Reliability, cost of ownership and life cycle cost (LCC) considerations

for switchmode power supplies in trainborne- and trackside applications

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Power-One is one of the world's largest, independent, power supply companies with more than 1'850 employees, manufacturing on three continents. The company is listed on Nasdaq (PWER), and supplies power conversion products to professional communications, industrial and transportation markets.

Through it's Swiss based site (formerly Melcher), Power-One CAPS (Compact Advanced Power Solutions) supplies to almost all leading manufacturers in the railway industry high performance, rugged DC-DC and AC-DC converters. They are designed to meet international railway- and global safety standards. With over 30 years experience, Power-One CAPS is a leading supplier of products into the railway industry, with hundred thousands of products installed on rolling stock and more than 26'000'000 power supplies shipped worldwide.

With power levels from 4 W to 500+ W for use in transportation, the products feature ultra-wide input voltage ranges, high efficiency, wide operating temperature ranges, designed to satisfy T3 (-7) and TX (-9) requirements, self-cooling, fully enclosed cases, high immunity to electrical, mechanical and thermo- mechanical stress, low cost of ownership and demonstrated high reliability.

Our Applications Centre conceives application specific power supply system solutions to meet customer's requirements by using standard converters as main parts. Such solutions are economic and reliable.

STANDARD PRODUCT FEATURES

- Compliance with IEC60571, EN50155, EN50121-3-2, BRB RIA 12, 13, 18, 20, EN60950
- High efficiency, low heat generation, low Life Cycle Cost, LCC
- Wide input voltage ranges 1:10: Regulators, 1:5: M, K and S, 1:2.5: IMX, Q and P families
- Wide output voltage trim ranges for ease of use, standard V_o 3.3 to 24 /48 V_{DC}
- High isolation input-output, 1.5 kV_{DC} to 5.6 kV_{DC}, 1 kV_{AC}, to 4 kV_{AC}.
- All circuits are dip- varnished for high mechanical durability and humidity storage withstand
- Rugged aluminium pressure cast- or extruded cases
- The units are self cooling with no derating over the specified temperature range
- Nominal inputs of (12V), 24V, 36V, 48, 52V, 60, 72V, 110 & 220 V_{DCin}, global AC_{in}
- Complete families of products offering single, dual and quad outputs
- Isolated outputs for easy series, and in most cases, parallel configuration
- Our Applications Centre conceives applications specific systems to meet customer's requirements by using standard converters. Such solutions are reliable and economic.

1 Synopsis

The use of switchmode power supplies in trackside and trainborne railway applications is careful considered, with particular emphasis on the selection process for determining cost of ownership; long-term high reliability (low life cycle cost, LCC).

Key words: DC-DC-, AC-DC- converters, cost of ownership, life cycle cost LCC, isolation test voltage, missuse and abuse, partial discharge voltage, potting, regulators, reliability, solder recrystallization, switchmode power supplies, random vibration, thermal cycling.

2 Introduction

In today's rail environment, low cost of ownership (low life cycle cost, LCC) is a key requirement. The reliability required to assure that this requirement is fulfilled is highly dependent on the integrity of complex electrical and electronic control equipment, essential for the safe operation of vehicles and the network. Such equipment requires reliable DC/DC converters or AC-DC power supplies to transform on board traction, signalling or trackside voltages to stable DC voltages for powering auxiliary equipment.

The following outlines some of the important issues the design engineer shall consider in specifying power supplies in an industry, which increasingly relies on the transfer of know-how, and where the consequences of a bad decision may be heavy penalty costs and/or loss of future business.

Sophisticated electronic equipment is becoming increasingly important in trackside, signalling and trainborne applications. Conventional equipment such as train radios and door controls are being supplemented with complete train management systems, ATC, ATP, data highways, accident recorders, satellite vehicle location equipment, ERTMS = ETCS + GSMR and other sophisticated control and monitoring equipment measuring everything from brake wear to passenger load levels. Not to forget to mention passengers comfort systems from air conditioning, passenger reading lamps, built in TV sets and

LCD passenger information systems, restaurant table illumination, high tech vacuum toilet flush to noise cancellation systems.

Such equipment requires reliable supply of power, usually involving the conversion of either

DC or AC supply voltages superimposed with heavy transients and surges to a safe, clean and ever lasting DC (or AC) supply. The power supply has to cope with wide voltage- and temperature variations, is subjected to severe voltage surges and heavy voltage transients, high levels of random vibration and humidity. Failure of such power supplies can cause anything from minor irritation, traveller's dissatisfaction, missing connections to loss of life, but in many instances it is lost revenue, delays and increased costs the rail operator and the traveller have to bear.

This paper considers the importance of reliability, (as the basis of the systems life cycle cost LCC) in the selection of power supplies for use in railway applications. The article provides an overview of some of the most important factors to be taken into consideration in the decision making process.

3 Switchmode versus linear

The conventional linear regulator (Fig. 1); uses a series pass element (i.e. a bipolar transistor) to drop the voltage, which is not required by the load. A feedback loop is used to maintain regulation with variations in load and source voltage accommodated by changing the resistance of the series pass element. This means that efficiency is directly related to the difference between input and output voltage. For example, if $U_i = 2 \times U_o$ then efficiency will be less than 50 per cent.

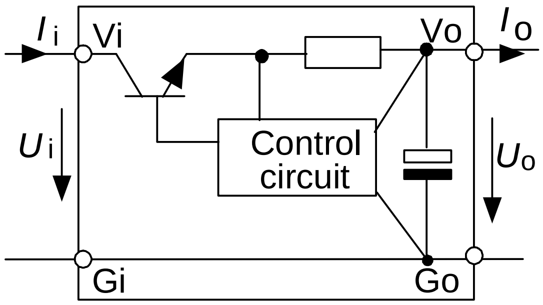


Fig. 1 Linear Regulator

A switching regulator (Fig. 2) uses a series switch (a Field Effect Transistor FET) to charge storage components (inductors and capacitors) to maintain a constant voltage at the load. The feedback loop in this case controls the series switch, varying the on / off times to maintain voltage regulation at the output.

The *L* and *C* elements are used to smooth the output voltage. The advantage of this technique is that the series switch is operating in either the "off" or "on" condition, with very low losses in both cases. In contrast to the linear regulator, efficiency remains virtually unaffected by variations of the input voltage (Fig. 3).

Both have no input to output isolation (no galvanic separation; common ground with the source or chassis) and the formation of ground loops is therefore an inherent danger.

A summary of the main advantages and disadvantages of both topologies is considered in Table 1.

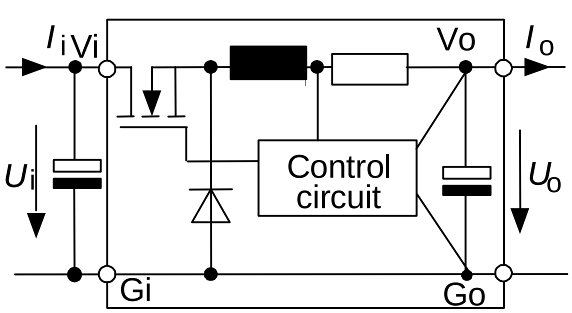


Fig. 2 Switching Regulator

Switchmode and linear topologies are used independently or together in a variety of configurations to form most power supply products seen on the market today, either as nonisolated products (Fig. 1 and 2), or fully isolated products where the output is galvanic separated from the input by means of a transformer.

