Design Principles for EMI/EMC Compliant, Industrial Grade Products for Global Market

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***Abstract*–Products designed for international market need to comply with various standards for EMI/EMC and environmental requirements. The compliance requirements could vary depending on the country where the product is intended to be sold. As a result it is extremely important to understand the compliance requirements for the target market and include them in the product requirement specifications before the start of design cycle. EMI/EMC compliance includes tests for Radiated/Conducted Emission, Radiated/Conducted Susceptibility, Electro Static Discharge, Fast Transient Bursts, Surge, etc. Environmental compliance includes testing the product for a wide temperature range and humidity, mechanical tests such as shock, vibration, bump, etc. In order to achieve compliance for production units, it is very much essential to consider these requirements during the prototype design stage and conduct enough tests on prototype units so that there are no surprises during the final compliance testing. EMI/EMC compliance can be achieved by proper design of electronic circuits, proper component selection, carefully done Printed Circuit Board (PCB) layout and finally a mechanical enclosure which is co-designed with PCB. Additionally, it requires great planning for pre-compliance and compliance testing, which includes writing a good test plan document, designing stable test software and choosing a proper test lab. Environmental compliance requires proper design of mechanical enclosure by selecting right material, proper heat transfer mechanism between Printed Circuit Board Assembly (PCBA) and enclosure. This also requires knowledge of potential hotspots in the PCBA by estimating power dissipation values of critical components. This paper discusses design principles for such products, starting with a detailed overview of EMI/EMC and environmental compliance requirements, followed by design challenges for achieving compliance.**

***Keywords*–Compliance/Pre-compliance, Electro Static Discharge, EMI/EMC, Emission, PCB/PCBA, Susceptibility.**

I. Introduction

With time, the electronics systems have grown in complexity and at the same time kept on reducing in size. The highest clock frequency of the system has gone up to GHz range and the slew rate of high-speed signals has fallen to sub-nanosecond range. As a result, emissions from these modern electronics devices have grown many folds. With proliferation of multiple wireless devices, e.g. cellphones, laptops, pads, etc. modern electronics devices are susceptible to unwanted radiations from these surrounding devices. Falling level of operating voltage in the system has only increased the level of susceptibility. In order to ensure that the electronics products work in such harsh environments as per their specification without disturbing other electronics equipment in their vicinity, they should comply with various standards defined by international standardization and certification bodies. From an operating temperature point of view, industrial grade products are defined as the products which use electronics components with industrial temperature specification (-40°C to +85°C). From EMI/EMC point of view, a Class A device is intended to be used in a commercial environment whereas a class B device is meant to be used in residential environment. The focus of this paper is on requirements and design principles for class B products with industrial temperature grade. These classes of products are henceforth simply referred to as "product" or "products" throughout this paper, unless otherwise described explicitly. Various compliance requirements of these products are described in section II. The whole process of specifications to the compliance and various design challenges for achieving compliance are discussed in details in section III followed by conclusion in section IV.

II. Compliance Requirements

Compliance requirements for a product can be broadly classified into three categories: EMI/EMC, Environmental (Temperature & Mechanical) and Safety. In-depth descriptions of these requirements are presented in the following subsections.

A. EMI/EMC

By definition, Electromagnetic Interference (EMI) is the unwanted effect of electromagnetic energy on an electronics product. Electromagnetic compatibility (EMC) is the branch of electrical sciences which studies the unintentional generation, propagation and reception of electromagnetic energy with reference to the unwanted effects that such energy may induce [1]. Day-to-day example of EMI is the flickering of TV display if someone calls to a cell phone which is kept near the TV set. Another example is the noise in the radio set when someone switches on light in the same room. Purpose of EMC is to keep these effects under control by: (1) reducing EMI from the device under a certain limit so that it does not have much impact on the neighboring equipment and (2) by enhancing the immunity level of the device such that it is not affected by the external sources of EMI.

In United States of America (USA), the Federal Communications Commission (FCC) regulates interstate and international communications by radio, television, wire, satellite and cable [2] and any electronics equipment sold in USA must comply with Title 47 of the Code of Federal Regulations (CFR). Part 15 of CFR 47 covers all radio frequency devices which radiate intentionally, unintentionally or incidentally and may be operated without a license. A digital device is classified as an unintentional radiator, if it generates and uses timing signals in excess of 9 KHz and used digital techniques [2]. In Canada, Industry Canada (IC) regulates radio and wireless communication. Harmonized test requirements and test standards exist between FCC and IC.

