Qualification Tests for Emission of Electromagnetic Interference and Power Quality for Fault Tolerant Power Distribution System

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Abstract

Increasing use of electronic devices in daily life has greatly increased the electrical stresses caused by harmonic currents on low-voltage alternating-current public mains networks. To maintain the quality of these networks, European Standard EN 60555-2 was created to set levels for harmonic currents injected by loads back on to the network. There has however been much discussion about equipment classes and limits to apply to electronic equipment in general and equipment power supplies in particular. EN 60555-2 has recently been superseded by IEC 61000-3-2 which sets some more practical rules and provides a clearer definition of equipment classes. Thus we spend efforts to control the input power quality of equipment power supply by enhancing power-factor (PF) close to unity and controlling the Total Harmonic Distortion (THD); to reduce the harmonic contents of the input current. In the latest embodiment of Fault Tolerant Power Distribution System ECPS^{TM} (Electronics Corporation Power Supply) developed for NPCIL (PHWR700MW plant) we carried out Power Quality Tests as per IEC 61000-3-2; for PF and THD limits. In Electro Magnetic Interference (EMI); the equipment power supply emits the electronic noise by conducted path or via radiation. The term conducted emissions refer to physical phenomena which enables electromagnetic energy being created in an electronic device and gets coupled to its input power cords (AC or DC). The reason that conducted emissions need to be controlled or mitigated is: (i) Electromagnetic (EM) energy that is coupled to a device power cord can finds its path to the entire power distribution net-work of C&I system that the electronic device is connected to. (ii) This EM energy coupled to the power wiring uses the larger net-work (i.e. the power wiring itself) to ‘radiate’ more than this particular device itself. As a result the other electronic devices and systems can receive the electromagnetic interference through a radiated path (or much less frequently via a direct electrical connection). The conducted emissions (CE) are regulated by CISPR22 conducted emission (CE) limit extends from 150 KHz to 30 MHz. After the product is developed, the quantification of the same is carried out in certified EMI-EMC set-up to get these figures of conducted emissions (CE) and radiated emissions (RE), and its mitigation as per limits of the chosen standard. In the latest embodiment of Fault Tolerant Power Distribution System ECPS^{TM} (Electronics Corporation Power Supply) developed for NPCIL (PHWR700MW plant) we carried out CE and RE tests and quantified the spectrum obtained for CE and RE, and mitigated them as per CISPR22 standards, and power quality certification as per IEC 61000-3-2 standards.

Introduction

The power supply to run all electronics systems for Control and Instrumentation (C&I) of Nuclear Power Plants are one of the most important components to enhance overall plant performance, [3], [6]. This aspect was realized by us , and thus from very basic the design which aimed for a rugged fault tolerant hot-pluggable, load sharing power supply was conceived and then engineered by ECIL and utilized in very large numbers in Nuclear Reactor Protection and Control Systems, for NPCIL plants, [1], [2], [4]. These are modular power Switched Mode Power Supplies (SMPS) are termed as 'Fault Tolerant Power Distribution System' (FTPDS). These are configured as M+N system, what we term as SMPS M+N configuration. The number M will cater total load, and number N are redundant units and all M+N sharing the load equally. Say our load is 185W, to cater that we use two (M) units of 100W and one (N) unit of 100W as redundant. Thus failure of one unit will not interrupt the load current. This configuration is therefore enhancing plant reliability and availability. This FTPDS (SMPS M+N) is Trade-Marked product [5] [8], [9] as ECPS™ XX; like ECPS SM60 indicating 60W modules, ECPS SM100 indicating 100W modules. The latest embodiments [2],[8], [9] for NPCIL-PHWR700MW plant, is ECPS SM100 with two variants the first one is with DC-DC (input 220V DC), and second one is with AC-DC with input as 230V AC and this one having added circuits with boost convertor for Power Factor Correction (PFC) and Total Harmonic Distortion (THD) controls. For both embodiments output is regulated DC voltages of 5V, 12V, 15V, 24V. In this article we will report the conducted (CE) and radiated emission (RE) tests-as per CISPR22 standard, and power quality certification as per IEC 61000-3-2 standard, conducted on the latest embodiments, of ECPS SM100. The CE and RE qualifications are must, so that they are qualified for usage in C&I systems. The CE and RE levels give the figure of electronic noise that is generating from this device; to be under acceptable limits; so that it is not detrimental to other electronics equipments sharing the power line or at near proximity [7]. Presently about 10,000 numbers of ECPS100 are being fabricated for NPCIL-PHWR700MW. The detailed test results are kept in CAD NPP, ECIL-Hyderabad.

Product Embodiments since 1993

The first phase is called ECPS-I, where basic inherent load sharing was demonstrated. This product was well utilized in very large numbers by ECIL for NPCIL power plant control and instrumentation systems from Kaiga-1 & 2 to PHWR-500 TAPP 3 & 4; and then to Kaiga 3 & 4 and RAPP 5 & 6.

Fig: 1: Various stages of product development since 1993 (*a*) Modification with forced third wire connectivity for current sharing on ECPS; (*b*) (*c*) The prototype of final embodiment of ECPS with all modifications and with front display

Few of these were employed in up-gradation of C&I for- Dhruva reactor, NAPP 1&2, KAPP 1&2, and MAPP 1&2. The second phase called ECPS-II had forced share daisy chain circuit to forcefully and equally share the load current, despite wide difference in individual voltage setting of each module. This circuit modification now has been retrofitted in older plants also-by doing site modification in earlier ECPS-I. Various stages of product development since 1993 at BARC and ECIL are depicted in figure-1. Based on feedback from all users the third generation advancement of the earlier models (embodiments) was taken up in mid-2006. This new product [8], [9] is complete, (1) with two front panel displays (for unit voltage and unit current), (2) with reduction in width, (3) with inclusion of forced third wire current sharing circuit, (4) with voltage adjustment in front-panel, (5) with in built circuits to have good input Power Factor by emplying active Power Factor Correction (PFC) circuitry along Total Harmonic Distortion (THD) Control-as per IEC1000-3-2 Standard. This is new-product for NPCIL PHWR-700MW reactor C&I systems. In this embodiment only 100Watt (width 16T) with two models DC-DC and AC-DC; are fabricated; for output 5V, 15V, 24V.

Fig-2: Latest embodiment of ECPS SM100 fourteen of them sharing the load

Regarding need to control Electromagnetic Emissions

The term conducted emissions refer to physical phenomena which enables electromagnetic energy being created in an electronic device and gets coupled to its input power cords (AC or DC). The reason that conducted emissions need to be controlled or mitigated is: (a) Electromagnetic (EM) energy that is coupled to a device power cord can finds its path to the entire power distribution net-work of C&I system that the electronic device is connected to. (b) This EM energy coupled to the power wiring uses the larger net-work (i.e. the power wiring itself) to 'radiate' more than this particular device itself. As a result the other electronic devices and systems can receive the electromagnetic interference through a radiated path (or much less frequently via a direct electrical connection). The frequency range where conducted emissions are controlled or regulated is typically lower than the frequency range where radiated emissions are regulated.

The conducted emissions (CE) are regulated by FCC over frequency range of 450 KHz to 30 MHz, and CISPR22 conducted emission (CE) limit extends from 150 KHz to 30 MHz. Here measurements are done with CISPR22 standard [7]. The radiated emissions RE is recorded at 10m distance at frequency range 30 MHz to 1000 MHz. The Conducted Emission (CE) measurements recorded in terms of voltage (as dB micro-volts) via impedance Stabilizing Network (LISN) are common mode currents in power wires connected to earth (body) wire. Radiated emissions are measured by RF receiver as field strength in dB micro-volts / meter. Both the emission spectra are recorded on Spectrum Analyzer, and are shown in figure 5.

Causes of Emissions in Electronics System

Since about late eighties, the C&I systems in Nuclear Power Plants have started using the Switched mode Power Supplies (SMPS). The first of SMPS was used in Dhruva Research Reactor (ECCS: Emergency Core Cooling System) in 1986, then for Research Reactor-Kamini (Reactor Regulation System), 1988 and then in KAPP Plant (PDCS: Programmable Digital Comparator System) 1990. The reason that SMPS are inherently larger contributors to conducted and radiated Emissions i.e. CE and RE than the linear regulated supplies is due to the power MOSFET transitioning at the switching frequency. The switching frequency (80K Hz-for the latest embodiment of ECPS) and its harmonics are well within the frequency band regulated for conducted emissions. Electromagnetic energy at this frequency and its harmonics gets coupled back onto the power cord (AC or DC) of the electronic device. In the latest embodiment of ECPS that we tested, the configuration is prone to CE problems because the switching element is on the primary side of the main power transfer transformer, where it creates the interference that couple directly to the input power cords. Thus the energy that is coupled to the power cord is much higher in amplitude than if the MOSFET switch is on the secondary side of the transformer, where it would be switching a stepped down voltage. A very good power supply line filter is needed for these SMPS to mitigate the emissions. These power line filters are provided in the design of individual ECPS as well as placed on power-mother boards.