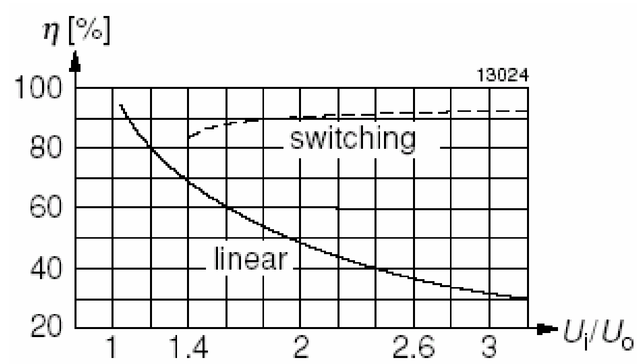


Fig. 3 Efficiency of switching versus linear regulator.

Table 1 Comparative advantages

Switched Mode	**Linear**
• Near constant efficiency	• Simple to design
• wide input voltage range	• low price
• low heat generation	• low noise
• potentially high reliability	
• low weight and size	• easy to use

Please bear in mind:

neither switchmode regulators nor linear regulators do have input to output isolation!

Nevertheless, in applications where there is no need to ground the load, switchmode regulators are comparably cheap and very reliable alternatives to the much more complex and thus more costly DC/DC - converters. In the case of Power-One, we speak about factor two to three lower cost and up to five times higher reliability.

Before proceeding further to consider topologies, it is worth noting, the main factors affecting reliability of any electronic assembly.

4 Reliability

The governing reliability issues are:

- heat (dependent on environment +efficiency)
- voltage stress (dependent on derating)
- mechanical shock
- vibration, namely random vibration
- complexity
- humidity
- lack of adequate protection measures
- misuse and abuse.

In the rail environment all such elements are present, although for power supplies, temperature, voltage stress and the mechanical environment are perhaps the most common causes of failure.

The simplest way to increase reliability is to avoid all of the factors listed above. That may be easier said than done. To avoid heat, one can increase the system's efficiency. Lowering voltage stress means applying heavy derating at component level. Humidity is no problem during operation. – Even Power-One's very high efficiency enclosed power supplies generate enough heat to dry out quickly. For safe storage, all rugged and industrial grade units are conformally coated (varnished). Vibration immunity is achieved with rigid mechanical solutions. Complexity is countered with gate arrays, ASICs and AlO_2 hybrids wherever economic and possible.

Tackling adequately all of the factors described is neither simple nor inexpensive. The great advantage of doing so is long, problem free operation: lower LCC. This turns into low cost of ownership for the operator. Simply said: one gets what one pays for…

The last points on the above list, misuse, abuse and lack of adequate protection measures cannot be avoided. We are ready to help our partners in this respect with global application support. See more in section 12 (pages 19, 20).

As a general rule, reliability of an electronic assembly is estimated to halve for every 10°C rise in temperature. A key feature of the rail environment is the highly variable source voltage and wide range of operating temperatures which electronic equipment may be subjected to. This is particularly the case for the traction environment, where the supply voltage may vary by as much as 70...125 per cent of the nominal rating with 15 per cent superimposed ripple to the DC voltage, sags to as low as 60 per cent and surges as high as 140 per cent plus very high energy voltage transients up to 8.4 kV (Rail Standard for rolling stock IEC60571, EN 50155).What makes one transient more dangerous than another is not it's voltage level but the amount of energy involved.

These factors work definitively against the use of linear regulators, whose efficiency will be in many cases very low (< 50 per cent) and will in turn generate significant heat, both within the dissipating semiconductor and into the local environment. Many events have been reported where equipment failure can be directly attributed to the heat generated by such and other devices. Switchmode power supplies or DC/DC - converters, whose efficiency remains constantly high with wide input voltage variations, provide a better opportunity to maximise reliability.

4.1 Equipment Reliability and Component Selection:

The European Rail Standard EN50155 states that the demonstration of the reliability of equipment *may* be required. The accepted method of calculation is based on MIL Handbook 217. Since availability of such figures is normally the case, a check should be made as to how and under which condition the calculation has been made for the power supply.

Users should check that the calculation has been done by the "Parts Stress Analysis" method, which takes into account the voltage, current and power stress as well as failure factors seen on every single component.

The simpler "Parts Count" method of calculation produces a misleadingly high MTBF figure. Furthermore, since the MTBF calculation is based on specified ambient temperature and mechanical ratings, the user should take into the consideration the comments made earlier.

A high MTBF figure calculated to MIL217F will not in itself assure high reliability in any environment. However, the standard does not adequately differentiate between the many different types of components available on the market and the subtle differences in specification, which may be critical to their actual application.

4.2 Component Evaluation.

For example, there are capacitors, and there are capacitors. On paper they may look the same. In reality they represent the difference between high numbers of infant failures, or continuous reliable operation. The term "long life" may well be suited to a design application, where e.g. voltage stress is high, but ripple currents are low.

In switchmode power supply use, low equivalent series resistance (ESR) is an important issue for capacitors used to carry steep current rises d_i/d_t and high ripple currents seen at the input and output(s). The ESR of certain brands of capacitors increases with age and may have a long term and detrimental effect on the reliability of the power supply resulting in a high level of mid-life failures. Power supply manufacturers should be able to demonstrate the reliability potential of the capacitors used in their designs based either on manufacturer's data, accelerated life-testing or long term field experience in rail industry.

The "long-life" designation or an MTBF calculation to MIL217F is not sufficient to assure reliable operation in traction environment, where service life of 15 years or more and low LCC are expected.

Magnetic feed-back versus optocouplers: capacitors are not the only components which affect long term reliability. Most power supply manufacturers rely on optocouplers for the feedback from the output (secondary) to the input (primary) side controller. This feedback is at the switching frequency of the power supply which may range from typically 25 kHz to 1 MHz and higher. Whilst optocouplers are quite reliable at DC, their use at high frequency can result in mid-life failures as a result of the degradation of the light emitting source. This is accelerated by the higher ambient temperature, which can be found in rail environments. Ideally a magnetic feedback device in the form of a small transformer will provide a significantly higher mean time between failure, suffering no ageing effects whatsoever.

4.3 Derating = lowering voltage-, current- and power stress.

The only measure to reduce voltage-, current- and power stress is to apply heavy derating at component level. A typical industry standard derating factor may be 0.8 (MIL STD 0.6) of the rated value of the components concerned whereas Power-One goes in some cases as low as 0.5, which gives a tremendous competitive edge in view of field life expectancy directly impacting operator's cost of ownership and LCC.

4.4 Humidity = conformal coating, varnishing

Humidity as stated earlier in this article is no problem during operation. To mention it another time: Power-One's very high efficiency enclosed power supplies still generate enough heat to dry out quickly. For safe storage, all rugged units are tropicalised. The type test applied to underline the effect of the tropicalisation is 56 days at 40 °C with 93 + 2–3 % relative humidity.

4.5 Vibration = rugged mechanical construction

Power-One bolsters the design of their rugged power supplies with rigid mechanical design directives and adapted solutions. Careful consideration is given to internal mechanical component fixing, vibration damping measures and adequate interconnection techniques. For rugged environment the type test specifications are:

- Shock 100 g_n = 981 m/s^2
- Continuous shock 40 g_n = 392 m/s^2
- Vibration 5 gn = 49 m/s^2
- Random vibration 4.9 g_{rms}

4.6 Reducing complexity = high level of integration

The obvious way to reduce and keep complexity low is to use Gate Arrays, ASICs and AlO_2 hybrids with printed, passive and active trimmed resistors, wherever economically possible. This hybrid circuit technology, thick film technology on aluminium oxide substrates is extensively used for reducing the number of discrete components, improving the interconnection reliability and assuring low thermal component stress by nearly ideally distributed heat in the AlO_2 substrates. Nowadays some product are 100 % integrated hybrid circuits.