For rest of the world, test requirements, standards and procedures have been harmonized by International Electrotechnical Committee (IEC) which works closely with International Standards Organization (ISO). There are two technical committees working on EMC standards: TC77 (Electromagnetic compatibility between equipment including networks) and International Special Committee on Radio Interference (CISPR). IEC and CISPR standards coexist to define most technical aspects related to EMC [3].

A separate organization, the Committee for European Electrotechnical Standardization (CENELEC) is responsible for developing European standards for electrical equipments, whereas European Telecommunication Standards Institute (ETSI) is the standardization body for telecommunications equipments. Standards defined by these two organizations are usually based on IEC and CISPR and are referenced by European Number (EN) prefix [3]. The list of harmonized EMC standards as defined by European Union can be found in [4], [5].

In general there are three kinds of standards: Product standards, Generic standards and Basic or Test standards. Product standards are published in the Official Journal of European Union. These standards are specifically designed to cover a particular aspect of EMC for a particular product or product family, such as Information Technology Equipment (ITE) or Industrial, Scientific and Medical Equipment (ISM). Generic standards are developed for industry sectors for which no Product standard is available. These standards are divided into two basic categories: emission and immunity. Environments are defined as residential, commercial, light industrial or heavy industrial. Generic standards take precedence when a relevant Product standard is not available. Basic or Test standards include most IEC and CISPR standards which are in turn referenced within Generic and Product standards.

Different types of emission and immunity requirements are described below.

1) Conducted Emission (CE): Conducted Emission is defined as the component of radio frequency energy that is transmitted through a medium as a propagating wave, generally through a wire or interconnect cables [3]. Most standards require conducted emission to be measured in the frequency range of 150 KHz – 30 MHz.

2) Radiated Emission (RE): Radiated Emission is defined as the component of radio frequency energy that is transmitted through a medium as an electromagnetic field. Radiated emission is generally measured from 30 MHz to 1 GHz, or up to 100 GHz for special products and applications.

3) Conducted Immunity/Susceptibility (CI/CS): This is defined as a product's relative ability to withstand electromagnetic energy that penetrates it through external cables, power cords, Input/Output (I/O) interconnects or chassis. In order to verify immunity, electromagnetic energy in the frequency range of 150 KHz – 80 MHz is induced into the product through each cable and interconnect and the product is expected to operate within the set criteria. Upper limit of the frequency range can go up to 100 MHz depending on the applicable standard. EN 61000-4-6 is the basic test standard for CI/CS.

4) Radiated Immunity/Susceptibility (RI/RS): This is defined as a product's relative ability to withstand electromagnetic energy that penetrates it through free air. In order to verify immunity, electromagnetic energy in the frequency range of 80 MHz – 1 GHz is induced into the product through radiation and the product is expected to operate without any issues. Upper limit of the frequency range can go up to 3~6 GHz depending on the applicable standard. EN 61000-4-3 is the basic test standard for RI/RS.

5) Electrostatic Discharge (ESD): Electrostatic discharge is the transfer of electric charge between bodies of different electrostatic potential in proximity to each other or through direct contact. This condition is simulated during the test either as direct/contact discharge, air discharge or indirect discharge through coupling planes. Applicable ESD voltage generally starts from ±0.5 KV and can be as high as ±8 KV. EN 61000-4-2 is the basic test standard for ESD.

6) Electrical Fast Transient Burst (EFTB): The EFTB test aims to simulate the disturbances created by a 'showering arc' at the contacts of ordinary AC mains switches or relay contacts as they open, due to the flyback voltages caused by inductive energy storage in the current path. EN 61000-4-4 is the basic test standard for EFTB.

7) Surge Immunity: The surge test aims to simulate the effects of lightning on AC power supplies and any long cables. Generally, a cable is subjected to surge test if the length is longer than 30m. EN 61000-4-5 is the basic test standard for Surge immunity.

8) *Pulse Magnetic Field Immunity:* Pulse Magnetic Fields are produced as a result of a large current impulse through a conductor. An example is lightning current flowing through a grounding conductor at a power sub-station. Current field amplitudes required by these standards range from 100 - 1000 A/m. EN 61000-4-9 is the basic test standard for Pulsed Magnetics Field.

9) Power Frequency Magnetic Field Immunity (PFMF): PFMF aims to simulate the effect of the magnetic fields on a product in the vicinity of power transformers. These magnetic fields are applied on the AC power input. The current field strength is between 1A/m and 3Amps/m. EN 61000-4-8 is the basic test standard for PFMF.

