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White Paper

Safety Considerations When Using Optocouplers and Alternative Isolators for Providing Protection Against Electrical Hazards

Introduction

Optocouplers and alternative isolation technologies find widespread use in a variety of products for signal isolation and high voltage level shifting. These devices can also be used to provide safety related insulation. Considering these electrical concerns, it is necessary to understand the safety related characteristics of the optocoupler or alternative isolator.

Basis of Electrical Safety

Electrical shock caused by the passage of electrical current through the human body can result in physiological effects ranging from injuries caused by involuntary moments to death from ventricular fibrillation. The voltage threshold of risk is somewhat erratic due to variations in health, moisture levels and body impedance, but the level of voltage that is generally considered safe is DC voltages up to 42V and AC voltages up to 60V. Any electrical application that exposes people to voltages greater than this is consider a hazard, and sufficient electrical insulation is required.

Concept of Safety Factor

When human safety comes into the equation, designers are forced to consider so-called safety factors. The aim of safety factors is to take into account user conditions that are not fully deterministic, with the aim of ensuring an extremely remote chance of failure. Safety factors are widely used in a wide range of engineering disciplines.

As an example, in civil engineering a common safety factor frequently used for scaling support members in the construction of buildings is typically 2. A higher factor can be used when the quality of the material is not as well known. For aerospace a factor of safety of 1.25 is typically used. In these applications, weight penalties are extreme and the costs of higher quality control and frequent servicing checks are more tolerable. So on this basis, a lower safety factor is justifiable. For safe electrical insulation applications, often referred to as reinforced insulation applications, the typical safety factor used is 2.

Continuous Working Voltage

During the course of normal operation, it is expected that the optocoupler or isolator is subjected to a continuous voltage stress. This voltage is typically referred to as the working voltage.

Since this stress voltage is continuous, the probability of risk to people is much higher should the insulation fail. For this reason, the working voltage rating is usually derated by a factor of two from the designed continuous voltage stress capabilities of the optocoupler or isolator.

Transient Voltage Capabilities

In addition to being capable of holding of the continuous working stress voltage, the optocoupler or isolator is also required to hold off or survive high transient voltages. The types of transient voltages can be categorized either into high energy or low energy transients (Figure 1).

High energy transients have the propensity to be hazardous. Although low energy transients are generally not directly hazardous to health, they do present significant risk to the well being of the insulation material, which could in turn lead to a safety hazard.

Table 1: IEC60664-1 Impulse Rating Coordinates

Nominal Voltage of the Supply System (V)		Voltage Line to Neutral ac or dc (V)	Rated Impulse Voltage (V)			
			Overvoltage Category			
Three Phase	Single Phase		I	II	III	IV
		50	330	500	800	1500
		100	500	800	1500	2500
	120-240	150	800	1500	2500	4000
230/400 277/480		300	1500	2500	4000	6000
400/690		600	2500	4000	6000	8000
1000		1000	4000	6000	8000	12000

Low Energy Voltage Transients

ESD is a particularly common voltage transient event that comes under this category. Since ESD events can quite easily exceed more than 15 kV, they can, and often do, exceed the creepage and clearance distance requirements of most optocouplers or alternative isolators. The consequence of this is flashover across the optocoupler or isolator. Fortunately, this flashover event does not represent a significant direct safety hazard.

Pertaining to the insulation stress, the occurrence of flashover is a self-limiting event, minimizing the maximum voltage stress to the insulation. Despite this, transient voltage loading up to the point of flashover can still be extremely high. There is a large variation in the flashover inception voltage due to environmental conditions such as altitude and humidity. Even relatively low level ESD events are potentially capable of causing significant damage to the insulation, either in the form of latent damage or immediate damage. This subsequently can result in a hazardous situation if the continuous working voltage falls within the hazard limits.

In the case of the optocouplers, this failure scenario is well taken care of through the scaling of the insulation thickness. In particular, thick insulation material is used, ensuring that that the breakdown voltage of the internal insulation is sufficiently higher than the external flashover voltage. However, such protection is much more difficult to achieve in alternative technologies where fundamental operation is dependent on the use of extremely thin insulation layers.

