductive load an inductive load that was both beyond the relay contact ratings and insufficiently suppressed was evaluated. An analysis of the relay normally open contacts showed substantial material transfer more often observed in high current pulse loads. The discoloration and diffusion or matted finish of the moveable contacts was indicative of substantial heat from current carrying during load switching. The amount of material transfer and discoloration indicated a gross overload condition when viewed in terms of approximately 100 switching operations.

The load indicated both inductive (733mH) and resistive (56 Ohms) loading of the relay contacts. With 28Vdc it indicated a current load of 500 milliamps. With Equation 1 the stored energy was calculated as:

$$0.5(LI^2) = \text{energy}$$

$$(0.5)(733\text{mH})(500\text{mA})^2 = 91.63\text{mJ or mW-s}$$

When compared to the rated M39016/18 inductive load stored energy of 6.4mJ the load released over 14 times inductive energy. The insufficient TVS suppression of a bidirectional TVS device P6KE56CA which operated in either current direction limited the inductive load transient voltage to a much higher -56Vdc resulting in the accelerated contact erosion and material transfer.

The inadequate TVS suppression of -56Vdc placed an inductive load upon the relay contacts that was 250% of the current rating and 229% of the inductance value when compared to the M39016/18 specification for the relays of 0.2 Amps, 28Vdc at L = 320mH unsuppressed inductive load rating. [19].

RELAY SUPPRESSION TESTING

RELAY TYPES - The testing of multiple transient suppression devices on different relay types illustrated the impact they have on each relay's operating characteristics. Most importantly the impact on the load breaking time and any increasing in the duration of contact eroding arc times are critical. To fully explore what is found in aircraft applications three popular relay configurations were selected. They encompassed low-, mid- and high-current devices in terms of the intended loads they would interrupt. Each configuration would interrupt a typically rated load while being subjected to no suppression and the three popular types of suppression devices previously discussed and tested.

Low-Current Relay - The low-current relay selected is from the MGSC .100 grid, double pole, double throw, relay family. The relay family is qualified to M39016/41 military specification. This specification is for a 1A 28Vdc resistive contact rated electromechanical relay, hermetically sealed, with no internal suppression devices. The particular part number selected, JMGSC-26M, has a high silver content contact material. It is qualified to M39016/41-036M specification. This relay has a 26.5Vdc, 3200 Ohms nominally rated coil.

Mid-Current Relay - The mid-current relay selected is from the FCA-325, cube style, three pole, double throw, relay family. The relay family is qualified to M83536/32 military specification. This specification is for a 25A 28Vdc resistive contact rated electromechanical relay, hermetically sealed, with no internal suppression devices. The particular part number selected, FCA-325-3205L, also has a high silver content contact material and is qualified to M83536/32-005L specification. This relay has a 28Vdc, 290 Ohms nominally rated coil.

High Current Contactor - The high-current contactor selected is from the K-500, buss bar mount, double break contactor family with a high tungsten content contact material. The contactor family is qualified to several military and commercial aircraft customer specifications. This particular configuration is for a 500A 28Vdc resistive contact rated electromechanical contactor, dust and moisture resistant sealed. The contactor has a 28Vdc, 6 Ohms pull-in, 170 Ohms hold, nominally rated coil with internal zener-diode combination coil suppression devices that were disconnected for the following unsuppressed and transient suppressed experiments.

LOAD TEST CONFIGURATION - A configuration was created to allow proper measurement and capturing of the coil performance and load testing parameters. The test circuit illustrated in Figure 8 was utilized for all three relay types. It provided two separate regulated power supply sources and use of 1% precision resistors for all loading and measurement values. Wiring lengths were minimized to reduce extraneous signals that could alter the results.

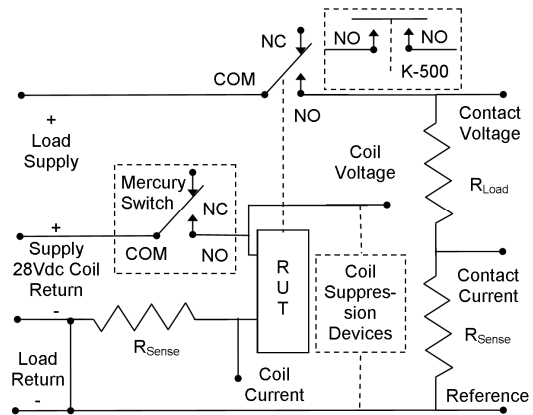


Figure 8 - Test Schematic

TESTING PROCEDURE - To illustrate the effects of the previously tested inductive load suppression devices, when placed across the coils of the relay configurations, several critical parameters outlined in Table 3 needed to be determined. For purposes of this experiment it was determined to observe the effects of transient suppression upon the coil and contacts release timing. It was also determined that additional attention would be placed upon the relationship that may exist between transient suppression and any negative effects on relay contact performance by lengthening undesirably long arcing time which could reduce the useful lifespan of relay contacts in aircraft applications.

For the relay under test (RUT) coil input section a separate 12 amps, 28Vdc regulated supply was used to operate the coil. The coil was energized utilizing a mercury switch to minimize any arcing effects from controlling the coil that may alter measuring the desired coil performance parameters. A small coil current sensing resistor was placed inline with the coil path to measure and record the coil current waveforms. The coil sensing resistance values in Table 2 were chosen to develop approximately a 500mV signal at the coil's 28Vdc nominal voltage. The value was also chosen to be small enough to introduce a nominal 1.8% measurement error to the circuit acceptable for oscilloscope measurement accuracy.

For the relay under test (RUT) contact load section a separate 18 amps, 28Vdc regulated supply was used to operate the contacts. The load was operated by the normally open contacts. In the case of the K-500 contactor the load was operated by the double break contacts. The load resistance values in Table 2 were chosen to provide a large power load within the nominal to upper ratings limits of each relay configuration. This insured sufficient switching and arcing stresses were placed on each relay contact to provide opportunity for realistic contact performance measurements while undergoing various coil transient suppression methods. The contact load sensing resistance values in Table 2 were chosen to develop approximately a 1000mV signal