Prior to year 2002, the CE standards set by FCC and by CISPR were different. In 2002 the FCC changed the CE standard to match CISPR standard. The frequency range in the previous version of FCC in CE tests was 450 KHZ to 30 MHz, while frequency range of CISPER is 150 KHz-30MHZ for CE tests. But higher/lower range for specific (special) standard is allowed, where special Line Impedance Stabilized Network (LISN) is required. The standard LISN to measure CE as per CISPR is basically a High Pass filter for the measuring equipment with 50 Ohm input resistance. These standard LISN provides 50 Ohms (2% tolerance) impedance at frequencies greater than 100 KHz, and impedance rolls off at lower frequency. At 80KHz our fundamental frequency the LISN impedance is about 20 Ohms.

Figure-3 gives a general SMPS configuration of buck converter. The figure-3 show the leakage capacitors marked as C_{Stray}, provide coupling impedance at high frequency for leakage current path. The P N E lines represent input Positive Negative and Earth Lines of power cord respectively. The earth line of the power cord is connected to the Chassis Ground (Body) of the ECPS. For DC-DC models the primary of transformer sees a 220V DC voltage (between P and N), and for AC-DC model the boosted DC (about 390V) is provided by another pre-boost (AC-DC) switched convertor (switching at about 100 KHz in the latest embodiment of ECPS) for PFC and THD control. This new circuit has helped to make (Power-Factor) PF as 0.99 from, with THD of 0.8 while the earlier embodiments had PF as 0.55 with THD more than 1.1. The P and N in case of AC-DC are corresponding to Phase and Neutral lines. The boosted switched convertor is placed after P and N and then DC Voltage of 390Vgoes to the same Switcher circuit as shown in figure-3. However, this is representative figure to give the idea of leakage current (I_P , I_N in figure-3) that is the source of emission.

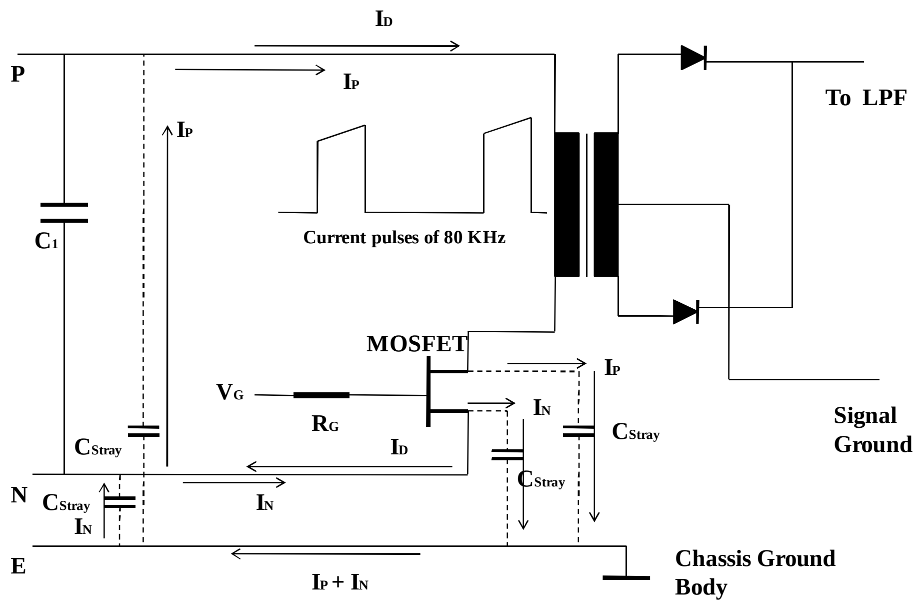


Fig-3: A representative figure of SMPS and leakage current

The pulsed current has DC component plus all harmonics. The DC component does not leak through, only the pulsating current harmonics leaks to the E-wire. In the figure-3, the dotted lines represent the leakage current path via stray capacitors; in reality these are distributed capacitor which couples the harmonics of the pulsating currents to the earth (E) line. This generates common mode current components namely I_P and I_N , with $I_P + I_N$ current flowing in the E-wire; which is the cause of emission.

Measurements

The CE tests (as per CISPR 22) are done via utilizing Line Impedance Stabilized Network (LISN) connected to P and N leads of the ECPS (individual case as well as shared case). The voltage spectrum corresponding to CE current is (in dB micro-volts) measured across 50 ohm impedance on spectrum analyser i.e. i.e. $V_p = (I_P)$ (50 Ohm), and $V_N = (I_N)$ (50 Ohm). The set up is shown in figure-4, and record of spectrum V_P is shown in figure-5.

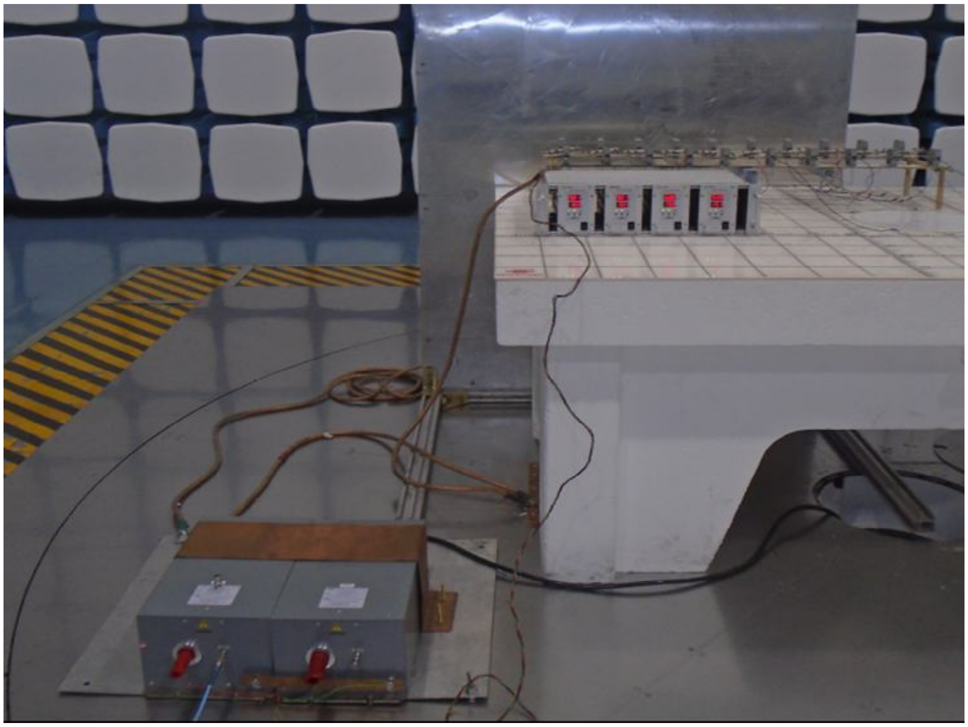


Fig- 4: The CE test set-up with LISN connected to input power cord of ECPS bin containing four ECPS SM100

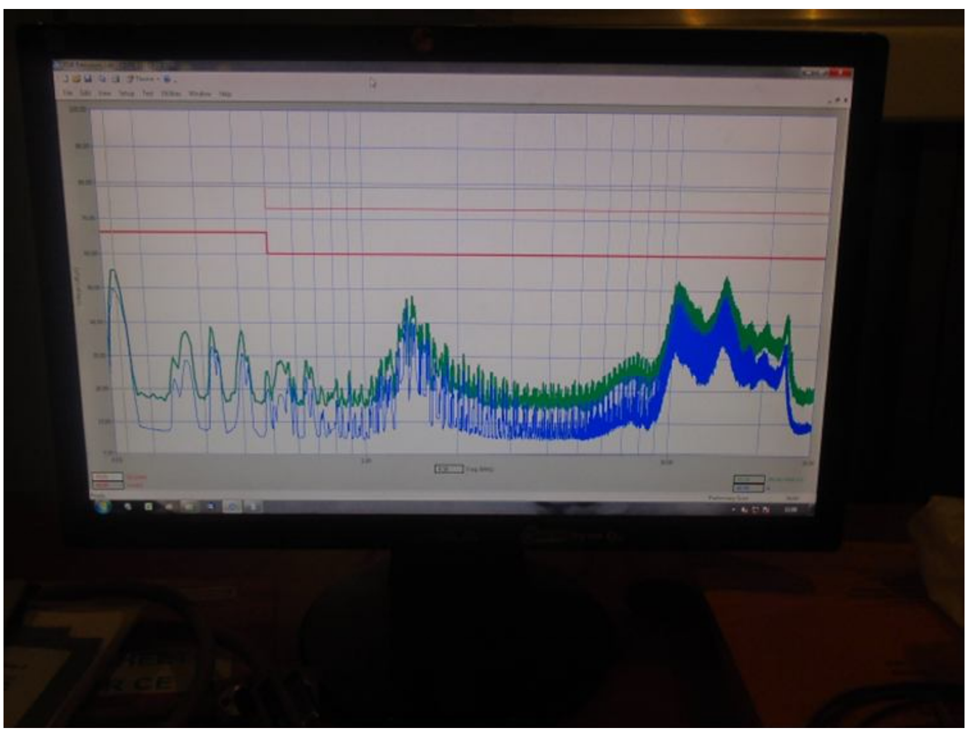


Fig-5: Screen of Spectrum Analyzer Showing Various Spectra Lines for CE Tests from 150 K Hz to 30 M Hz, with limit lines for CISPR22 case