These types of devices are particularly vulnerable to ESD breakdown. Alternative isolator technologies can be characterized into two construction types: Type 1 using spin on polyimide coatings for primary insulation, and Type 2 devices using silicone dioxide (SIO2) insulation for the primary insulation.

In the case of type 2 devices, SIO2 insulation is particularly prone to ESD damage. In fact, most integrated circuit designers go to great lengths to provide protective structures to limit ESD damage to SIO2 structures on exposed interconnects.

This normally takes the form of voltage clamp devices. In the case of an isolator device, it is extremely impractical to connect a voltage clamp across the isolation; this inevitably results in an extremely vulnerable isolator due to insulation damage by ESD.

High Energy Voltage Transients

High energy surge type events are commonly experienced on power distribution systems. Such power surges might be caused by the operation of heavy machinery connected to the same distribution network or in rare cases lighting strikes.

Since such surges have the capability to be directly life threatening, it is important that the isolator dimensions are correctly scaled to ensure protection against such events. This problem is taken care of within the end equipment standards by the so-called installation category or overvoltage class. For each application usage, the relevant equipment standard determines the maximum surge voltage transient for which the insulation should be capable of withstanding.

High Voltage Component Testing

Verification of the suitability of the optocoupler or alternative isolator to provide safe protection against continuous and transient voltage stress is normally verified by a combination of constructional requirements and electrical testing.

Dielectric Testing

The principle objective of this test is to establish the capability of the isolator or optocoupler to withstand a high voltage for a short period of time, typically 1 minute.

Examples of such test standards are UL1577. The pass or fail criteria is determined on the measured leakage current. This in turn establishes the capability of the component to withstand an in situ end equipment dielectric test.

This limits the applicability of such a test rating. In particular the rating does not establish the safe continuous voltage.

Partial Discharge Testing

Partial discharge testing is an insulation test procedure, which is carried out to not only establish the capabilities of the insulation to support high transient voltages, but also to establish the integrity of insulation at nominal working voltages. In particular, it checks for the presence of so-called *microvoids*. While under voltage stress, corona discharge in microvoids can cause insulation erosion, eventually resulting in the breakdown of the insulation.

By stressing at test voltages closer to the nominal operating level and checking for the presence of partial discharges, this offers the benefit of being able to check for an inherent degradation mechanism that might be activated under nominal load conditions. This better enables the establishment of a safe continuous working voltage.

The second advantage of this method is that it enables testing at lower test voltages, using those closer to the intended application, reducing the possibility of pre-stressing or damaging the insulation. The ultimate aim of partial discharge testing is to prove that the insulation material is so-called *void free*.

Void free, however, is a misnomer. No insulation material is ever 100% void free, so it will always be a relative measure, with the absolute resolution being limited by the measurement system. A typical partial discharge test setup has a resolution down to 1 pC, but to enable reliable testing in a manufacturing test setup, the test limit is normally set at 5 pC.

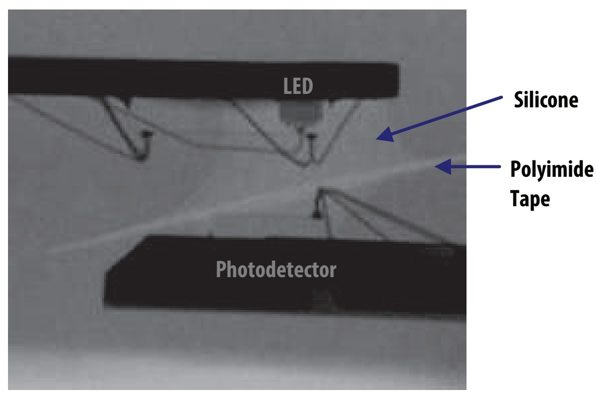
An example of partial discharge testing, which was developed to assess the high voltage safety characteristics of optocouplers, is VDE0884. This standard has subsequently been developed into the international optocoupler safety standard IEC60747-5-5.

Optocouplers are effectively a hybrid construction consisting of an optically transparent insulation layer with an opaque over molded insulation epoxy.

