Practical Papers, Articles and Application Notes

Robert G. Olsen, Technical Editor

In this issue you will find one practical paper that should interest members of the EMC community. It is entitled, "The Jammed Wheelchair: A Case Study of EMC and Functional Safety," by Dick Groot Boerle and Frank Leferink. In this paper, the authors note that it is not always straightforward determining which standard or standards apply when conducting EMC product safety tests. Further, they note that the answer to which one or ones apply can have a large influence on the parameters used for the testing. I think that the paper will cause all of us to think a bit harder before conducting product safety tests. The paper was originally presented at EMC Europe 2004.

The purpose of this section is to disseminate practical information to the EMC community. In some cases, the material is entirely original. In others, the material is not new but has been made either more understandable or accessible to the community. In others, the material has been previously presented at a conference but has been deemed especially worthy of wider dissemination. Readers wishing to share such information with colleagues in the EMC community are encouraged to submit papers or application notes for this section of the Newsletter. See page 3 for my e-mail, FAX and real mail address. While all material will be reviewed prior to acceptance, the criteria are different from those of Transactions papers. Specifically, while it is not necessary that the paper be archival, it is necessary that the paper be useful and of interest to readers of the Newsletter.

Comments from readers concerning these papers are welcome, either as a letter (or e-mail) to the Associate Editor or directly to the authors.

The Jammed Wheelchair: A Case Study of EMC and Functional Safety

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Abstract: The assessment of the influence of electromagnetic phenomena on the functional safety of electric equipment can be improved. The product standards for electric equipment with safety relevant functions still focus on the functional behaviour. The EMC requirements are quite often composed by following the same approach as for the Generic Standards for the EMC Directive in which only two environments are taken into account. In order to explain this and to show a better approach, a case study has been carried out. The essence of this case is an accident with an electric wheelchair where the culprit was a GSM-phone booster. Point of interest is that the wheelchair did meet the relevant product standard for electric wheelchairs. The shortcomings of this standard with respect to EMC have been established. In addition, it is shown that an assessment should start with an inventory of the environments in which the product might be operated. This improved assessment is in line with the relatively new IEC Technical Specification 61000-1-2: 'Methodology for the achievement of functional safety of electrical and electronic equipment'.

I. Introduction

Figure 1. An ordinary street with cars and an electric wheelchair: one environment – different EMC requirements.

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The picture shows cars as well as electric wheelchairs. For cars we have to apply the word vehicle per Automotive Directive 95/476/EEC [1]. This Directive has, unlike most other Directives, EMC immunity requirements included. Let us take just one example and look at the requirement for Radiated Immunity. In this standard we see that a car should not become unsafe at electric field strength up to 30 V/m in the frequency range 20 MHz to 1000 MHz. In practice, however, product standards like the SAE J1113 [2] or ISO 11452 [3] are used in which the field strength is 200 V/m for most frequencies.

Next we take a look at the wheelchair. At first we have to establish which Directive is applicable and for that reason we need the definition of a vehicle, coming from the former Vehicle Directive 70/156/EEC [4], Article 1:

"For the purposes of this Directive, "vehicle" means any motor vehicle intended for use on the road, with or without bodywork, having at least four wheels and a maximum design speed exceeding 25 km/h, and its trailers, with the exception of vehicles which run on rails and of agricultural tractors and machinery."

So, obviously, a wheelchair is not under the scope of the Vehicle Directive. Instead, the use of electricity makes EMC Directive 89/336/EEC applicable. The standard to be used to refer to in the Declaration of Conformity is the product standard for electrically powered wheelchairs EN12184, 1999-11[5]. This standard is currently under revision and will make a normative reference to ISO 7176-21 [6]. Moreover IEC 60601, Medical Electrical Equipment, [7] will include domestic electrical medical equipment and equipment for people with disabilities, thus electric wheelchairs will be included.

If we again consider the requirement for Radiated Immunity we see in the ISO 7176, [6] the most severe requirement: the chair should not become unsafe at an electric field strength up to 12 V/m in the frequency range 26 MHz to 1 GHz. So if we compare the product standards we see a 24 dB difference in field strength. Still the car and the wheelchair are operated in the same environment!