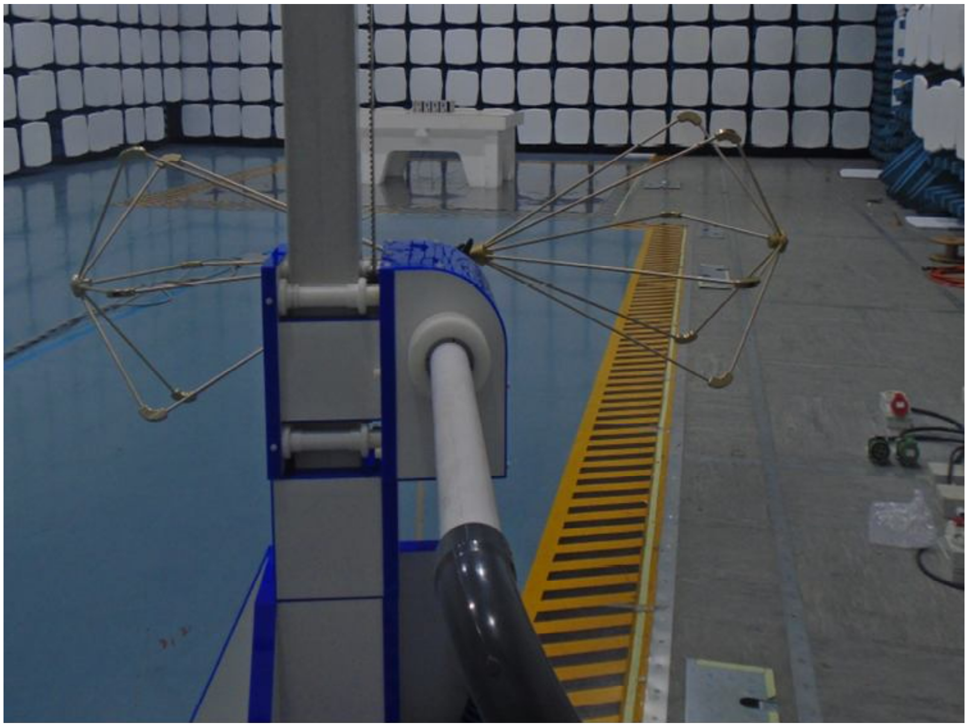


Fig-6: Antenna at 10m for RE measurement in range 30 M Hz to 230 M Hz

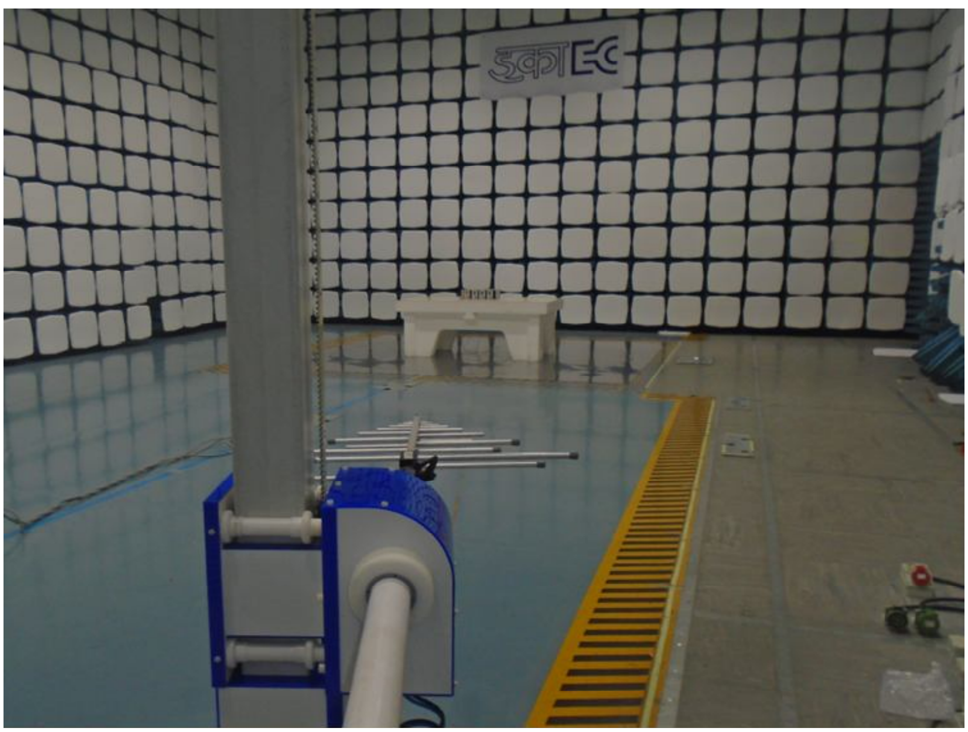


Fig-7: Antenna at 10m for RE measurement in range 230 M Hz to 1000 M Hz.

For RE tests two sets of antenna are used. First we recorded the radiated emission for 30MHz to 230MHz, with Bi-Conical antenna kept at 10m from ECPS bin in an-echoic chamber, shown in figure-6, and then we use log-periodic dipole antenna system to record the RE from frequency 230 MHz to 1000 MHz, shown in figure-7.

Observations for EMI emission tests

After placement of filters at rear side on mother-board-which houses the ECPS; and shielding the internal cable at the power ON/OFF switch, for the DC-DC ECPS and the AC-DC ECPS , the maximum value 3-4 dB micro-volts was observed in CE tests. This value is much less than the lower limit CE i.e. 60 dB micro-volts, in the range of 150 KHz-30 MHz spectral range (defined by [7]). This corresponds to V_P and V_N of less than 1 mV that amounts to leakage currents I_P and I_N less than 20 micro-amperes.

After placement of the ECPS units inside shielded bins, then insertion of ferrite beads placed on long wires connected to load; twisting the load wires; and shielding the internal cable at the ON/OFF switch, RE measurements done on the DC-DC ECPS and AC-DC ECPS showed; 2 dB micro-volt / meter. The maximum value, observed is, lesser than the lower limit of RE i.e. 37 dB micro-volts / meter, (=20 log (E /1 micro-volt per meter) in the range of 230-1000 M Hz spectral range. This corresponds to electric field of lesser than about 71 micro-volts / meter comes from E $=10^{(37/20)}$ = 71 micro-volts / meter. In actual we still expect lesser dB micro-volts / meter, as the system will be inside RF shielded Instrument Racks (IR) in the Nuclear Plant sites.

As required by BHEL same experiment was conducted again as per CISPR11. The DC-DC model of ECPS cleared the limit for CE test by 4 dB micro-volt and AC-DC model cleared the CE limit by 7 dB micro-volt margin. Further in order to record the RE from the rear side of ECPS where we have load wires connections, it is observed at RE tests both the models crossed the limit at antenna height of 2m. This test was done on unshielded system; actually the entire assembly at site is housed inside shielded instrument rack-that will reduce the RE from rear side of the ECPS assembly.

Interpretations of observed spectrum

A Pulse Width Modulated signal (PWM) signal can be considered to be sum of an infinite amount of sine and cosine waves of varying amplitude and frequency. We can obtain expressions for the amplitudes of these waves by computing the Fourier series for signal. In essence the original signal here denoted by $v(t)$, with time period $T_p = 2L$ is expressed as

$$v(t) = \tfrac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\left(\tfrac{n\pi t}{L}\right) + \sum_{n=1}^{\infty} \sin\left(\tfrac{n\pi t}{L}\right)$$

In this Fourier series the coefficients a_n and b_n are obtained as

(1) $a_0 = \frac{1}{L}\int_{-L}^{L} v(t)dt$, the DC component

(2) $a_n = \frac{1}{L}\int_{-L}^{L} v(t)\cos\left(\frac{n\pi t}{L}\right)dt$; $n = 1, 2, \ldots$

$b_n = \frac{1}{L}\int_{-L}^{L} v(t)\sin\left(\frac{n\pi t}{L}\right)dt$, $n = 1, 2, \ldots$; the amplitudes of fundamental components and the harmonics.

For simplicity take $L=1$; and define the PWM signal, with duty cycle D as $v(t)=0$ for $-1<t<-D$, $v(t)=V$ for $-D<t<D$ and again $v(t)=0$ for $D<t<1$. We get the amplitudes as $a_0=2VD$, $a_n=\frac{2V}{n\pi}\sin(n\pi D)$ and $b_n=0$. We note that with duty cycle $D=50\%$ we will have only fundamental, and other odd harmonics, plus DC. For PWM signal of $D<50\%$ we will have DC component fundamental plus all harmonic components; with decreasing amplitude. The fundamental in DC-DC model of ECPS is 80KHz and in AC-DC model of ECPS two fundamental frequencies 80KHz and 100KKz (due to extra Boost Convertor employed for PFC and THD controls).

The PWM is thus having multi-frequency components, and here Inter-Modulation Noise at several frequencies due to beats appears in CE and RE measurements. Inter-Modulation Noise is due to concept of Inter-Modulation Distortion (IMD). The Inter-Modulation (IM) product at frequencies f_{IM} are generated by two ore more signals at frequencies f_1, f_2, f_3; … . The relation between f_{IM} and these f_1, f_2, f_3 is expressed as

$$f_{IM}=\left|m_1 f_1+m_2 f_2+...\right|$$

with $m_j=0,\pm1,\pm2,...$. The order of IM product is given as $n=m_1+m_2+...$.This means that the frequency of second order IM product IM_2 with $n=2$, $m_1=m_2=1$ results in $f_{IM}=\left|f_1\pm f_2\right|$.