4.7 Negative input impedance.

Power supplies are dynamic in performance - that is that they are influenced by the source impedance, changes in input voltage and load. Switchmode power supplies feature ***negative input impedance,*** which means that the input current *decreases* as the input voltage rises.

A switchmode power supply connected by long input supply lines may not operate successfully, if the power supply turns on at a low input voltage, and where the initial turn-on input current is very high under all circumstances (as may been seen especially with a weak battery). Under such circumstances, voltage drops in the input lines may cause the input voltage to effectively collapse producing a “lock-off” situation, from which the power supply might not be able to turn on. Interestingly, such characteristics may not be seen in a laboratory where a bench power supply with high source impedance limits negative input resistance effects of the inrush current - plus the initial switch - on current.

Even if the power supply turns on, the rating of cables and circuit breakers for worst case currents will increase cost. Users should check to assure that a power supply turns on in a controlled manner under all operating conditions, and that the turn-on voltage is not set excessively low. See also 12.37, page 23.

4.8 Outputs.

High currents at the output can cause other problems. In an effort to maintain the correct voltage at the load, sense lines are often considered a useful feature. This is particularly the case where long interconnections exist, and for 5 V or 3.3 V loads where currents and dynamic load changes can be quite high. In such cases, the voltage at the load can be seen to fluctuate by more than 1 V.

With long interconnections the reservoir capacitance in the power supply is no longer in the correct place. Ideally it should be located at the load where it can instantly provide current to address load step changes. With the capacitance located at the power supply, the speed of the feed-back loop and the impedance of the interconnections will dramatically affect the dynamic performance of the power supply.

Furthermore, the sense lines themselves act as an inductive feedback loop, which may cause an oscillatory condition on the output voltage (ringing), provide a relatively unprotected path to the control circuit of the power supply, susceptible to EMI and transients. In a traction environment this is highly undesirable. Ideally avoid using sense lines, use heavy cross-section cabling to minimise losses, and keep interconnection lengths to an absolute minimum.

Figure 4 illustrates the voltage drop, which can be seen for different cross-sections of conductor.

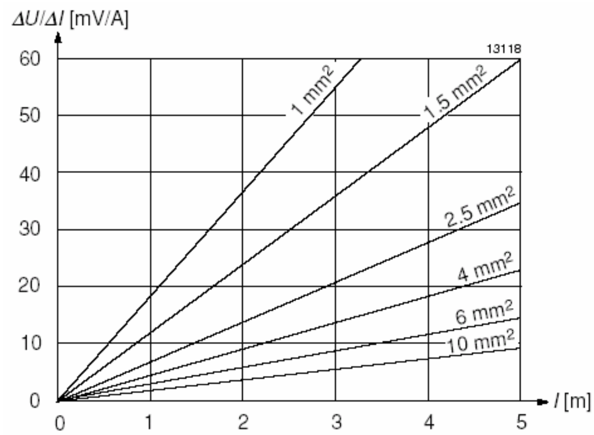


Fig. 4 Voltage drop versus line length (copper)

5 The case for input-output isolation

When the input to the power supply is DC, there is one very important question to address:

"Is input to output isolation really required?"

As mentioned earlier, isolation is expensive. It involves an additional input stage, increased complexity and size. Frequently, isolation is specified without identifying any reasons why. The main reasons why isolation might be required include:

- safety isolation (between user and hazardous voltage)
- different ground potentials
- inverted output with respect to input
- output voltage very different from input voltage
- elimination of ground loops.

However, in various instances, many of these reasons namely elimination of ground loops are not valid and by the careful use of non-isolated regulators considerable cost of ownership benefits such as lower buy price, higher efficiency and lower complexity (longer useful life, lower LCC) may be gained. See Fig. 7 and 8.

5.1 Safety Isolation.

The requirement for safety isolation depends on the integrity of the interconnections between the output of the power supply and the safety isolation provided by the load. If the load has inherent safety isolation, then the need to introduce a further safety isolation barrier at the power supply is in question.

Furthermore, it should be noted that voltages guaranteed to remain below 60 V_{DC} are classed as safety extra low voltage (SELV) and precautions to protect the user are far less stringent. Reference should be made to international standard IEC950 and European Norm EN60950 or related national standards for further details (see Fig. 5 to 8).

Restriction of user access is another good and inexpensive way to overcome safety isolation without jeopardising public safety and safety agency requirements.

5.2 Inverted output with respect to input.

Switching regulators are normally only thought as being similar to linear regulators, dropping the input voltage to a lower level. However, there are in fact two fundamental topologies for switching regulators which form the basis of virtually all switchmode power supplies - these are referred to as "buck" and "boost"- from which a third - "buck-boost" - is also derived (Fig. 5 and 6, next page).

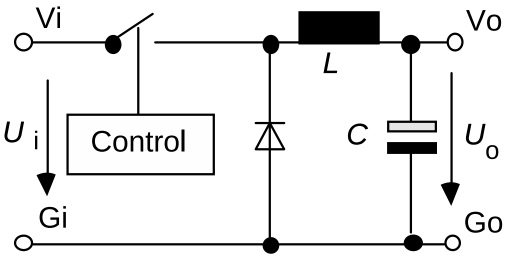


Fig. 5 Buck - regulator

A buck regulator takes power from the input in form of pulses with a duration determined by the value of the input- and output voltage. The *L* and *C* components are acting as low pass filter and are averaging the duration of the pulses. The diode allows current to flow into the load during the ”off time”.

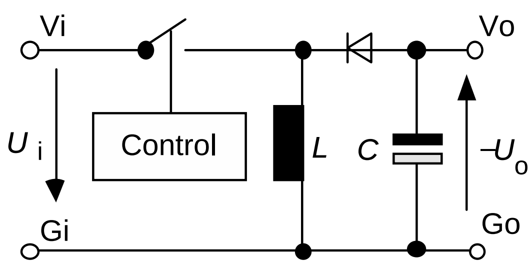


Fig. 6 Boost regulator

A boost regulator also takes power from the input in pulses, with similar considerations to pulse duration as for the buck regulator. Energy is stored in the inductor during the ”on” period and subsequently released during the ”off” period. During the ”on” state, current flows from the input via the switch and inductor L to G_i . In the ”off” state the current continues to flow via the diode and into the output capacitor C. G_o will therefore charge to a positive voltage with respect to U_o. The features of these two topologies are detailed in table 2:

Table 2

Comparison of the buck and boost topologies

Buck Regulator	Boost Regulator
$U_i > U_o$	$U_i < U_o$
U_o same polarity wrt U_i	U_o negative wrt U_i

wrt = with respect to U_i

It can be seen that boost mode provides an inverted output with respect to the input and so can be used in applications, where a common ground line is considered acceptable.

5.3 Output voltage higher than input voltage.

Considering the above, boost mode can also be used to good effect to generate voltages that are of a higher potential than the input, albeit inverted. Consider an application which is two wire input (i.e. where the load will not be referenced to ground) and which features inherent safety isolation either at the source or at the load. The polarity of the output voltage with respect to the input (or train supply voltage) in this case is irrelevant.