Sometimes the question is asked, what are we testing with the IEC60747-5-5 partial discharge test—the overmold packaging or the internal insulation layer?

To a greater extent, the answer is both (Figure 1).

Figure 1: Optocoupler Double Insulation Construction



In determining void free insulation, the relevance of the partial discharge pass threshold needs to be taken into perspective with the total stored charge on the dielectric material. If the electric field can be considered to be homogenous, the stored charge is evenly distributed through the insulation construction, so the partial discharge measurement is equally applicable to the overall insulation construction. A typical optocoupler has a total package capacitance of ~0.7 pF. While the electric field is not totally homogenous and there is a small charge imbalance at different areas of the construction, it is still a valid assumption that the partial discharge test result has a significant applicability to both the overmold insulation and the internal optical insulation.

Sometimes a similar partial discharge test methodology is also applied to alternative isolator technology, either magnetic or capacitive based. In this case, the validity of such test methods is severely limited by the fact that the electric field in such technologies is not anywhere near as homogenous as with optocouplers.

For example, a typical alternative isolator might use a micro insulating structure with a capacitance of 100 fF. At a test voltage of 1000V, such an isolation structure stores 100 pC of charge.

In this context, the partial discharge test limit of 5 pC represents a very relaxed pass level criteria. If 5 pC discharges did actually occur in such a small insulation structure, it would, in all probability, be rapidly followed by avalanche breakdown.

While the partial discharge testing might be suitable for detecting problem voids in the alternative isolators overmold packaging, it is irrelevant for detecting problem voids in the principle insulation structure, which arguably is the weakest area of alternative isolators.

Optocoupler/Isolator Construction Requirements for Electrical Safety

When talking about constructional requirements for safety, the two main areas of consideration are the internal construction and the external mechanical dimensions.

Internal Construction

Before deciding on the construction requirements, it is first necessary to determine the intended use, basic or reinforced insulation:

- Basic insulation is used for providing functional insulation proprieties on its own and might not be used to provide protection against electrical shock risks.
- Reinforced insulation is used when the insulation is required and rated to ensure protecting against the risk of electrical shock. The term reinforced is also sometimes interchanged with the expression double insulation.
  - Double insulation means literally that, the capability to support double the rated electrical voltage. The physical method of achieving this can also be literal, i.e., providing two separate insulation layers each capable of holding off the required voltage. In some cases, the requirement of reinforced insulation can be achieved with the use a single layer of solid insulation.
- A suitable single solid layer of insulation for safe insulation varies somewhat between regulatory standards. If we take the end equipment standard IEC60950 as an example, a single thick (>0.4 mm) homogenous material is considered suitable for providing double or reinforced insulation. In terms of the definition of solid insulation, it’s not just the material itself that is important, but also the material processing, e.g., thick polyimide insulation can quite well be considered to be solid insulation, but solvent based polyimide (enamel) layers might not.

External Mechanical Dimensions

External requirements are also important to support safe insulation requirements. The two key dimensions in this regard are clearance and creepage distances (Figure 3).

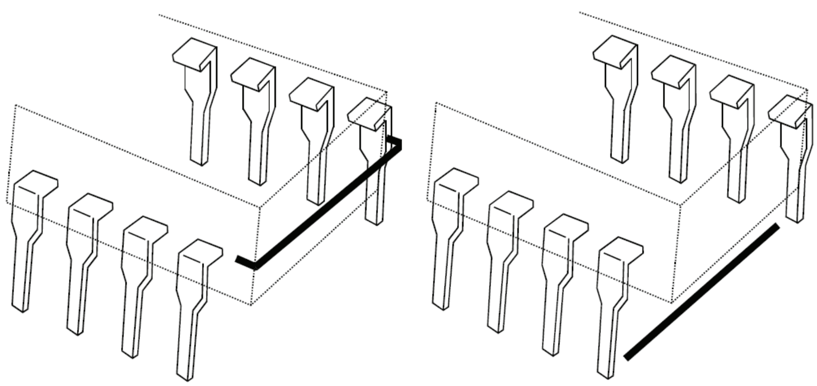
Clearance

Clearance distance is the shortest distance between the input and output terminals through air. The key objective of sufficient clearance distance is to ensure that no electrical flashover can occur across the terminals.