The third order IM_3 ($n=3$, $m_1=2$ $m_2=1$) gives $f_{IM}=\left|2f_1\pm f_2\right|$ or $f_{IM}=\left|2f_2\pm f_1\right|$, i.e. with $m_1=1$ and $m_2=2$.

In our experiments we observed odd plus even harmonic components and various other spectral lines-and sometimes with increasing amplitude at a particular frequency range. We note that first of all we are having in our system a square wave (of basic frequency 80 K Hz, in DC-DC model) with Duty-cycle less than 50%, at full load. For CISPR CE-RE, recording is from 150 KHz onwards. Thus we are supposed to get infinite numbers of harmonics (as per Fourier series) as-DC, first harmonic (80KHz), second harmonic (160KHz), third harmonic (240Kz) fourth harmonic (320 KHz) … 8MHz, 16Mz, 24MHz, (32Mz)… ; and so on. Because we restricted our record from 150 KHz to 30 MHz, we are not seeing the first harmonic components. Not only one sees these components, but also one observes addition and subtraction of the components, as described in Inter-Modulation Noise.

For the AC-DC model, apart from the infinite frequencies due to 80 KHz, we also have 100 KHz as basic frequency for pre-boosted DC-DC circuit for PFC and THD control. Therefore we are also recording 200 KHz, 300 KHz, 400 KHz…….10MHz, 20MHz, 30 MHz….in addition to the frequencies listed ones for DC-DC model. Here the 100KHz component is getting added and subtracted and we are also getting 180KHz, 260KHz, 340KHz, ….16MHz+100KHz, 16MHz-100KHz, 24MHz+100KHz, 24MHz-100KHz,….20MHz+100KHz, 20MHz-100KHz,…… Here also at higher decades showing continuous spectral lines (figure-5); due to Inter-Modulation Noise as described above.

For CE recording, we are measuring the 'leaked' current components, I_P and $I_{N,}$ from P-leads and N-leads respectively to the Earth- (E-leads); at the Spectrum Analyzer, via LISN. We are therefore measuring $V_P = (I_P)$ (50 Ohms), and $V_N = (I_N)$ (50 Ohms) through LISN (at 50 Ohm terminal impedance). The stray-capacitors (C_{stray} that is always present), at higher frequency band is presenting a very-very low impedance path to those high Fourier components; plus all components that are generated via Inter Modulation Noise Thus we are observing at these frequency ranges higher amplitude of V_P and V_N (in dB micro-volts), due to increased leakage currents (I_P and I_N) at those higher frequencies and due to IMD; as explained above.

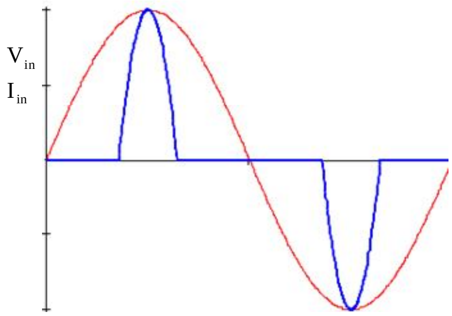
Power Quality Control

As of 2001, all electrical and electronic equipment that is connected to public mains up to and including 16A max, rated input current must comply with IEC 61000-3-2. Passive and active harmonic line current reduction solutions can be used to fulfill the limits of the standards which greatly influences the design of all power supplies. EN 61000-3-2 came into effect on 1995 and has replaced EN 60555-2 as on 2001. The last version of this standard has been accepted by CENELEC on 2006. It is based on IEC 61000-3-2:2005; in the meantime two amendments (A1:2008 and A2:2009) have been published. Since 2009 only IEC 61000-3-2: 2006 is applicable all older versions of EN-61000 are expired.

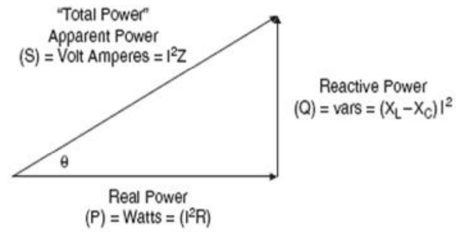
Harmonic line current reduction can be achieved by using different techniques. The most common techniques for harmonic current reduction are line filters, using passive components; and active electronics circuitry. Harmonic line current reduction technique using passive components (inductors and capacitors) introduces high impedance for harmonics thus smoothening the input current to electronic equipment.

Harmonic line current reduction using the active electronic circuitry is shaping the input current of electronic equipment proportional to the applied line voltage thus giving sinusoidal input current in phase with the line voltage. The corresponding electronic circuitry is called Power Factor Correction (PFC) circuitry; although power factor correction is not the correct wording but has become synonymous for harmonic line current reduction. The harmonic line current reduction using the passive components sometimes called passive PFC.

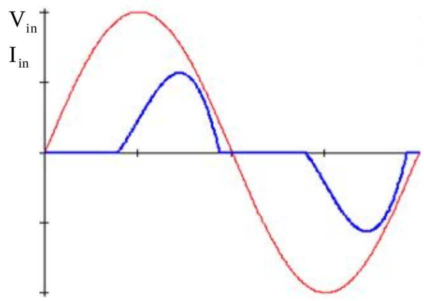
Figure-8 shows the principal behavior of the AC line input current reduction. Without any harmonic current reduction circuitry the input current achieves very high limits as the current is only limited by the small input impedance (filter and cabling) of the power supply. Adding additional inductances (passive solution) reduce the input current as well as its harmonic contents. Best harmonic current reduction is achieved by active PFC. In our latest embodiment of ECPS SM 100 we have followed active PFC circuitry.



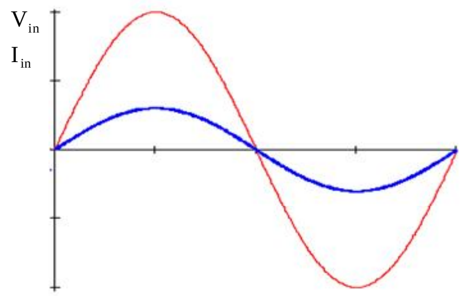
a. Typical Input Current with-out harmonic line current reduction



d. Power factor Triangle (lagging)



b. Typical Input Current with-Passive PFC



c. Typical Input Current with-Passive PFC

Fig-8: Line current with and without harmonic reduction circuitry

Passive harmonic line current reduction has advantage as; simple and robust circuitry; less costly than active PFC (Especially in 3-phase). Disadvantages are; large and heavy low frequency magnetic needed; not applicable for wide input range & higher power; no sinusoidal input current. Active harmonic line current reduction has advantages as; extensive elimination of line current harmonics; Power Factor (PF) nearly unity (PF is about 0.6 for uncorrected system); and wide input voltage range possible. The disadvantages of active PFC are; requires additional expense circuitry; increased number of parts and has negative impact on power conversion efficiency (due to losses in switching technique used).

Some measurement parameters for Power Quality quantification defined

The real power (watts) produces real work; this is the energy transfer component (example electricity to run motor rpm). Reactive power is the power required to produce the magnetic fields (lost power), in lagging PF system; to enable the real work to be done; where apparent power is considered the total power that the power company supplies-and charge for it. This total power is the power supplied through the power mains to produce the required amount of real power. The lagging power factor triangle is depicted in Figure 8d. This stated definition of power factor related to phase angle is valid when considering "ideal-sinusoidal" wave-forms for both current and voltage; however most power supplies draw a non-sinusoidal current. When the current is not sinusoidal and the voltage is sinusoidal, the power factor consists of two factors: 1) the displacement factor related to phase angle and 2) the distortion factor related to wave shape. When the power factor is not equal to one, the current waveform does not follow the voltage waveform. This results not only in power losses but may cause harmonics that travel down the neutral line and disrupt other devises connected to the line. The closer the power factor is to one, the closer the current harmonics will be to zero since all the power is contained in the fundamental frequency. Therefore, the purpose of the power factor correction circuit is to minimize the input current distortion and make the current in phase with the voltage.

For Power Factor we take ratio of the Active Power in Watt (W) to Apparent Power in Volt-Ampere (VA); for the fundamental current.

$$\mathrm{DPF} = \frac{\text{Active - Power (W)}}{\text{Apparant - Power (VA)}}$$

This is also called Displacement Power Factor (DPF). Whereas the Total Power Factor (TPF), is ratio of composite wave (current)-including all harmonics.

$$\mathrm{TPF} = \frac{\text{Total Active - Power (W)}}{\text{Total Apparant - Power (VA)}}$$

Thus we have TPF < DPF. Total Harmonic Distortion (THD) is defined as

$$\mathrm{THD} = \sqrt{\sum_{n=2}^{40} \left(\frac{I_n}{I_1}\right)^2}$$

where I_n is, RMS value of higher harmonic components, and I_1 is the fundamental RMS value of the current. IEC-61000-3-2 gives THD values taking 40 harmonic components.

Crest Factor is defined as ratio of peak current to RMS current. This defines deviation from ideal sinusoid.

$$\mathrm{CF} = \frac{I_{peak}}{I_{RMS}}$$

For ideal sinusoid this crest factor is $\mathrm{CF} = \sqrt{2} = 1.414$; that is for pure sinusoid we have $I_{RMS} = \left(\frac{1}{\sqrt{2}}\right) I_{peak}$.