This may be illustrated by the following example. A conventional method of powering a train headlamp is shown in Fig. 7. This solution provides a fully isolated power supply being used to power the lamp and therefore allows free choice of ground reference. Additionally, e.g. the load can be grounded either to the plus - or the minus potential.

DC/DC converter with input to output isolation

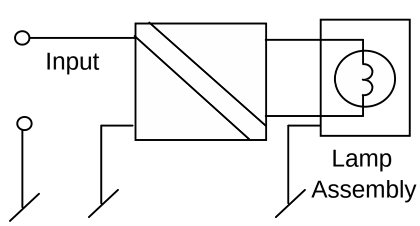


Fig. 7 Free choice of ground reference

Fig. 8 outlines the use of a regulator (buck or boost) to do the same task. As long as safety isolation is maintained at the interconnections between the regulator and the load (lamp) and at the load (lamp) itself, then this solution provides the following benefits over its fully isolated counterpart:

- higher conversion efficiency (lower heat generation, lower LCC)
- much smaller size and lower weight
- lower complexity in design
- lower cost (factor two to three lower)
- much higher reliability (potentially three to five times higher)

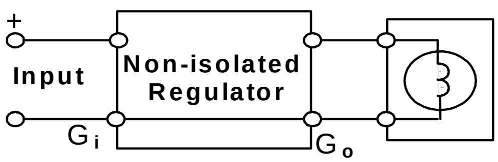


Fig. 8 Double insulated load arrangement

5.4 Elimination of ground loops.

Perhaps, at least theoretically, one of the strongest arguments against the use of non-isolated regulators is the need to eliminate circulating currents in the ground line. Such ground loops allow fast changing currents demanded by the regulator to generate a high noise voltage (normally at the fundamental switching frequency of the regulator). The current path can be very long, generating a noise voltage which is directly proportional to the line inductance (0.6…1.27 nH/mm) in accordance with the formula:

$$DU_{iL} = L_L \frac{dI_i}{dt}$$

where L_L is typically 1 nH per mm of conductor and dI_i/dt is typically 5 - 15 A/µs.

To eliminate such noise voltages, several strict procedures must be followed including:

- the use of star point connections
- the use of two wire connections in systems where the chassis is used as the ground return line
- use of twisted input leads and additional filter components.

Similar measures shall be carefully considered in trainborne applications, where it should be the state of the art for auxiliary supply return to be isolated from the vehicle chassis and as such may support considerable transients and surges referenced to the electric ground. Usually the outputs of remote power supplies are then grounded locally, aiming to eliminate ground noise that may affect the load. If the power supply is non-isolated, then the system will need to be designed to cope with these effects being seen by the load and with the generation of one or more ground loop(s).

In summary, the switchmode power supply may be considered both complex and expensive in many applications. However, the contribution to system reliability, weight gain and power savings, with the benefit of isolation in noise-sensitive applications, can more than offset the additional investment, given that the product is properly designed, manufactured and installed.

6 Standards

6.1 Which Standard?

In the past, train design and production was highly a national activity and in some aspects it still is. Nowadays more and more rolling stock is built locally under licence, in joint ventures or within consortiums. In this process of globalisation it is technical know-how, which crosses continents and oceans, particularly to rapidly developing regions such as the Far East, China, Central Asia and the Indian sub-continent. Such economies are able to adopt the latest technology, benefiting from decades of technological evolution with a single contract. However, in the rush to adopt state-of-the-art western products, there is the risk of inheriting unnecessarily complex product solutions which have evolved to solve historical problems and which are irrelevant to the "green field sites" where the whole infrastructure is new. This is particularly the case with standards.

In the Far East, British Standards developed by the UK's Railway Industries Association (RIA) until recently where being used for building new rolling stock, despite many parts of the standards being developed for historical reasons to address problems seen in the UK with electro-mechanical DC to 3 phase AC-converter. Whilst such standards may contain many excellent issues, which assure highly reliable products in older rolling stock where needed, their application elsewhere may result in unnecessarily complex and expensive solutions.

6.2 Latest Standards.

In the past the global standard IEC571 was applied mainly in Europe. In the USA, the mayor players use North American Standards. The US based ATCS Steering Committee drafted their Advanced Train Control Systems - Specification 110.

Traditionally the UK rail industry has been dominated by standards produced by the Railway Industry Association (RIA), British Rail and London Underground.

Such standards have centred on construction and performance issues and have been developed from a wealth of experience in the industry. The standards are not written to establish "preferred sources", but more to reflect the much specialised characteristics seen in the rail environment.

With the harmonisation of Europe, many such standards have been integrated into new European Norms, namely the EN 50155 enforced since Sept. 1995 or EMC Directive, valid since January 1996 with its today valid issue dated August 2001. Others are preliminary (prEN's or ENVs).

Table 3 Old Railway Standards

International	**IEC571**	**Part 1:** General requirements and tests for electronic equipment **Part 2:** Standardisation of certain mechanical and electrical quantities - Principles of test devices
National, GB	**RIA12**	General Specification for Protection of Traction and Rolling Stock Electronic Equipment from Transients and Surges in DC Control Systems
	RIA13	General Specification for Electronic Equipment used on Traction and Rolling Stock
	RIA18	General Specification for Interface Testing Electronic Equipment used on Traction and Rolling Stock
	RIA20	Requirements for Vibration and Shock Testing of Equipment for Railway Vehicles

Harmonised railway standards in Europe are a relatively new phenomena, with the introduction of European Norms (En's) was being adopted very slowly by some countries for a variety of reasons. Habitually, older standards are still applied to export contracts, which in turn are then adopted by the recipient country as "best practice" even though newer and perhaps more relevant standards exist.

Notably the EN 50155 provides probably the best general purpose standard today for the specification of electronic equipment used on rolling stock. It makes reference to more than forty other IEC and EN standards and encompasses such topics as environmental conditions, equipment design, component selection, constructional issues, reliability, safety, testing, and documentation.

Table 4 **New Railway Standards**

International	**EN 50121**	Railway applications. **-1** Electromagnetic Compatibility - General **-3-2** Electromagnetic compatibility, Rolling stock - Apparatus **Part 4**: Standard for Emission and Immunity of the Signalling and Telecommunications Apparatus
	EN 50122	Fixed installations **Part 1:** Protective Provisions relating to Electrical Safety and Earthing **Part 2:** Protective Provisions against the Effects of Stray Currents caused by DC Traction Systems.
	EN 50124	Railway applications. Insulation co-ordination; basic requirements: clearance and creepage distances.
	EN 50125	Railway applications. Environmental Conditions for Rolling Stock
	EN 50126	Railway applications. The specifications and documentation of dependability, reliability, availability, maintainability and safety (RAMS).
	EN 50155	Railway applications. Electronic Equipment used on Rolling Stock General Specification
	EN 50163	Supply voltages of Traction Systems

Q **family**

P **family**

Power-One's Q- family, 60…132 W and P-family, 100… 183 W power supplies* with one to four isolated output voltages are vastly used in any kind of rail applications. Designed to meet the latest rail specifications IEC60571 and EN50155, they offer four times the power density, a lower price, and increased reliability over earlier products designed to meet older national standards:

RIA12: EM, ES and EK, Power-One DC/DC converter families* complying with the "surge A" requirement.

USA: special case: V_{in} 20…100 V_{DC} FM, FS and FK- families meeting requirements "jogging" diesel-electric trains with on-board batteries.

Very useful: Booster MD087 with Q- and P- units!