In the Netherlands a couple of years ago, an electric wheelchair unintentionally drove off a subway-platform [8]. The driver was badly injured and her insurance company started an investigation with the help of an EMC laboratory. They found that the chair was activated by a field of only a few Volts/meter at a frequency of 1.89 GHz. The manufacturer of the chair did not accept his responsibility by arguing that his chair did meet the relevant product standard for wheelchairs. The radiated susceptibility test in this standard, however, did not go beyond 1 GHz. The judge decided that the manufacturer could have known that 1.89 GHz was a commonly applied frequency for the digital telephone network. The manufacturer was sentenced because he had put an unsafe product on the market. Based upon the cause of the accident, which has been taken as a starting point for this study, it is also interesting to take a look at the frequency bands prescribed in the standards. The product standards for electric wheelchairs, EN 12184[5] as well as ISO 7176 [6] have a clause on EMC, which in fact is taken over from the Generic Standard EN 61000-6-2, Immunity Requirements for the typical industrial environment [9]. The requirements for Radiated Immunity as well as for ESD are practically identical. For the electrical field this means a highest frequency of 1 GHz. Thus, the frequencies for mobile telephones above 1 GHz, like the 1.89 GHz, are not included. Instead, only in EN 12184 there is an informative, and thus not mandatory Annex F, which recommends advising the driver of the chair not to use a mobile phone while seated in the chair. This implies that the accident [8] might happen again, even today. Both standardisation and European Directives are introduced to guarantee the relatively safe participation of people in traffic. If one takes a closer look to the standards and directives, a huge variety appears to be available. If it was only the name of a standard or a directive there would not be questions, but the point is that we see quite different requirements. We also see different approaches in the way safety aspects are treated. The EMC Directive does not include safety aspects. The commonly applied Generic Standards under this Directive even explicitly exclude safety considerations. The reason is obvious; one cannot just add safety tests without knowledge of the product. Therefore, it is important to take a look at supplementary guidance for manufacturers of electric wheelchairs in order to extend their technical construction file with sufficient evidence that all possible measures were taken to avoid unsafe situations. The most suitable possibility is mentioned in [8] and [11], which is the application of IEC 61000-1-2: 'Methodology for the achievement of functional safety of electrical and electronic equipment' [10].

II. Safety analysis methodology

One of the first steps of the methodology presented in IEC 61000-1-2 is to establish in which environments the product might be operated. The document gives recommendations for defining the electromagnetic environment and the corresponding recommendations for testing for safety. It is noted that environments are not stable and the influence of mobile electronics has to be taken into account. In this particular case, one might easily conclude that the automotive environment is applicable, although additional possibilities are the 'railway environment', since wheelchairs are allowed in most trains. However, establishing the proper test levels is not the first concern. The methodology includes more and the 'safety analysis' is essential.

The introduced analytical assessment method is based upon one of the "Dependability methods", namely the 'Fault Tree Analysis'. This method is a top-down method.

III. Application of IEC 61000-1-2

According to clause 8.2, [10] the following steps have to be considered:

1. Aim and intended functions of the equipment
2. Hardware structure of the equipment
3. Software configuration, preferably with the same structure as the hardware
4. Electromagnetic environment and functional test levels
5. Purposes of the hazard and risk analysis (top events)
6. Fault tree analysis
   6.1 Construction of the Fault tree
   6.2 Evaluation of the Fault tree with regard to safety
7. Recommendations for the design of the equipment
8. Conclusions with regards to the test plan for safety:
   - which tests are relevant
   - which tests levels

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IV. Aim and intended functions

Obviously, the electric wheelchair controller is intended to control a wheelchair, which has to be regarded as safety-critical. The controller should carry out two main functions:

- Control the functions of the wheelchair
- Safeguarding

i.e. check for one independent failure, which might cause an unsafe situation. If such a failure is detected, an independent shut down is necessary. This involves a sequential check for sleeping failures during power-up as well as continuous checking during "power on." Broadly speaking, the system can be in one of three states: off, standby and driving. In the standby state, the wheelchair is stationary with the solenoid brakes applied. Note: The solenoid brakes indicated in Figure 2 are not used for stopping the wheelchair normally. This is done by regenerating power from the motors back into the battery. The solenoid brakes are there as a backup in case the battery is disconnected. One could also regard these brakes as a "parking brake" facility and stop the chair in the event of power failure.