The Boost Converter is the Main element of Active Power Factor Correction

Boost converter is used to accomplish the active PFC in many discontinuous/continuous conduction modes (DCM/CCM). First we see how the inductors can produce very high voltages-is depicted in Figure-9. Initially the inductor is assumed to be uncharged, so the voltage V_0 is equal to V_{in}. When the switch closes, the current I_L gradually increases linearly as $I_L = \frac{1}{L}\int V_L dt$. Voltage V_L across it increases exponentially until it stabilizes at V_{in}. Notice the polarity of the voltage across the inductor, as it is defined by the current direction (in side taken as positive). When the switch opens causing the current to change from I_{max} to zero (which is a decrease, or a negative slope). That is L times the change in current per unit time, the voltage approaches negative infinity (the inductor reverses the polarity).

$$V_L = L\frac{di}{dt} \approx L\frac{\Delta i}{\Delta t}$$

Since the inductor is not ideal, it contains some amount of series resistance, which loads this "infinite" voltage to a finite value. With the switch open and inductor discharging, the voltage across it reverses and becomes additive with the source voltage V_{in}. If a diode and capacitor were connected to the output of this circuit, the capacitor would charge to this high voltage (after few switching cycles). This is the operation of Boost Converter (Figure-10).

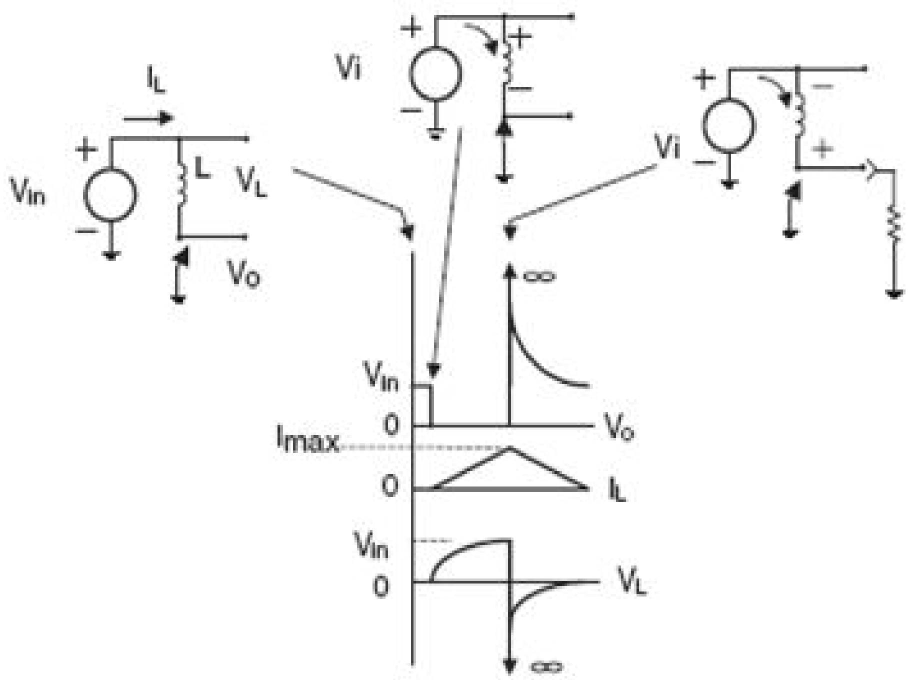


Fig-9: Fly back operation of Inductor

The input to the converter is full rectified AC line voltage. No bulk filtering is applied following is applied following the bridge rectifier, so the input voltage to the boost converter ranges (at twice line frequency) from zero volts to peak value of the AC input and back to zero. The boost converter must meet two conditions simultaneously; 1) the output voltage of the boost converter must be set higher than the peak value (hence the word boost) of the line voltage (we used 390V DC to allow high line voltage 265V RMS); 2) the current drawn from the line at any given instant must be proportional to the line voltage. In Figure-10 the Boosted DC Voltage (390V DC) of this PFC stage goes to the second stage of power converter circuit, which is a current mode PWM DC-DC (Buck Converter) converter of ECPS circuit, operating on 80 KHz. The Figure-10 circuit is pre-Boosted converter which operates on Fixed Frequency 102 KHz. This complete set is for latest embodiment of ECPS 100W system.

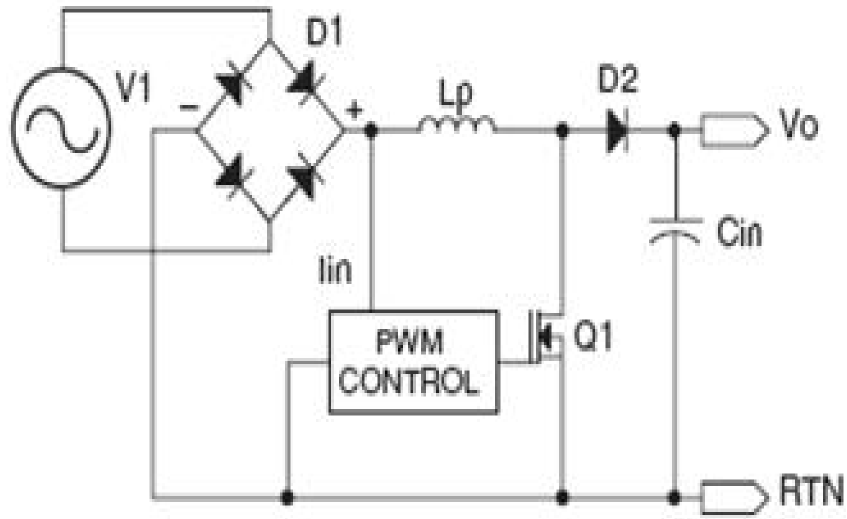


Fig-10: Boost Converter Circuit

Power Quality Test on SMPS without PFC

Without using PFC a typical SMPS has PF around 0.6, therefore having considerable odd-harmonics distortion (sometimes with the third harmonic as large as fundamental). Having a power factor less than one along with harmonics from peaky loads reduces the real power available to run the device. In order to operate a device with these inefficiencies, the power company must supply additional power to make up for losses. This increase in power causes the power companies to use heavier supply lines, otherwise self-heating can cause burnout in the neutral line conductor. The harmonic distortion can cause an increase in operating temperature of the generation facility, which reduces the life of the equipment including rotating machines, cables, transformers, capacitors, fuses, switching contacts, and surge suppressors. Problems are caused by the harmonics creating additional losses and dielectric stress in capacitors and cables, increasing currents in windings of rotating machinery and transformers and noise emission in many products, and bringing about early failure of fuses and other safety components. They can also cause skin effect, which creates problems in cables, transformers and rotating machines. The test results of SMPS without PFC is shown in Figure-11; and Figure-12 depicts the harmonics of current that is recorded. See the PF is poor at 0.436 and poor crest factor of 4.65 (ideally it should be 1.414); and the current having large harmonic contents giving THS as 216%. This is for earlier embodiments of ECPS without PFC.

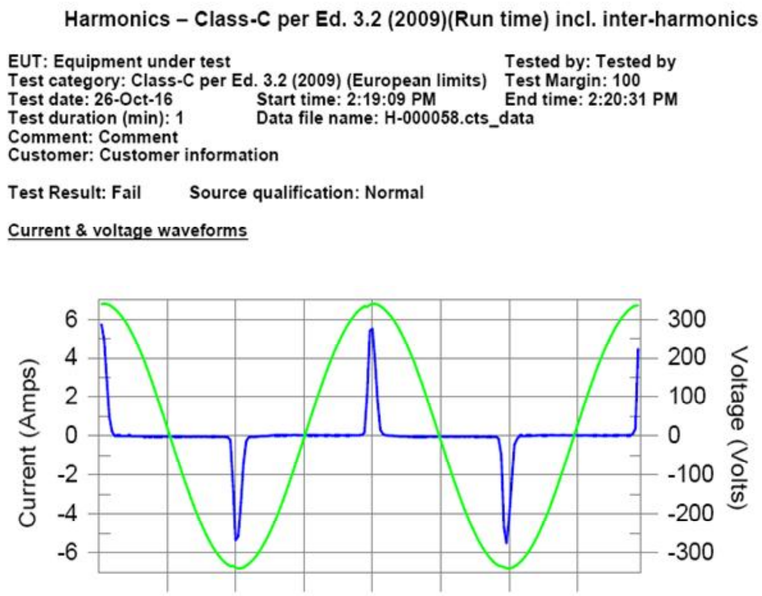


Figure-11: Current Voltage Wave-form measured at Power Quality Test Equipment

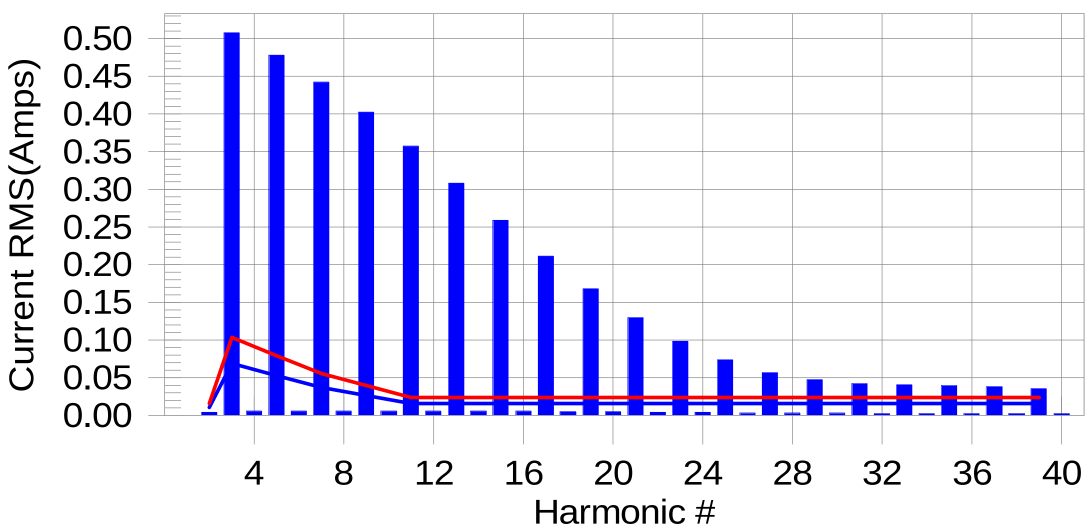


Fig-12: Test result of Harmonics SMPS without PFC

This is why power companies are concerned with growth of SMPS that will cause THD levels to increase to unacceptable levels. Having the boost pre-converter voltage higher than the input voltage forces the load to draw current in phase with AC line-voltage that in turn reduces the harmonic emissions.