- Internet home page: **http://www.power-one.com** family, Extended Datasheet and General App Note

7 Writing a Specification

7.1 Power Supplies - some Key Considerations.

A power supply may meet the latest international standards. But is it right for the job, will it work reliable for 15 to 20 years and will it fulfil LCC requirements? To answer these questions, it is necessary to address more product specific issues, not found in the standards, and which either serve to differentiate one power supply product from another, or influence how the product should be used for correct operation.

Many of these industry specific standards make further reference to more general standards developed by international bodies like IEC, ISO, CENELEC and national counterparts.

Supplementing these standards, the rail operators and prime contractors may generate additional specifications, laying down more detailed requirements related to specific pieces of equipment. It is perhaps this area, which presents the greatest opportunity for variation, interpretation and possible problems.

This is frequently the case in the specification of power supplies, where it is difficult to maintain a balance between providing not enough information - which might result in a product that is not fit for purpose - and providing too much information such that only a custom built unit may comply. Many characteristics of a power supply should be defined carefully in a procurement specification. In addition to basic input/output voltage and current levels, physical size and interconnection details, particular attention should be given to the following:

7.2 Dynamic performance.

Dynamic performance specifies the ability of the power supply to deal with load step changes, fluctuations in input voltage etc. and the effects on other output lines.

7.3 Efficiency.

What's the difference between two power supplies – one with a typical conversion efficiency of 75 %, the other with a more impressive 85 %? The correct answer is: ***a 47 % reduction in losses*** and a significantly higher reliability. What seems an insignificant 10 % improvement in conversion efficiency actually makes a big difference in lower heat generation and may be worth paying the extra for. With battery powered applications, consider also the much longer battery service life and a more powerful battery charger.

High conversion efficiency is not just useful - it is essential for long term reliability and thus for low Life Cycle Cost LCC. Heat kills electronic equipment, and an inefficient power supply will not only run hotter, reducing its own reliability, but it will also dissipate the extra heat generated into the local environment impairing overall system reliability. Inefficient power supplies require larger heat sinks to assure correct semiconductor junction temperatures thus increasing system weight and size.

Rule of thumb: a 10 °C increase of the working temperature halves life time.

Conversion efficiency will also change with input voltage and load, and the figure quoted will not always be at full load, or at the nominal input voltage. Normally power supply manufacturers specify only one figure, and it is no surprise that the conditions under which this figure is determined are either not defined or are not representative for typical operating conditions. It is important to confirm the efficiency over the operating range, which will be seen in a given application to assure that no thermal problems will arise.

7.4. Inrush current.

Inrush current should be specified to assure correct dimensioning of fuses, switches, contactors and circuit breakers, etc.

7.5 Short-circuit characteristic.

Units with foldback current limiting may go into shut-down as a result of the peak current drawn by the load at turn on. This may necessitate additional circuitry to overcome this problem. Ideally, power supplies should feature a relatively "square" or U / I current limiting characteristic where the power supply can under any circumstances recover from momentary overload conditions.

7.6 Protection

In addition to the frequently quoted input voltage reverse polarity requirement, a power supply should be able to operate under a wide range of conditions, which may affect performance. For example input under-voltage lock-out to protect the source, particularly battery low discharge against excessive input currents (into the power supply) as the input voltage falls towards zero. Other examples include the ability of the unit to sustain continuously applied short-circuits at the output, over temperature protection and over voltage protection (both input and output). Input overvoltage protection can prevent switching elements from damage to a certain degree.

7.7 Temperature Ratings

This is perhaps one of the most important issues to be considered when specifying a power supply, since temperature besides voltage, humidity and mechanical stress has a proven and severe direct impact on system reliability.

Whilst EN 50155, on page 9, Table 1 qualifies four grades of ambient temperature specifications and calls for evidence of equipment reliability, there is still plenty of scope for thermal stress to be inadvertently introduced in a design. For example, most power supply manufacturers today still continue to specify either an ambient or a base plate operating temperature range only, and do not clearly specify the operating case temperature range. Ambient temperature is a highly ambiguous measurement since it will vary depending where and under which conditions it is measured. It is no use in assuring that the junction temperatures of heat dissipating components such as power semiconductors and transformers within a power supply are operating well within their specified ratings. The specification of case temperature assures that a clear correlation exists and can be verified between a specified measuring point accessible by the user of the power supply, and the temperature of internal components.

It should also be noted that the specification of both ambient and case temperatures does not necessarily mean that they are inter-related unless specifically stated by the power supply manufacturer. For example, a manufacturer quoting a maximum ambient of 55°C (perhaps suited to class "T2" of EN50155) and with a maximum case temperature of 80°C may be misleading. The maximum case temperature may be seen well before the ambient reaches 55°C, particularly under worst case conditions such as minimum input voltage, maximum load, or under an overload or a full short-circuit condition at the output. In every instance, it is necessary to check with the manufacturer the operating conditions, which apply to a specified temperature rating, and clarify the behaviour under worst case or fault conditions.

Power-One's engineering standar for rugged and industrial power supplies:

$T_{Ambient}$ + 25°C = T_{Case}; $T_{Ambient}$ + 55°C = $T_{Junction}$ whereas worst case $T_{Junction}$ is 125°C maximum, satisfying the T3 (EN50155) requirement with suffix -7 and TX with -9 for temperature.

Furthermore, how a power supply is physically configured, positioned and mounted within a system, has a direct impact on the temperatures, which are seen by the product, and hence the reliability of the system. To assure correct design-in, case temperatures should be measured with the power supply fitted in the final equipment, after allowing sufficient time for warm-up and under worst case conditions. If temperatures are too high, corrective measures may include the use of additional heat sinking, relocation to a cooler part of the system, or the specification of higher conversion efficiency for the power supply.

7.8 Topology

This paper cannot cover in depth the relative strengths and weaknesses of the many different topologies, which are known (some 300). Suffice to say that there are many texts (see references), which can help to identify the correct topology for a given application.

In addition to considerations of the above, specifiers should seek evidence of reliable performance in the field, since compliance cannot guarantee reliability in operation. Whilst a power supply may be easily designed to meet type tests, there are many factors (for example repetitive thermal cycling, continuous random vibration, repetitive high energy transients, etc.) that are specific to an application, but will not form part of any specification. In these instances, proof of reliable operation in diverse rail applications can offer some measures of the experience and capabilities of a given manufacturer.

Ideally, trials should be conducted with a clearly defined test programme, allowing units to be operated in the actual environment and at a stage in the development programme that will allow changes to the design to be incorporated in favour of and to meet long-term reliability needs.

8 Constructional issues

8.1 The quest for miniaturisation.

One significant advantage of a switchmode power supply is the input is switched at high frequency. In case of isolated power supplies this allows the converter transformer to be reduced dramatically in size and weight according to the standard equation:

$$A_c = \frac{E_{in} \cdot 10^6}{4.44 \, B_{max} K N 1}$$

This relationship between core size, switching frequency and the commensurate benefits in size compared with 50 Hz transformers has been the primary reason vast acceptance of switchmode power supplies. Furthermore, many manufacturers have been quick to use surface mount component techniques and ”off-the shelf” control ICs to reduce size. The market is virtually awash with manufacturers claiming power densities as high as $40W/in^3$.

However, there are two distinct characteristics of a switchmode power supply, which cannot (at present) be overcome and which dictate the ultimate size of the complete solution:

1) Efficiencies for switching power supplies are typically 75...95 per cent. The combined conduction- and switching losses are generated as heat, which needs to be dissipated evenly and effectively to maintain component temperatures, which shall be well below their maximum rating to assure long term reliability. Consequently, no one can ignore or avoid the law and rules of physics! (see 7.3)

2) Switchmode power supplies generate conducted and radiated emissions which require components not suited to surface mount technique.