V. Hardware structure

A typical hardware structure is shown in Figure 2. General safety measures are related to the process (safety risks):

- Motor current feedback, to detect incorrect speed control and normal braking
- Motor voltage feedback
- Motor temperature feedback, to prevent damage by prolonged heavy use

Specific safety measures are related to the controller:

- Primary safeguards like the watchdog, a check of the watchdog for sleeping failures at power-up, power supply check, reset circuit and sensor checks. The watchdog as well as the processor can activate the solenoid brake driver in case a failure is detected

Note: The single-fault criterion is normally applied for wheelchairs, in combination with detection for sleeping failures. This is assumed to provide an acceptable safety level. Obviously, [10] this is a lower level prescribed, for instance, than for electronic gas burner controllers which have to fulfil the two-failure criterion. This is not a point of criticism, it is just noted. The degree of safety remains an arbitrary and an ethical issue.

VI. Software configuration

For simplification in this example, only the safety related functions are considered herein.

There are two groups of safety functions to mention:

- Safety checks initiated after power on, sequential checks: battery-voltage, motor voltage, motor temperature
- Diagnostic self-checks, made continuously during the operation of the controller and the wheelchair

VII. EM-environment and functional test levels

The wheelchair is intended to operate in many environments. The corresponding EMC functional immunity and safety tests are specified in Table 1. For the automotive environment, higher immunity and safety test levels shall be considered. Note that not all the electromagnetic phenomena listed in Table 1 have been judged of being relevant for this kind of equipment.

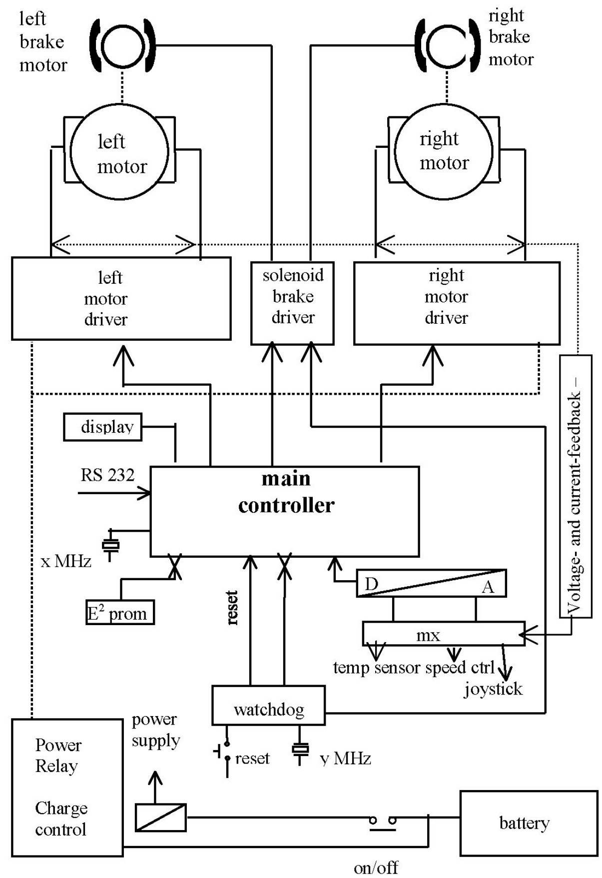

Figure 2. Wheelchair controller: Hardware structure

VIII. Purpose of the hazard and risk analysis

The purpose of the hazard and risk analysis is for the undesirable safety risks or top events, to detect:

- Which electromagnetic phenomena can cause these risks or basic events
- At which places in the device, in order to take appropriate mitigation measures

For an electric wheelchair, four top events can be distinguished:

While driving:

1. Unable to stop
2. Incorrect speed control

In standby:

1. Release of brakes
2. Driven movement of motors

IX. Fault tree analysis (FTA)

For the purpose of this example, only the case of "Unable to stop" is developed here. In practice, similar FTA's should be made for the other cases.