Current Test Result Summary (Run time)

Test Result: Fail   Source qualification: Normal

THC(A): 1.12   I-THD(%): 216.50   POHC(A): 0.214   POHC Limit(A): 0.050

Highest parameter values during test:

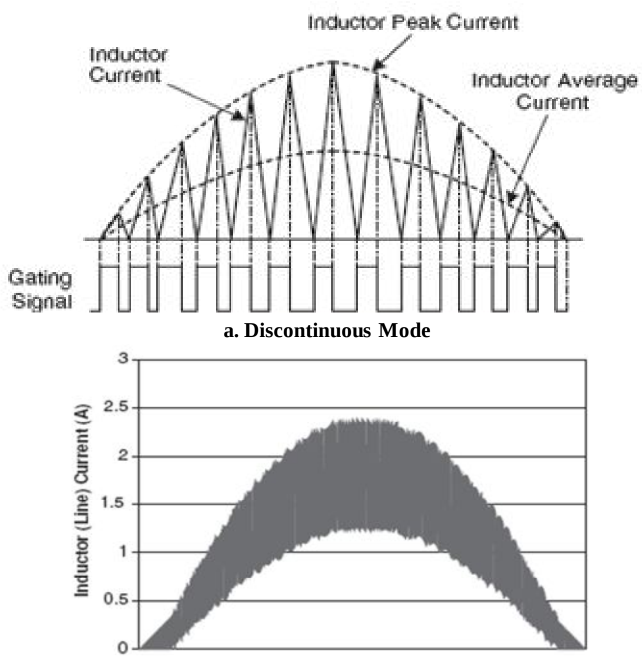
V_RMS (Volts):	240.40	Frequency(Hz):	50.00
I_Peak (Amps):	5.787	I_RMS (Amps):	1.248
I_Fund (Amps):	0.529	Crest Factor:	4.645
Power (Watts):	126.8	Power Factor:	0.436

Harm#	Harms(avg)	100%Limit	%of Limit	Harms(max)	150%Limit	%of Limit	Status
2	0.005	0.011	44.3	0.005	0.016	0.00	Pass
3	0.508	0.069	735.5	0.508	0.104	490.81	Fail
4	0.007						
5	0.478	0.053	904.6	0.479	0.079	604.48	Fail
6	0.007						
7	0.443	0.037	1196.3	0.445	0.055	801.39	Fail
8	0.007						
9	0.403	0.026	1525.1	0.406	0.040	1025.12	Fail
10	0.007						
11	0.358	0.016	2255.6	0.362	0.024	1522.66	Fail
12	0.007						
13	0.308	0.016	1944.9	0.314	0.024	1320.10	Fail
14	0.007						
15	0.259	0.016	1633.5	0.265	0.024	1115.92	Fail
16	0.007						
17	0.212	0.016	1337.6	0.219	0.024	920.74	Fail
18	0.006						
19	0.169	0.016	1064.7	0.176	0.024	739.02	Fail
20	0.006						
21	0.131	0.016	823.3	0.137	0.024	576.40	Fail
22	0.006						
23	0.099	0.016	623.3	0.104	0.024	439.17	Fail
24	0.005						
25	0.074	0.016	469.6	0.079	0.024	330.69	Fail
26	0.005						
27	0.057	0.016	362.6	0.060	0.024	252.13	Fail
28	0.004						
29	0.048	0.016	300.2	0.048	0.024	203.29	Fail
30	0.004						
31	0.043	0.016	271.9	0.045	0.024	187.16	Fail
32	0.004						
33	0.041	0.016	260.9	0.043	0.024	181.71	Fail
34	0.003						
35	0.040	0.016	253.6	0.042	0.024	175.50	Fail
36	0.003						
37	0.038	0.016	242.7	0.039	0.024	165.22	Fail
38	0.003						
39	0.036	0.016	224.9	0.036	0.024	151.19	Fail
40	0.003						

Table-1: Test Result of Power Quality Test without PFC for SMPS

Active Power Factor Correction (PFC) Schemes

There are two modes of PFC operation; discontinuous and continuous mode (DCM and CCM). Discontinuous mode is when the boost converter MOSFET is turned on when the inductor current reaches zero, and tuned off when the inductor current meets the desired input reference voltage as shown in Figure-13a. In this way the current waveform follows that of the input voltage, thus attaining PF close to one. Discontinuous Mode is used for SMPS that have power levels of 300 W or less. In comparison with continuous mode devices the discontinuous mode uses larger cores and have higher I^2R and skin effect losses due to larger swings of inductor current. With the increased swing a larger input filter is also required. On the positive side since discontinuous mode devices switch the boost MOSFET on when the inductor current is zero, there is no reverse recovery current I_{RR} specification required on the boost diode.



a. Discontinuous Mode

b. Continuous Mode

Fig-13: Modes of operation of Active PFC

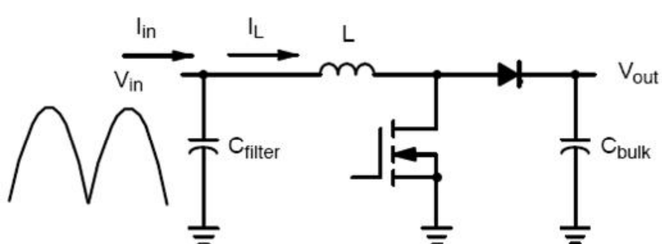
In the figure-13a the AC line current is shown continuous waveform where the peak switch current is twice the average input current. In this mode, the operation frequency varies with constant on time.

Continuous mode (is also called Average Current Mode) typically suits SMPS power levels greater than 300W. This is where the boost converter's MOSFET does not switch on when boost inductor is at zero current, instead the current in the energy transfer inductor never reaches zero during the switching cycle. This is depicted in Figure-13b. With this in mind the voltage swing is less than in discontinuous mode-resulting in lower I^2R losses-and lower ripple current results in lower inductor core losses. Less voltage swing also reduces EMI and allows for smaller input filter to be used. Since MOSFET is not turned on when the boost inductor current is zero, a very fast reverse recovery diode is required to keep losses to minimum. In our PFC we used continuous mode.

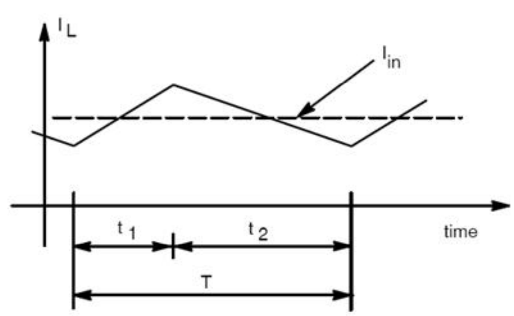
Fixed Frequency Continuous Mode for PFC in ECPS

In the latest embodiment of ECPS, Power Factor Correction (PFC) boost controller is operated in circuit in fixed-frequency Continuous Conduction Mode (CCM) or Average Current Mode. Fixed frequency operation eases the compliance with EMI standards and the limitation of possible radiated noise that may pollute surrounding systems. The CCM operation reduces the application of di/dt and the resulting interference. A CCM PFC boost converter is shown in Figure-14a. The input voltage is rectified 50 Hz sinusoidal signal. The MOSFET is switching at a high frequency (102 KHz) so that inductor current I_L basically consists of high and low frequency components. Filter capacitor C_{filter} is essential and very small value capacitor in order to eliminate the high-frequency component of the inductor current I_L. This filter capacitor cannot be too bulky because it can pollute the power factor by distorting the rectified sinusoidal input voltage. As shown in Figure-14b, the inductor current I_L in a switching period T includes a charging phase for duration t_1 and discharging phase for duration t_2. The voltage conversion ratio is obtained by following relation

$$\frac{V_{out}}{V_{in}} = \frac{t_1 + t_2}{t_2} = \frac{T}{T - t_1}; \qquad V_{in} = \frac{T - t_1}{T} V_{out}$$



a. Boost Converter of CCM PFC



b. Inductor Current in CCM

Fig-14: Boost Converter and Inductor Current

The input filter capacitor C_{filter} and the front-ended EMI filter absorb the high-frequency component of inductor current I_L. It makes the input current I_{in} a low-frequency signal only of the inductor current

$$I_{in} = I_{L-50}$$

The suffix 50 means it is with a 50 Hz bandwidth of the original I_L. From above expressions we write