10) Voltage Dips/Interruptions: These phenomena occur on the AC mains as a result of a fault in the distribution system such as an open circuit breaker or a sudden large load being turned on in the immediate vicinity. EN 61000-4-11 is the basic test standard for these tests.

B. Environmental Compliance

In USA, National Electrical Manufacturers Association (NEMA) defines product standards for environmental test such as temperature and mechanical. NEMA TS2: Part 2 is one such example of product standard. Worldwide, IEC defines temperature and mechanical tests for products. IEC 60068-2-xx is the basic standard for these tests.

Temperature compliance aims to simulate the various thermal & humidity conditions through which product is expected to go through in actual installation/operation and during storage conditions. In this test, the product is operated as per functional specifications within the product operating temperature range. The temperature is varied from ambient to the minimum/maximum value at a certain rate along with the change in Relative humidity as defined by the Product standard. Also the Product standard defines ramp up/down rate control. In NEMA TS2: Part 2 the ramp up/down rate must not exceed 17°C/hour and relative humidity should be 18% RH at maximum temperature. IEC 60068-2-1 defines cold test which is done at -40°C in non-operating condition. IEC 60068-2-2 defines dry heat test which is done at +80°C in non-operating condition. IEC 60068-2-30 defines cyclic damp heat test which is done at +25°C and +55°C at humidity level of 95% RH in operating condition.

Mechanical compliance tests include vibration, shock and bump tests. IEC 60068-2-6 defines sinusoidal vibration test in the frequency range of 5 Hz to 500 Hz, whereas IEC 60068-2-64 defines random vibration tests in the same frequency range. Both these tests are conducted while the product is in operation condition. Shock and bump tests are defined in IEC 60068-2-27 and IEC 60068-2-29 respectively.

C. Safety Compliance

Safety standards aim to protect devices and personnel against excessive current, short circuit, earth leakage current and earth faults in primary circuits. EN 60950 is an example Product standard for safety of Information Technology Equipments (ITE).

III. Design Principles for Achieving Compliance

A regular product design cycle involves following well established steps: requirements capture, requirement analysis and system feasibility study, system design (hardware/software partitioning), hardware/software design and implementation, testing and validation of individual components, system integration and finally system acceptance testing. In order to design an electronics product which will eventually comply with various stringent regulatory requirements additional steps need to be included to regular product design cycle. These additional steps are explained in the following subsections in details.

A. Requirement Specification Phase

This is the most critical phase during the design cycle from the point view of product compliance. The designer must understand the compliance requirements for the product to be designed considering several aspects. These include identifying the target application segment for the product (IT/Telecom/Medical, commercial/military etc.), geographical area for deployment and end usage scenario (indoor/outdoor, commercial/industrial, tabletop/wall-mount, stationary/vehicular, naturally/air cooled etc.). Depending on these requirements, the right Product standard is chosen. If a Product standard is not available, then a Generic standard must be used. Once these standards are identified, they must be listed in the Product Requirement Specifications (PRS) document and referred to throughout the product design/testing cycle.

B. Design Phase

Design phase starts with detailed study of product requirement specifications. All the requirements related to compliance needs to be understood in detailed from the applicable product standards. This is the starting point for Compliance Test Plan (CTP) document. Objective of CTP is to provide Test Requirements, Test Setup and Test Procedure, which should be used to validate the compliance requirements of the product. It should capture all the environmental test conditions along with detailed test procedure, details of the Performance Tests to be conducted on the Equipment Under Test (EUT) / Device Under Test (DUT) when it is subjected to environmental tests. Designer must go through each standards mentioned in the CTP and incorporate those requirements in the design so that compliance can be achieved. Design considerations for achieving EMC and thermal compliance are presented in the following subsections.

1) EMC: The design goals for EMC are as follows: (1) reduce the sources of emission using proper circuit design, PCB layout and shielding, (2) increase radiated immunity by proper isolation and shielding of potential victim circuits, (3) reduce radiated emission and increase radiated immunity by providing a very low impedance return path between circuit ground and earth connection, (4) increase all other immunity by adding the respective protection circuits for all the power and I/O signals and placing them correctly on the PCB.