Many manufacturers, who have developed very high power density products, have simply left out some or all of the important elements such as heat sinks and input/output filters. As a result, it is necessary for the user to configure these to suit the application. This is not always a satisfactory solution, given that it may involve specialist design skills coupled with potential additional costs in type testing.

Furthermore, the use of ceramic components and aluminium-oxide substrates or FR4 PCBs in larger power supply assemblies can create thermal stress, with components becoming detached after being subjected to thermal cycling. Also ceramic substrate with heavy components is not ideal for applications, where there are high levels of vibration as seen in the traction environment.

8.2 Encapsulation versus Conformal Coating.

Encapsulation (potting) of power supply assemblies is quite common, particularly for low power products (< 15W output power). In this power range, dissipation of heat is not normally a serious problem, as most heat is brought outside of the assembly and confected away. However, field experience prove unpotted board mount DC-DC converters being much more reliable than potted ones. The reason is increased thermo-mechanical stress at temperature cycling due to mismatch of thermal expansion factors of substrates and components used plus hardening and softening of the potting with temperature changes. Change of hardness of up to 40 times over a Δt of 100 °C (-25°…+75°) is not uncommon. At low temperature cracking can often be observed accelerating negative impact of humidity. MIL338 recommends 5000 cycles from – 40 °C to +75 °C to simulate 15 years of real life in mobile applications. Higher power products, particularly those using conventional discrete components; see additional problems concerning heat generated in components, which do not have their own heat sink.

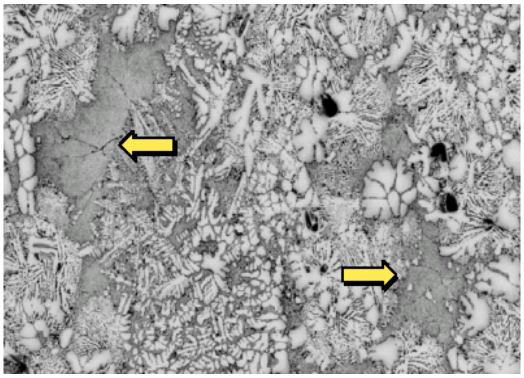
For example, at high currents all interconnecting leads and tracks on printed circuit boards (PCBs) etc. begin to generate heat (conduction losses). If the assembly is then encapsulated, such heat is contained and most likely unevenly distributed, with various stresses introduced into the assembly. Over time, with thermal cycling, such stresses can result in a significant level of mid-life component failures, particularly with axial leaded components that use dissimilar materials (for example glass diodes rely on the integrity of a glass to metal seal for reliable operation). Indeed, there are very few arguments in favour of encapsulation, other than being a low cost means of selling a product against a hostile external environment. In general, such practise should be restricted to low power products as mentioned above.

In contrast, conformal coating can provide an excellent improvement in the mechanical durability of a PCB assembly without creating thermal stress problems. This process can be applied to the whole power supply, but can only be relied on to improve the mechanical performance of components with a mass less than 7 grams. For larger components and subassemblies, additional fixing (for example screws, glue or ties) should apply.

8.3 Solder recrystallisation.

Much research work has been done studying the effects of temperature and humidity on materials over time. However such research is often overlooked by power supply design engineers, particularly when considering measures for so called ”cost reduction”. The use of single sided PCBs without plated through holes and pads on the top side for power supplies (and indeed perhaps most industrial electronic circuits) must be avoided. At temperatures above 32 °C, tin solder begins to recrystallize, losing its mechanical ability to securely connect and hold components in place.

Many tests have been performed to show that such recrystallization is of less significance for plated through holes, where depending on the thickness of the PCB used one to several mm of solder is in contact with the component leads. However, with single sided PCBs, the amount of solder in contact with the component leads is significantly less, 35 to 170 μm and with mechanical stress and / or vibration (or even under the weight of the component itself) components will eventually become detached. Failed solder joints may not be visible to the naked eye, but the consequences will be intermittent operation and higher levels of mid-life failures.



Picture 1 solder recrystallisation, arrows point to recristallized areas

8.4 Thermal stress

Thermomechanical stress is an often overlooked reason for increased mid-age field failures. It can occur due to varying thermal expansion characteristics of the vast variety of materials used like FR4 PCBs AlO_2 substrates and resistors, ceramic for capacitors, glass (signal diodes) plastic encapsulated integrated circuits and power devices etc. Thermal cycling tests over a period of just two weeks can clearly show the deficiencies of using such PCBs. MIL338 recommend 5000 plus cycles to simulate 15 years of hassle free field operation.

Please bear in mind:

-40 °C…+70 °C plus self heating of say +30 °C give a Δt of 140 °C with each temperature cycle!

9 EMC performance

A consideration of the use of switchmode power supplies could not be made without paying some attention to electromagnetic compatibility (EMC). Even though OEM power supplies are considered as components and thus are specifically excluded from the EMC Directive, this does not obviate the need for a power supply to have inherently good performance both in conducted and radiated emissions as well as in susceptibility. Firstly, a power supply that demonstrates low conducted emissions (for example less than level B according to EN55011/22 or FCC), will often present less problems with regard to radiated emissions, since the latter are often generated as a consequence of the former. Conducted emissions are relatively easy to resolve with additional filters, the values of which are usually determined through an iterative process of type testing and modification.

If radiated emissions are a problem, the user will need to assure that this is directly related to the power supply itself and not as a consequence of poor application of the power supply (for example generating emissions from ground loops, long unscreened interconnections or in failing to satisfactory bond metal parts of the power supply to ground). The source of radiated emissions can sometimes be quite difficult to determine, and it is worth while obtaining emissions plots from the power supply manufacturer to assure that these can be reasonably well replicated by the user's own test house.

Often switchmode power supplies are cited as the reason for more inherent problems within the overall system, whilst many loads (especially microprocessors) are producing significantly more radiated emissions than the power supply. In general, radiated emissions can be reduced by the use of fully enclosed power supply assemblies, high-frequency filtering as close as possible to the interconnections of the power supply using ferrite materials, good earth bonding at multiple points (be aware of ground loops!) and the routing of wiring away from equipment walls or noise sensitive circuits.

Further measures such as the elimination of narrow slots in metal enclosures, which may act as an effective wave guide, may be beyond the normal user's expertise, and at this level the guidance of a specialised EMC test engineer is highly recommended.

The same complex issue is valid for interconnections, cases, enclosures and heat radiators: they all may act as transmitting - as well as receiving antennas. The know how of specialised engineers is essential here as well.

10 Evaluating what's on offer

10.1 Custom versus "Off-the-Shelf".

There have been several studies, which have clearly shown the risks and associated costs of opting for a full custom product. First and foremost, it is important to recognise the significant investment necessary to establish a new design, which is fully addressing all important aspects of power supply performance. Designing switchmode power supplies involves many different disciplines, including analogue and digital design, careful PCB layout, Electromagnetic Compatibility (EMC), magnetics, thermal management, high frequency effects and mechanical design.

Neglecting one of these core skills is certain to result in a power supply with at best "average" performance and most likely a non-compliant and perhaps unreliable assembly.

To conclude a satisfactory design normally takes at least several design iterations, including re-layouts of PCBs and sometimes involve complete changes in topology. Deadlines and budgets for the design of good power supplies can never be accurately estimated or predicted.