$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{T - t_1}{T}\frac{V_{out}}{I_{L-50}}$$

Power Factor is corrected when the input impedance Z_{in} is constant or slowly varying in the 50 Hz bandwidth-i.e. Z_{in} behaves as resistive quantity.

a. CCM PFC Duty Modulation

b. CCM PFC Timing Diagram

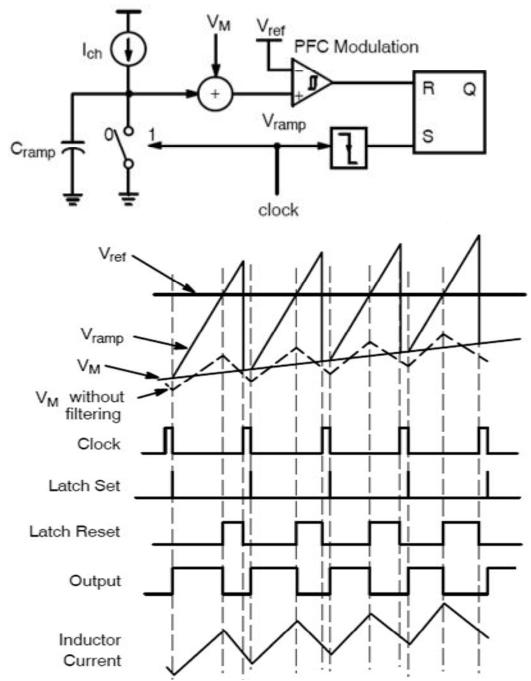


Fig-15: CCM PFC Duty Modulation and Timing Diagram

The PFC duty modulation and timing diagram is shown in figure-15. The MOSFET on time t_1 is generated by the intersection of reference voltage V_{ref} and ramp voltage V_{ramp}. A relationship is following

$$V_{ramp} = V_M + \frac{I_{ch}}{C_{ramp}} t_1 = V_{ref}$$

The charging current I_{ch} is specially designed as

$$I_{ch} = \frac{C_{ramp} V_{ref}}{T}$$

$$V_M = V_{ref} - \frac{t_1}{C_{ramp}}\frac{C_{ramp} V_{ref}}{T} = V_{ref}\frac{T - t_1}{T}$$

From above set of equations we get input impedance as re-formulated as

$$Z_{in} = \frac{V_M}{V_{ref}} \frac{V_{out}}{I_{L-50}}$$

Because V_{ref} and V_{out} are roughly constant with time, the multiplier voltage V_M is designed to be proportional to I_{L-50} in order to have constant Z_{in} for PFC purpose, is shown in Figure-16.

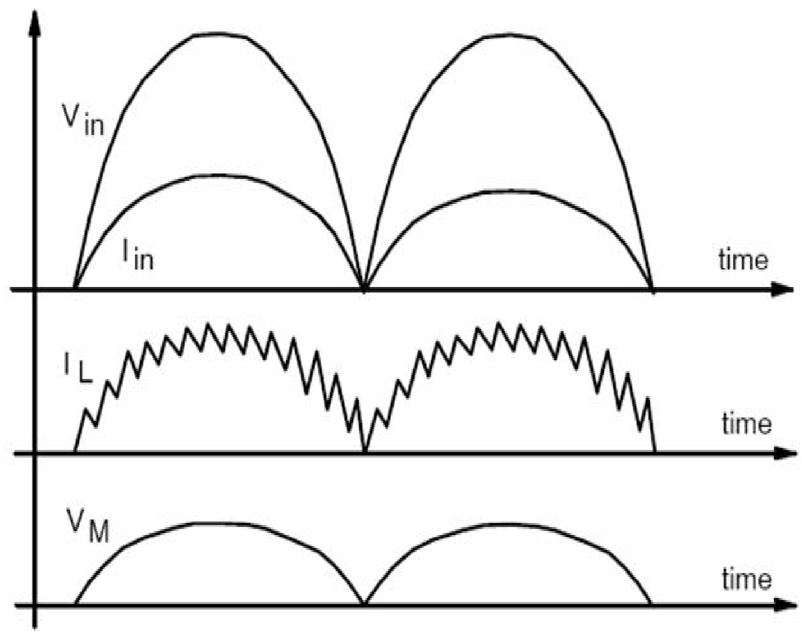


Fig-16: Multiplier Voltage Timing Diagram

The multiplier voltage V_M is generated by sensing the input current via inductor current consisting of switching frequency ripple (that comes from inductor current I_L). The duty ratio can be inaccurately generated due to this ripple. This modulation is so called-“peak current mode”. With the help of a filter capacitor C_M for filtering multiplier voltage V_M to bypass high-frequency ripple-the modulation becomes-“average current mode”.

The Power Quality Testing Results

The power quality tests are carried out in EMI/EMC Center of ECIL, with Power Quality Test Equipment-AMETEK US make. This equipment has Variable 115V-300V 16Hz-1000Hz source and also variable DC 115V-300V source of 15KVA rating. This is used to power the equipment under test, and record the parameters. Figure-17 depicts the Test-set up where ECPS system is connected to this source. The Tests were carried out for single ECPS, Multiple ECPS, and ECPS sharing loads equally in current share mode. The computer records the data and generates the report about the test-is given in Figure-18.

Fig-17: The Power Quality Testing Equipment Connected to ECPS (left showing testing of single ECPS unit, right showing the testing of Multiple ECPS units)

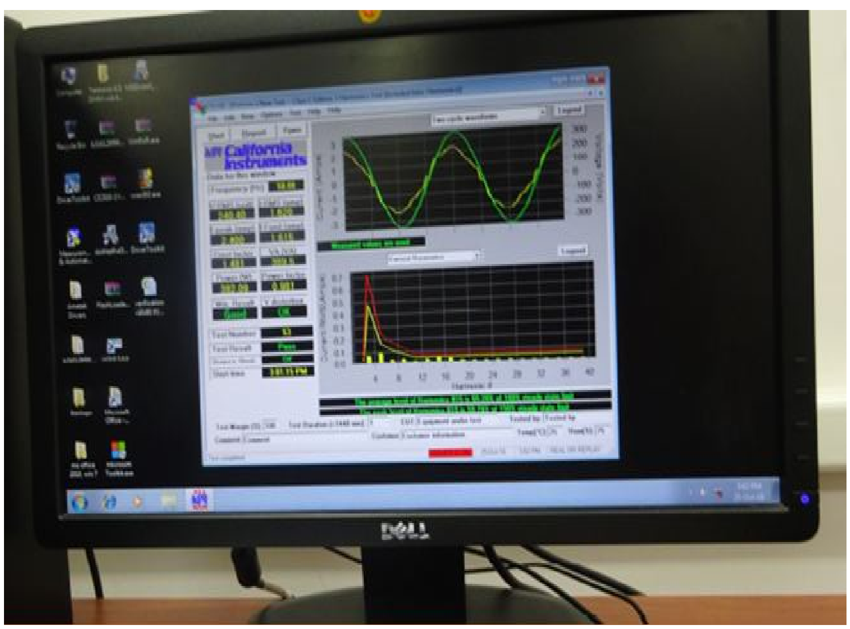


Fig-18: The computer record of data for input voltage and input current wave-form and display of harmonic contents of input current

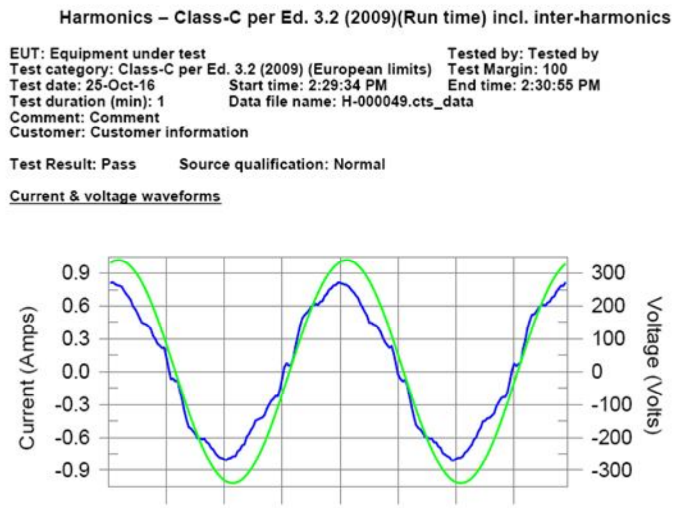
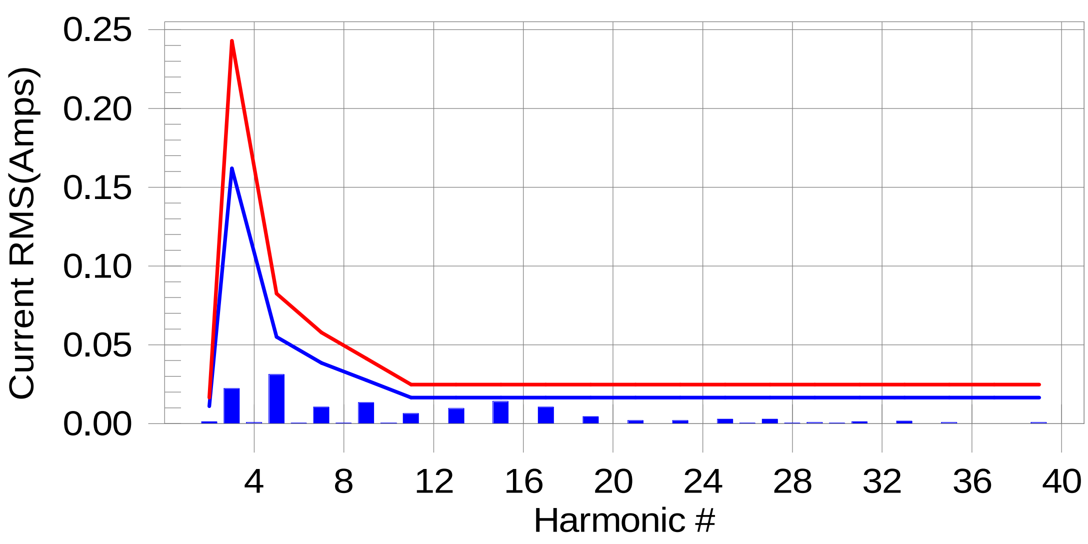