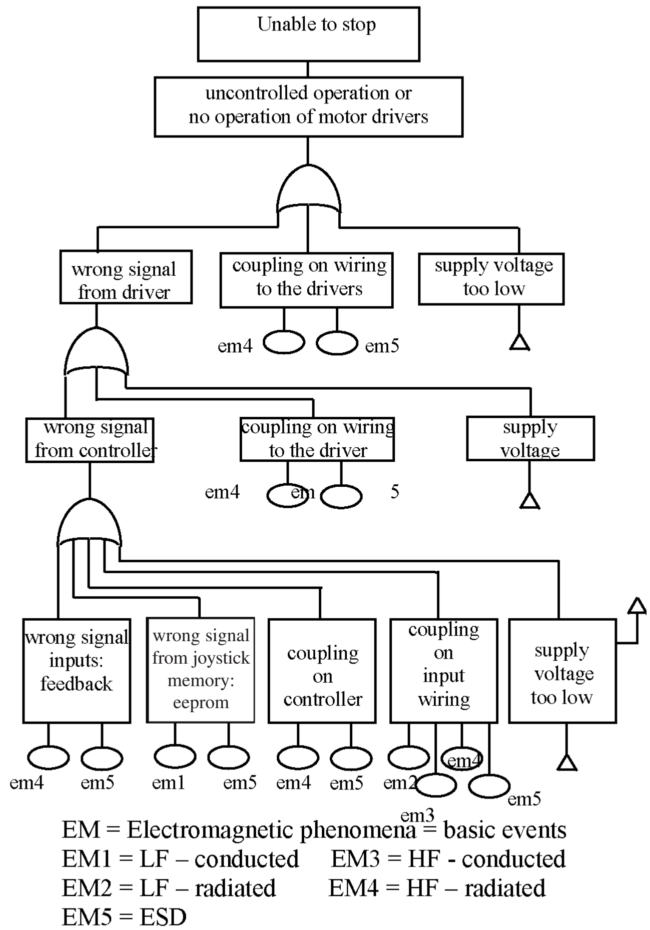

Figure 3. FTA for the top event 'unable to stop'

X. Construction of the fault tree

The construction of the fault tree has been carried out according to IEC 61000-1-2 [10]. Please note:

- The fault tree considers only EM influences. All other effects that may have an influence on the controller safety such as component failure, wrong handling by the operator etc., shall not be included in this fault tree, in order to be specific with regard to electromagnetic effects.
- Events and EM influences, which are not directly related to the top event, shall not be included in the fault tree.
- The "supply voltage" has to be considered in this case as a "common cause" and is treated only once at the lowest level with a transfer-out symbol. The supply circuit may be quite complicated and should be analysed as a separate sub-system in a separate sub-fault tree.

Disturbance basic event	*Immunity tests Typical functional test levels*	*Safety tests Typical safety test levels*
Mains-related phenomena	Not applied	Not applied
Oscillatory transients	Not applied	Not applied
Fast transients on control lines	0,5 kV_p	1 kV_p
Current injection 150 kHz - 80 MHz on control lines > 1meter	3 V_{emf} + 6 dB at ISM-frequencies	10 V_{emf} + 6 dB ISM-frequencies
Radiated immunity 20 MHz-18 GHz	30 V/m	100 V/m
ESD contact air	4 kV 4 kV	6 kV 8 kV

Table 1 Example of EM-phenomena and test levels

XI. Evaluation of the fault tree with regard to safety

The fault tree represents in a general manner which EM phenomena, the basic events, have an influence on the various parts of the device. These EM phenomena can have, according to their level, a more or less strong effect in this device which may lead to the different classes of degradation specified in clause 7 [10]: no significant effect, self-recoverable effect, operator recovered effect but no hazard, hazard. However, not all off these effects may have a critical safety effect. Based on the design of the equipment, e.g. protection measures and on experienced results with other similar equipment, the EMC engineer can evaluate which EM phenomena - at the highest environmental level of the disturbances - can/will have a critical safety impact. Such an evaluation is made for the case of "unable to stop" in Table 2. It shows that:

- Voltage dips and interruptions in the mains, all high frequency conducted and radiated phenomena, as well as ESD, may have a critical influence with regard to safety.