The actual flashover voltage is particularly dependent on altitude and humidity levels. Dry high altitude locations provide the highest propensity for flashover.

Suitable physical dimensions to prevent flashover are referenced from isolation coordinate standards such IEC60664. Within that IEC60664 document, tables are given for various working voltage conditions. These values are based on both empirical measurement data and phenomenological understanding of flashover. To meet the requirements for reinforced requirements, the distances are multiplied by a safety factor of 2.

Figure 2: External Package Isolation Distances



It is not just the mechanical construction of the isolator itself; it is also necessary to consider the overall mechanical separation, when the part is in situ in the end application. In particular, care needs to be taken to allow for reduced separation distance resulting from PCB solder contacts and interconnection traces.

Creepage

Another important external dimension is creepage distance. This is the shortest measured distance around the body of the package. The reason why this dimension is considered important is that in some circumstances a conductive tracking path can start to form along the insulation surface. Factors that influence this are external pollution such as moisture and dust, and the propensity of the insulation material surface to attract and retain pollution. The creepage distance is dependent on the external environment, the so-called pollution degree, and the material category of the overmold material. The appropriate creepage distance can be found in lookup tables in the IEC60664 standard.

Insulation Lifetime

Since the vast majority of applications utilizing optocouplers or alternative isolators are not subjective to regular servicing checks on the quality of the insulation, it is imperative that the insulation capabilities are rated to ensure safety for the lifetime of the end product without any user intervention.

Definition of Safe Lifetime

The definition of what is considered safe is somewhat subjective between manufacturers. For example, a manufacturer of alternative isolators might consider the safe usable lifetime as being the time point at which 1% of parts fail while operating at a continuous rated working voltage. The problem with this definition is that subjecting 1% of people to life threatening risks might seem rather high to some. It also doesn't take into account the influence of transient overvoltage's or the necessity for safety factors.

A more conservative and safer approach is to consider the end of life definition as being the time point at which there is a statistically insignificantly chance of either:

1. The insulation degrading to the point at which a rated transient overvoltage can result in permanent destructive breakdown.
2. The insulation has degraded to the point at which the insulation is no longer capable of continuously holding off 2 times the rated working voltage.

Since there are two possible failure scenarios, we will also consider the two wear out mechanisms separately. It should be noted that in practice they are not mutually exclusive mechanisms.

Transient Voltage Wear Out

The transient rating is taken care of to some extent by both the UL1577 dielectric test rating and the IEC60747-5-5 transient rating. But there is a problem in that it doesn't directly provide details on the transient voltage capabilities over the expected lifetime of the end product. In particular, the problem is that the test voltage ratings are tested only for very short time periods.

Since the likelihood of transient voltages causing insulation damage due to corona erosion and other degradation mechanisms is high, the associated accumulation of insulation damage over the equipment lifetime is very significant, even if the transient periods are short. It is easy to foresee that the sum time of all transient events over even a moderate equipment lifetime, can quite easily exceed the rated transient test time.

To establish the safe transient capabilities over the lifetime of the end equipment, it is necessary to appropriately scale the insulation construction. Verification of this capability can be achieved by performing extended life testing at high test voltages such as those used in UL1577 testing.

When comparing different technologies, optocouplers vs alternative technologies, this is a particular area where vast performance differences are observed. As an example, it would not be usual to find an alternative isolator failing a UL1577 dielectric test after a time period of less than 15 minutes; whereas an optocoupler typically demonstrates a UL1577 dielectric test lifetime exceeding hundreds of hours. This vast performance difference clearly has a very direct impact on the expected transient lifetime expectation in the end application.