To provide test- and burn-in facilities, ask for often overlooked investment. To prepare for, get approvals and entertain approvals bodies with repeating audits, to overcome infant failures are further issues to be considered.

The user shall weigh up the benefits of commissioning a custom product against adapting the procurement specification to suit products, which are already developed and which have a proven track record.

Suffice to say that the end product may only be as good as the procurement specification itself, and so this places additional emphasis on drafting this document to a high standard.

10.2 Make versus Buy.

Most leading power supply manufacturers invest heavily in both research and production facilities and this brings into question the level of resource required to produce switchmode power supplies in-house. In contrast to simple linear regulators, switchmode power supplies are complex assemblies requiring a significant level of design, development, production know how and test capability.

A study by Jeffrey D. Shepard showed that even for commercial grade power supply development, the costs of in-house development were not offset until quantities produced were in excess of 2000 per annum for several years. In the rail industry, volumes are generally much less, and it is clear that producing power supply products to operate reliably in the much more severe rail environments is likely to incur greater development costs and bring further into question the viability of in-house designs.

11 Developing a critique

Power supplies are one of the highest cost components within an electronic assembly and yet they are often selected against very vague specifications, or with little evaluation. Perhaps the most important message in this paper is for the potential user to develop a thorough critique for the assessment of potential products.

This process involves research of the market, background reading on power supply topologies, comparative studies of various manufacturers' data and products, in-depth testing of selected products and a thorough investigation into design, production, quality and organisational aspects of the chosen supplier.

It is not satisfactory to rely on certification to ISO9000 as a guarantee of quality, any more than it is acceptable to assume that a manufacturer will produce reliable products when developed in accordance with the standards specified in detail in table 4 on page 12.

A proposed structured approach to assess the suitability of a power supply is suggested:

1) Power density: - perhaps the first question to ask is whether the power rating of the product is realistic, given the overall size and mechanical construction. Since reliability is highly dependent on temperature, factors such as derating, heat sinking, airflow requirements and specified temperature ratings need to be carefully considered. Furthermore, a careful study of the mechanical construction will reveal the performance of heat sinking and the number of thermal barriers between dissipating components and the environment.

2) Interfacing to the environment - input/output filtering and protection levels need to be carefully considered, particularly given EMC legislation and the need to assure the compatibility of the power supply to the host equipment and environment. Power supplies, which are producing high levels of electrical disturbances, poor dynamic response and limited protection measures are likely to incur additional costs later in the design process or when operating in the field.

3) Specifications: the manufacturer should have detailed data sheets and supporting documentation for the power supply products under consideration. Whilst quantity does not necessarily meet quality, the actual amount of data provided may be a good indication of the level of testing that the manufacturer has performed before the product is made available to the market. If the amount of information provided is limited or omits key performance criteria, these should be thoroughly investigated before proceeding. Also, whilst specifications are important, they should not be allowed to drive the evaluation. It is very common for evaluations to centre around manufacturers' data sheets, rather than to concentrate on what is required for a given application. It is good practice to ask the manufacturer to demonstrate the performance of his products and allow plenty of time to cover all points.

4) Reliability - whilst much can be determined from the product on offer, a considerable amount more can be done to cross-check reliability potential. Where possible, establish the manufacturer's record on returns and what is judged to be an acceptable failure rate. Also, determine the manufacturer's development and production practices (e.g. type testing, performance checks, failure mode and effects analysis (FMEA), burn-in programme, component screening, component evaluation).

A copy of any mean time between failure (MTBF) calculations showing parts stress analysis according to MIL HDBK 217F using its latest NOTICE should also be considered, alongside actual field reliability studies to determine as close as possible real life expectancy of the product. The latter should include enough detailed information to confirm that any assumptions made in determining the MTBF figure are valid.

Finally, where possible, visit the manufacturer. As mentioned earlier, ISO9000 certification should be considered as setting only a minimum level of quality within an organisation. For example, two companies, both with ISO9000, quality certification can produce power supplies. One can choose to subject units to 24 hours burn-in at high temperature under varying load conditions and with continuous monitoring to eliminate infant failures. This is costly to the manufacturer, but can dramatically reduce failure rates seen in the field. The other manufacturer may choose to conduct a simple short duration soak test at room temperature with no monitoring.

12 Field Experience

12.1 Field returns

The biggest issue of units returned for repair: missing failure report, no failure description accompanying the unit in question.

Out of an average of 0.6 % of the ever manufactured switchmode power supplies shipped over the past thirty years we see a more or less homogenous picture of returns:

30 % no fault found
30 % infant or early failures
30 % misuse and abuse
10 % various failure reasons including human error, manufacturing- engineering- and related non-conformances.

12.2 Field failures found

To begin with obvious ones,

- left active inhibit open-circuit
- sense lines not connected or wrongly wired
- inverse input voltage
- powered through the output

Those are the easiest claims to find root cause and corrective action. The last two incidents are found by blown fuses or by shorted, burned, and in worst case vaporised “guarantee diodes”, standard 500 W/ms to 1.5 kW/ms TransZorb diodes at input and outputs of all rugged PSUs including the tiny 24 pin 4 W DC-DC ones.

Field returns with “no fault found” without accompanying failure description not showing any visual damage are critical. In case of intermittent failures caused by high voltage “shoot throughs”, intermittent connections, cold solder joints or solder recrystallization, it is extremely difficult to find the root cause and to take corrective action. A good practise to find the reason for failures in such cases is a minimum 24 hour burn-in with constant real time monitoring. In case of no fault found, what may the best to be done? Returning such devices to the user with no fault found, or return it as non reparable?

12.3 *Misuse and abuse*

12.31 Mechanical abuse

Weak mechanical supports accelerating vibration to up to factor 20 at specific frequencies have been observed. How such a device may look like internally, root cause and corrective actions are obvious.
In case of cold wall mounting, the utilisation of retention clips to hold the connector in place is vital.

12.32 Voltage withstand test

For batteries from 72 to 125 V_{DC}, IEC60571 and EN50155 ask for a voltage withstand test of 1000 V_{AC} 50 or 60 Hz equalling to 1.5 kV_{DC}. This is often mixed up with working isolation voltage and can lead to “shoot throughs” or to partial discharge effects. The same can happen in case of incoming inspection repeating high voltage withstand test. Whereas partial discharge of Y capacitors is not a problem, under certain circumstances *“shoot throughs”* can occur undetected being a possible reason for early field failure and unsatisfactory repair.

Our Application Specific Centre can offer adapted solutions in applications where high isolation working voltage equipment, gate units and the like are desired.

12.33 High voltage "shoot throughs"

High voltage "shoot throughs" can be found with high voltage withstand test, excessive isolation working voltage and incidents like failing power equipment on rolling stock, such as defective drives, air conditioning and the like. Shoot through failed units are not repairable.

12.34 Partial discharge voltage

Tow incidents may generate partial discharge:

1) High voltage isolation testing in Y capacitors. Basically, based on self-healing of the Y capacitors, such partial discharge occurrences, from a point of view of the capacitors are acceptable. For the DUT, (device under test) they may be ruinous. The reason is the dynamic behaviour most of the high voltage test equipment used and the time constant of their display. One can find oscillations up to 20 kV, whilst the instrument constantly shows 4 kV. The effect of such an incident is catastrophic: voltages close to 1 kV and very high, short peak currents can be found at IC pins. Such high power pulses vaporise bond wires in plastic bodies of affected electronic components. The remaining waste may work satisfactory under certain circumstances. Intermittent failures can be seen, when temperature cycling the damaged power supplies. The message is clear: do not repeat voltage withstand tests!