Design for EMC starts with good schematics design and proper component selection. Circuit design should follow well established signal integrity principles to reduce reflections and crosstalk between signals. All high speed signals (>10 MHz) should have proper terminations. All unused digital inputs should be either pulled low or high as recommended by device datasheets and not left floating. Each unused analog input should be grounded using capacitor. Differential signals must be used whenever possible which reduce emission by many folds. Adequate decoupling capacitors must be added at power supply pins of critical ICs to reduce high speed switching noise. Power supply input to the critical ICs must be filtered using high frequency ferrite beads. Main DC power input must have a lowpass LC pi filter with a cut off frequency of ~15 KHz for reducing conducted emission. Proper EMI filter and ESD diodes must be added for each I/O signal. All I/O connectors used in the design must be shielded. If it is not possible to find shielded connectors, separate metallic EMI shield must be added for such connectors. The metallic parts of the shields and connectors must be connected to the circuit ground. Many general signal integrity design resources can be found in [6], [7]. Once schematics design is complete, it must be critically reviewed by the EMC designer to ensure that all the requirements in PRS are considered in the design.

Next critical step is PCB design. Few important PCB design rules are discussed in this paragraph. Detailed discussion of this topic can be found in [3]. Stack up selection is a fundamental aspect of PCB design. The chosen stack up should have (1) one reference ground layer adjacent to each signal layer including top and bottom layers and (2) each power layer placed as close as possible to a reference ground layer. The ground layers should extend beyond the power layer as per 20H rule [3]. These multiple solid reference ground planes must be tied to each other using Printed Through Hole (PTH) VIAs. If the product has a metallic enclosure, it must be connected to the reference ground plane of the PCB using multiple 3.5 mm screws. The ideal distance between these screws is $\lambda\backslash 20$ where λ is the wavelength of the highest frequency of emission. To contain emission below 1GHz, distance between the screws should be at least 1.5 cm. This multipoint grounding approach between the PCB and the metallic enclosure helps in reducing ground loop current and the resultant radiated emission. For this scheme to be effective, the enclosure itself must be tightly connected to an earth connection using low impedance grounding wire. The same applies to products with non-metallic enclosures with external metallic tab. For products with non-metallic enclosures and no earth connection, the power-ground loops & I/O signal return path should be optimized.

Whenever possible the system should be operated at the lowest frequency which meets the desired specification. Similarly, if there is an option to vary slew rate and drive strength of a high-speed signal, the lowest number which meets system performance must be used. It may require a number of trial and error and actual testing in the EMC lab to finalize these values.

2) Thermal Compliance: The design goal for thermal compliance is to remove the heat generated on the PCBA due to active electronic components at a steady rate so that at the maximum rated ambient temperature of the product, the junction temperature of these components do not exceed their rated value. Thermal towers from component to the metallic enclosure, thermal screws between PCB ground plane and the metallic enclosure, use of heat-sink for critical components etc. are some of the passive methods employed by the mechanical designer to facilitate heat from the product to the external ambient air. Active thermal management includes use of fan for either blowing cool air into the product or sucking the hot air out of the product using proper air vents. Though active method provides much better thermal performance, fans add noise to the system and increase total power consumption of the system. Also, fans reduce system reliability because inherently they are the least reliable among all the system components. For products without metallic enclosures, active cooling is one of the methods for thermal management. In this case, the enclosure must have proper ventilation for air flow and fans must be chosen appropriately considering system reliability requirements. It may be necessary to have a mechanism where the fan failure is reported to the system controller which can raise an alarm to the user in case of such an event. Another option could be to add a redundant fan, which of course will add to the system cost.

For achieving thermal compliance, the first step is to choose all electronic components down to discrete resistors/capacitor with industrial temperature grade. The next step is to estimate worst case power consumption of each active component and arrive at total power consumption of the product. It is better to use switching regulators instead of linear regulators which have higher dissipation if current consumption is more than a few hundreds of mA or difference between input and output voltage is more than few volts. At the same time, it has to be kept in mind that switching regulator will cause conducted emission at the multiples of switching frequency and proper filtering at the power supply input stage must be provided to reduce emission. While the power supply circuit must be designed to handle peak power demand of the product, it is important to estimate average power consumption of the device. For example, a Dual Data Rate (DDR) Synchronous Dynamic Random Access Memory (SDRAM) IC consumes maximum power during a read or write cycle. However, on an average the memory device will be accessed only 60% of the time. As a result the average power dissipation the memory device will be close to 60% of the maximum power dissipation. Without the knowledge of average power dissipation value, the mechanical engineer would end up with an overdesigned heat-sink which will be bulky and costly. The designer must use the knowledge of actual device utilization by the software to estimate average power dissipation wherever possible so that thermal design is optimal.