	EM phenomena	**LF-cond**		**LF-rad**	**HF-cond**				**HF-rad**		**ESD**
	Part of the EUT	Har	Dip and Int	Magn. field	Surge	OscTransient	EFT/B	CW	CW	Dig Phone	
1	Power sup	-	-	-	-	-	X	X	X	X	X
2	Contr Mem	-	-	-	-	-	-	-	X	X	X
3	Sensors Joystick	-	-	-	-	-	-	-	X	X	X
4	Int wiring	-	-	?	-	-	-	-	X	X	X
5	Ext wiring	-	-	?	X	?	X	X	X	X	X

Table 2. Evaluation of the influence of EM-phenomena

NOTE: Every X means a probable critical influence
Every ? means an unlikely critical influence
Every - means a critical influence can be neglected

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- Power frequency magnetic fields and harmonics of the mains voltage are unlikely to have a critical influence, but should perhaps not be fully neglected.
- High frequency radiated phenomena may affect all the elements of the controller.

The table allows one to identify which parts must be:
- Carefully designed with regard to safety.
- Carefully examined in case of failure when testing for safety. Please note that Table 2 shows that some phenomena may be critical for safety, which have not yet been considered in the relevant product standard. These still should be tested.

XII. Recommendations for the design

The product standard for electrically powered wheelchairs does not prescribe anything about a "one or two failure criterion." In practice, however, the one-failure criterion is applied: no hazardous situation should be created by a single failure. If a failure occurs in the power supply check circuit only, it is a so-called sleeping failure, which does not cause a hazardous situation. When next the power supply circuit fails and provides a too low voltage, the main controller would not operate properly and might generate random signals to the outputs, which can cause an uncontrolled motor behaviour. This implies that the design requires two layers:
- The control layer
- The primary safeguard layer, being able to detect failures in the control layer and to stop the wheelchair independently

This explanation makes it clear that common cause errors due to electromagnetic phenomena have to be avoided. The control circuit and the primary safeguard circuit should not suffer from simultaneous failures. Therefore, the design requires circuits built with different technologies and different immunity levels. Furthermore, it is important to realise that if testing has demonstrated critical susceptibility, mitigation measures should be considered carefully. One additional capacitor to suppress a transient voltage that caused an unwanted operation of a motor driver can become defective and thus create a sleeping failure. Finally, it should be realised that the electromagnetic immunity of a separate control unit can change when this module is built into a wheelchair (many wheelchair manufacturers do not design and produce the electronic control units). The layout of the wiring as well as the properties of the enclosure can have a large influence. An immunity test of the entire wheelchair is necessary.

XIII. Conclusions with regard to the test plan for safety

Following the above analysis, the test plan for safety can be set up. It has to include the following information:
- The electromagnetic disturbances to consider, possibly also such disturbances which are not specified in the relevant product standard just with regard to functional immunity - in this case for the wheelchair controller: transients and conducted HF on the external wiring, i.e. from the joystick as well as radiated immunity above 1 GHz.
- The test levels for safety, either from the relevant product standard if the latter prescribes specific test levels for safety or the functional test levels enhanced by an appropriate security margin, or possibly specific national requirements.
- The unwanted safety events, the non-occurrence of which has to be checked.

In this case, with the example for just one safety risk, the required safety test levels are specified in Table 1.

Normally, the test set-up and procedures specified in the basic standards IEC 61000-4-xx should be applied, but more severe procedures may be considered. It is recommended not to test the controller alone but the wheelchair as a whole including the wiring, which may be influenced by high frequency radiation.

XIV. Conclusion

It has been established that different products, both intended for transportation of people, operating in the same environment, still have largely different product standards to meet. The plethora of EMC standards is illustrated again.

The coordination between ISO and IEC can be improved; unfortunately, also the new ISO/FDIS for wheelchairs does not refer to the safety analysis methodology applied in this paper. It is very likely that the accident with the wheelchair would not have happened if this methodology would have been applied.

XV. References

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