2) Our offering of units with up to 5.6 kV_{DC} voltage withstand test and other reasons may mislead users to "abuse" such units as a second safety isolation barrier in higher than 400 V_{DCmax} working voltage environment, which can lead to exceed partial discharge voltage. This can lead to failed TransZorbs and over time it can lead to partially carbonised FR4 PCBs or shoot throughs in the transformers. With carbonised PCBs such incidents are easily found root causes and irreparable damages. Based on the above, our standard units shall not be used in environments with working isolation voltages above 385 V_{DC}.

12.35 Different ground potentials

is is actually a rare root cause for failures. Nevertheless it can happen any time everywhere and based on extremely low impedances involved, most of the time with fatal damage.

As long as it may be an isolated incident, it is extremely difficult to detect.

In repeated events, there is one cure only: detach electronic equipment for the critical period of time.

12.36 Incorrect wiring on rolling stock

is a seldom detected incident. It can be fatal for the PSU and the load and difficult to find a root cause. If known, corrective action is obvious.

12.37 Failing battery chargers and dying batteries

Also, failing battery chargers and weak batteries are fairly seldom seen modes of generating trouble. PSUs with a correct working undervoltage lookout may show oscillations since the source impedance in both cases is relatively weak. The effect of both modes of malfunction is the same: generating continuous switch on and switch off of the PSU results in oscillating output voltage. Reason: it is impossible to implement a high enough histeresis in the undervoltage lookout control of the PSU to allow a secured switch off. In case this is a problem, protective measures at the design- and system integration level of the final equipment shall be observed. Inhibiting the PSU or the load circuits safely under undervoltage conditions and a time delayed restart are good design practises.

12.38 Lightening strokes, pantograph sparks

Such incidents should just not reach electronic equipment on rolling stock. Any deviations outside EN50155 and IEC60571 should be eliminated with appropriate measures by the OEM. In case it happens all the same, please observe *12.4 High voltage "shoot throughs"*

13 Summary

This article covers a broad range of issues with special emphasis to long term reliability considerations which collectively make up the process of decision making for choosing the right power supply for a given train borne or track side application to achieve low cost of ownership and in turn low life cycle cost (LCC).

The rail industry requires many diverse skills and must place much of the responsibility on specialist manufacturers to offer products which are fit for purpose and reliable.

Dependence on specifications, MTBF calculations and type testing cannot guarantee high quality or reliability. To quantify such intangibles requires the engineer to take a broader perspective, rising above the detail and asking more fundamental questions about topology, thermal management etc.

Equipment reliability: what this paper further highlights, is that standards cannot in themselves assure the high reliability of a power supply when used in the railway environment. What is more important is that the power supply manufacturer understands the environment, in which the power supply will operate, and has a clear and demonstrable knowledge of the factors, which will affect long-term reliability.

We trust, this article is of value for every professional in the rail market. In case you have further amendment, suggestion or question please do not hesitate to contact us.

14 Glossary

A_c	core area	L_L	inductance
B_{max}	maximum flux density of core material	MTBF	Mean Time Between Failure
C	capacitance	N_1	number of primary turns
E_{in}	applied voltage	R	resistance
?	switching frequency	R_{Go}	ground resistance
Gi	input ground	R_L	load resistance
Go	output ground	_T_{C-A}	Differential temperatures between case and ambient
I_i	input current	U_i	input voltage
I_o	output current	U_{iL}	input line voltage
K	stacking factor of core material	U_o	output voltage
L	inductor	U_{RGo}	ground voltage

15 References

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8) EN50155 European Standard August 2001

16 List of Figures

17 List of Tables

18. Abbreviations and useful internet addresses

AEIF	European Association for Railway Interoperability	http://www.aeif.org
ATP	Automatic Train Protection	
BTM	Balise Transmission Module	
DBAG	Deutsche Bahn - German State Railways	http://www.bahn.de
ECSAG	European Core SRS Assessment Group	
EEIG	European Economic Interest Group	
EIM	Rail Infrastructure Managers	
EIRENE	European Integrated Radio Enhanced Network	
EMSET	is an acronym for a project launched by EC	
ERA	European Railway Agency, a proposal for a regulation on the establishment of a…,	
ERRAC	European Rail Research Council	
ERRI	European Rail Research Institute	http://www.erri.nl
ERTMS	European Rail Traffic Management System, level 1, 2 and 3.	http://www.ertms.com
ETCS	European Train Control System	
ETSC	European Transport Safety Council	http://www.etsc.be/
ETSI	European Telecom Standards Organisation (GSMR)	http://www.etsi.org
EI	Euro-Interlocking	http://www.euro-interlocking.org/
EU	European Union	http://europa.eu.int/index_en.htm
EURATEL	European Railway Telecommunications	http://www.euratel.org
Eurobalise	the transponder technology of ERTMS	
EUROSIG	European Special Interest Group	
EVC	European Vital computer	
FRS	Functional Requirement Specification	
FS	Ferrovie Delle Stato - Italian State Railways	http://www.fs-on-line.it
GSMR	Digital Global System for Mobile Communications Railways	http://GSMR.uic.asso.fr
IRSE	Institution of Railway Signal Engineers	www.irse.org
International Railway Journal	Global information about the rail industry	www.railjournal.com
La Vie du Rail	Rail Magazine	www.laviedurail.com
JRU	Juridical Recorder Unit	
LEU	Lineside Electronic Unit – the signalling interface to the variable data version of the Eurobalise	
LINK-UP	**UK** Supplier Qualification & Registration Database	http://rail.achilles.com/
LMA	Limit of Movement Authority	
LTM	Loop Transmission Module	
MMI	Man Machine Interface	
MORANE	Mobile Radio for Railway Networks in Europe	
Railway Age	International Rail Industry magazine	www.railwayage.com
Railway Technology	rail industry links, exhibitions, products and services	www.railway-technology.com
Railway Gazette	business information to the world's railway, metro, and light rail industries	www.railwaygazette.com
RBC	Radio Block Centre	
RENFE	Spain State Railways http://www.renfe.es/ingles/index.html	
RTM	Radio Transmission Module	
SBB CFF FFS	Schweizerische Bundesbahnen - Swiss State Railways	http://www.sbb.ch/gs/textbild_e.htm
SNCF	Societe National d. Chemins de fer Français - French State Railways	http://www.sncf.com/indexe.htm
SPMU	Speed Monitoring Unit	
SRS	System Requirement Specification	
SRRA	Strategic Rail Research Agenda presented by ERRAC	
STM	Specific Transmission Module	
TSI	Technical Specification for Interoperability	
UIC	Union International des Chemins de Fer	http://www.uic.asso.fr
UNIFE	Union des Industries Ferroviares Europeennes - International trade association for European Railway equipment manufacturers	http://www.unife.org
UNISIG	Steering committee involved in the development and Implementation of ERTMS	
Via Libre	Spanish rail industry magazine	www.vialibre-ffe.com

Great links http://www.unife.org/industrylinks.htm
http://www.uic.asso.fr/database/site/site-resultat.html?mot=&geo=&motcleS%5B1%5D=Rail&OK.x=15&OK.y=3

Good glossary http://www.euro-interlocking.org/

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Detailed product data and application notes are available from www.power-one.com
Visit us also on www.railway-technology.com/contractors/electrification/power_one/index.html