Once average power dissipation of all critical active components are known, the next step is to arrive at PCB dimension, place these critical components on the PCB and label it with average power dissipation numbers. The thermal designer will use this layout to run thermal simulation and report potential hotspots on the board. One thing is to note here is that the PCB design might not have started at this stage, so PCB layout using standard Computer Aided Design (CAD) tool may not be feasible. Hence, alternate method such as hand drawing or word processor may be used to generate this layout. The key is to get to know the thermal hotspots early in the design phase and iteratively arrive at an optimum layout which is smaller in size while meeting the thermal requirements of the product. Final thermal simulation must also be performed after actual CAD placement is frozen which will give a lot of confidence going into thermal testing.

PCB CAD, mechanical CAD and thermal design must go hand in hand. While electrical design and PCB CAD is done by two different engineers, mechanical CAD and thermal design is usually done by the same engineer. In the complete design cycle the electrical designer coordinates all the design activities between these teams. The goal of the PCB designer must be to achieve EMC compliance by following the well-established rules described in previous section which might require the designer to place the certain components very close to each other, whereas the thermal designer might want to move these components away from each other to reduce heat exchange between them. Hence, both of them must interact with each other to arrive at the optimal placement of components and subsequently inform each other of any modifications they might require.

C. Compliance Testing Phase

Compliance testing requires an iterative approach. Before submitting the product for final compliance testing it is very much advisable to test the product in a certified test lab to identify any issues and take corrective action. This phase is typically known as pre-compliance testing, whereas the test labs may call this as Developmental Assistance (DA) and compliance testing as Performance Testing (PT). Corrective actions could be a simple change such as values of resistors/capacitors in the PCB or reduction of slew rate of a high-speed signal using software. In the worst case, it might involve redesign of the complete PCB. In practice, multiple rounds of pre-compliance testing might be required to solve all the compliance issues. Hence it is very important to consider at least two rounds of complete pre-compliance testing on a product before the final compliance testing and include budget and schedule for the same in the product plan.

Before heading into the test lab, the Compliance Test Plan Document (CTP) should be updated with some important information. First thing is to finalize the test labs for test execution. This involves identifying the labs adequately equipped for executing the tests, getting a quotation from these labs based on compliance requirements, visiting the labs to familiarize with the lab facility and finally selecting the lab based on their facility, suitability and cost. Multiple labs may need to be used if a single lab does not meet all the requirements. Also it may so happen that these labs are located in different cities. Hence it is important to budget travel cost in the project plan and consider any excise permissions that might be required for shipment of samples of the products to the labs.

The CTP should capture test setup diagrams and must contain list of all accessories/cables, hardware/software tools required for testing. It must define the hardware and software configuration of the product which is to be used during the compliance testing. Further, it must define operating procedure of EUT and list of observations to be made during the tests.

Software team must refer to the CTP and provide stable software which will run on the product during the compliance tests. Goal of this software should be to access all the hardware components used in the product, so that the product generates maximum emission and heat. The idea here is that if the product passes pre-compliance tests with the worst case software with a good margin, it will comfortably pass the compliance test even if the test were to be performed in a different lab.

Once the CTP is updated with the above details, the test team must use it to get an understanding of the product, the test standards and the exact test cases and the required test procedures. Once the functionally tested PCBA, mechanical enclosure and the compliance test software becomes available, test team must integrate all of these and be familiar with the operation of the product. During this time the test labs must be contacted to reserve required test slots for pre-compliance testing. Once all the pre-compliance tests are performed, test team must collate the results and generate the test report document and share it with the product design team. The design team will analyze the test report and decide about the corrective actions. The product must be retested to ensure that these corrective actions really work.

Once the product passes all the pre-compliance tests after one or more iterations, it should be offered to a certified test lab for Compliance Testing or PT. In this case, the lab will receive few samples of the product; run all the tests as per test plan and issue a test report. The test report will include the product serial number, test configuration, test set up diagram, software version number etc. apart from the details of the standards used for testing, test procedure and test results. The test report can then be used for declaration of conformity.

IV. Conclusion

Designing EMI/EMC compliant, industrial grade products for global requires design knowledge and capability in multiple disciplines e.g. electronics circuit design, PCB CAD, mechanical and thermal design. It requires very good understanding of global compliance standards, knowledge about product deployment scenario and use-cases. It further requires extensive product planning which involves managing multiple interdependent teams and independent test labs or agencies. Finally, it costs a good amount of money to execute the program.

As in case of any other program, this can be achieved with a dedicated and motivated design and testing team working synchronously with clear objectives and mandate to achieve product compliance.

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