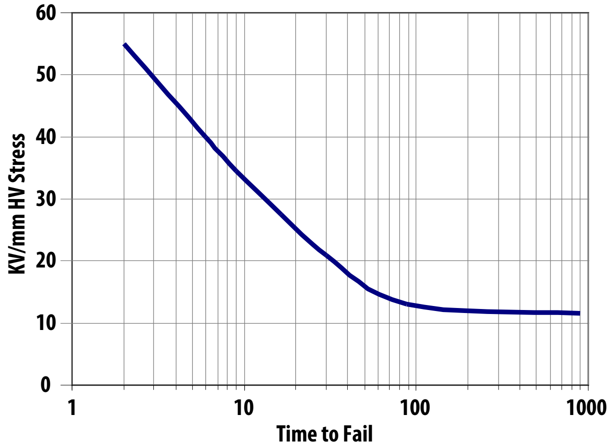
Working Voltage Wear Out

The second wear out mechanism occurs during nominal loading with a continuous working voltage.

The principal concern is that there should be no active wear out mechanism that is causing a significant aging affect, resulting in insulation failures during the intended equipment life.

One of the principal concerns is determining that no insulation erosion is occurring due to partial discharges in internal voids. There are also other aging effects to be considered. In the case of highly stressed polymer insulation materials, a significant aging mechanism is space charge degradation (Figure 3).

Figure 3: Typical Polymer Space Charge Degradation Characteristics



Space charge is the expression given to a charge injected into the insulation material when under high voltage duress. The injection of space charge alters the internal electric field causing ever increasing stress on areas of the insulation material. In terms of the quantity of space charge injected, the principle determining factor is the thickness of the material and the applied electric field, resulting in a kV/mm stress factor. Other significant factors include operating temperature and the waveform type and frequency.

Space charge aging in polymer materials is a very active research area. Despite this, the understanding of this aging phenomenon is far from complete. There are some clear and consistently observed characteristics of space charge degradation, which are of use in predicting lifetime. If the measured lifetime is plotted verses the stress test voltage, it is clear to see that the aging response curve has a clearly identifiable asymptote at lower kV/mm stress levels.

This characteristic indicates that when operating below a certain inception stress voltage level, the lifetime expectation increases at an extremely rapid rate.

Operation at a voltage stress less than this inception voltage effectively reduces the effect of space charge degradation to insignificant levels.

Because optocouplers make use of thick insulation materials with correspondingly low kV/mm stress levels, space charge degradation is invariably not a concern.

Space charge degradation is a very significant problem in alternative isolators using thin polymer coatings. In this instance, the inherently high kV/mm stress results in the onset of space charge degradation. This effect can be observed when testing the lifetime at high dielectric test voltages. But more worrying is the fact that longer-term testing at test voltages not so far away from the intended nominal operating voltage often indicates failures within time frames considered typical in end user equipment.

Conclusion

Optocouplers have found widespread use in electrical safety related applications for decades. Despite this, it can be argued that in some instances equipment and component related safety standards do not completely address the requirement of absolute proof of safe use.

The areas of concern are mainly in the areas of HV lifetime and HV transient damage. Fortunately, this is only a theoretical risk, since this issue is already taken care of by the inherent design of the optocoupler and can be both experimentally and phenomenological proven. Unfortunately, in the case of alternative isolator technology, this theoretical risk gets translated to a very plausible safety hazard.

In many cases, equipment standard definitions effectively prohibit the use of alternative isolator technologies for reinforced insulation on a construction basis.

This is not always the case; the specific risks relating to some legacy equipment standards of alternative isolators either offer ambiguous guidelines or none at all. This situation is often further compounded by the technically invalid usage of optocoupler component standards for assessing the safety of alternative isolators.

References

1. “A Space-charge Life model for ac electrical Aging of Polymers.” G. Mazzanti, G.C. Montanari, L.A. Dissado. *IEEE Transactions on Dielectrics and Electrical Insulation*.
2. “Contribution of Partial Discharges to Electrical Breakdown of Solid Insulating Materials.” C. Mayoux and C. Laurent. *IEEE Transactions on Dielectrics and Electrical Insulation*.
3. IEC60950-1 Second Edition 2005, Information Technology Equipment Safety.
4. IEC60664-1 Insulation coordination for equipment within low-voltage systems.
5. Broadcom Regulatory Guide for Isolation Circuits, Publication number: AV02-2041EN.