Fig-19: ECPS 100 (5V) Input Voltage Current Record at full load current

Harmonics and Class C limit line **European Limits**



Test result: Pass Worst harmonics H15-86.66% of 100% limit, H15-58.04% of 150% limit.

Fig-20: Harmonic current level display for ECPS 100 (5V) at full load

Current Test Result Summary (Run time)

Test Result: Pass **Source qualification: Normal**

THC(A): 0.05 **I-THD(%): 8.79** **POHC(A): 0.000** **POHC Limit(A): 0.052**

Highest parameter values during test:

V_RMS (Volts):	240.43	Frequency(Hz):	50.00
I_Peak (Amps):	0.833	I_RMS (Amps):	0.553
I_Fund (Amps):	0.550	Crest Factor:	1.509
Power (Watts):	130.2	Power Factor:	0.981

Harm#	Harms(avg)	100%Limit	%of Limit	Harms(max)	150%Limit	%of Limit	Status
2	0.001	0.011	11.7	0.002	0.017	0.00	Pass
3	0.022	0.162	13.8	0.023	0.243	9.36	Pass
4	0.001						
5	0.031	0.055	56.8	0.031	0.083	37.97	Pass
6	0.001						
7	0.011	0.039	27.6	0.011	0.058	18.59	Pass
8	0.000						
9	0.014	0.028	49.4	0.014	0.041	33.30	Pass
10	0.000						
11	0.007	0.017	40.0	0.007	0.025	27.43	Pass
12	0.000						
13	0.010	0.017	60.3	0.010	0.025	40.47	Pass
14	0.000						
15	0.014	0.017	86.7	0.014	0.025	58.04	Pass
16	0.000						
17	0.011	0.017	64.9	0.011	0.025	43.43	Pass
18	0.000						
19	0.005	0.017	27.5	0.005	0.025	0.00	Pass
20	0.000						
21	0.002	0.017	12.2	0.002	0.025	0.00	Pass
22	0.000						
23	0.002	0.017	12.4	0.002	0.025	0.00	Pass
24	0.000						
25	0.003	0.017	18.4	0.004	0.025	0.00	Pass
26	0.000						
27	0.003	0.017	16.9	0.003	0.025	0.00	Pass
28	0.000						
29	0.001	0.017	5.8	0.001	0.025	0.00	Pass
30	0.000						
31	0.001	0.017	8.9	0.002	0.025	0.00	Pass
32	0.000						
33	0.002	0.017	10.2	0.002	0.025	0.00	Pass
34	0.000						
35	0.001	0.017	5.7	0.001	0.025	0.00	Pass
36	0.000						
37	0.000	0.017	1.9	0.000	0.025	0.00	Pass
38	0.000						
39	0.001	0.017	5.3	0.001	0.025	0.00	Pass
40	0.000						

Table-2: Test Report on Power Quality of ECPS 100 (5V) at full load

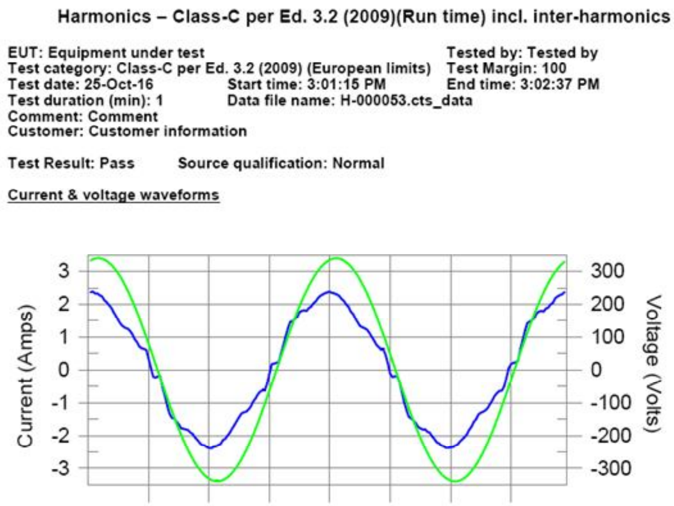
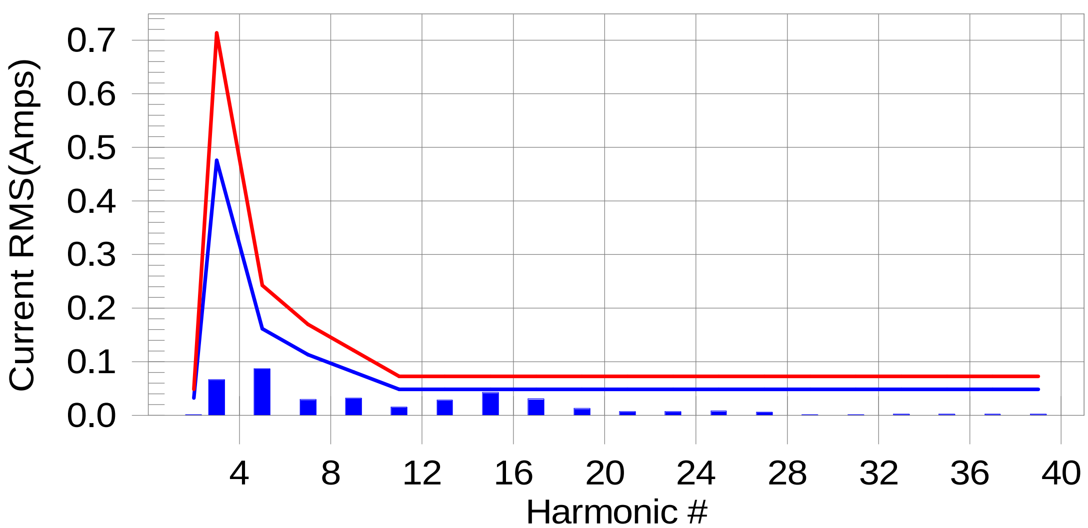


Fig-21: ECPS 100 (5V, 15V, 24V) three testing together Input Voltage Current Record at full load current for each

Harmonics and Class C limit line **European Limits**



Test result: Pass Worst harmonics H15-89.20% of 100% limit, H15-59.74% of 150% limit.

Fig-22: Harmonic current level display for ECPS 100 (5V, 15V, 24V) three testing together at full load current for each

Current Test Result Summary (Run time)

Test Result: Pass   Source qualification: Normal

THC(A): 0.14   I-THD(%): 8.54   POHC(A): 0.000   POHC Limit(A): 0.153

Highest parameter values during test:

V_RMS (Volts):	240.41	Frequency(Hz):	50.00
I_Peak (Amps):	2.417	I_RMS (Amps):	1.624
I_Fund (Amps):	1.617	Crest Factor:	1.491
Power (Watts):	382.5	Power Factor:	0.981

Harm#	Harms(avg)	100%Limit	%of Limit	Harms(max)	150%Limit	%of Limit	Status
2	0.001	0.032	3.6	0.002	0.049	0.00	Pass
3	0.067	0.476	14.2	0.068	0.714	9.53	Pass
4	0.001						
5	0.087	0.162	54.0	0.088	0.243	36.09	Pass
6	0.001						
7	0.030	0.113	26.3	0.030	0.170	17.67	Pass
8	0.001						
9	0.033	0.081	40.4	0.033	0.121	27.18	Pass
10	0.001						
11	0.016	0.049	32.1	0.016	0.073	21.78	Pass
12	0.001						
13	0.029	0.049	60.3	0.029	0.073	40.55	Pass
14	0.001						
15	0.043	0.049	89.2	0.043	0.073	59.74	Pass
16	0.001						
17	0.032	0.049	65.2	0.032	0.073	43.61	Pass
18	0.001						
19	0.014	0.049	28.8	0.014	0.073	19.33	Pass
20	0.001						
21	0.007	0.049	15.1	0.007	0.073	0.00	Pass
22	0.001						
23	0.008	0.049	15.5	0.008	0.073	0.00	Pass
24	0.001						
25	0.009	0.049	17.7	0.009	0.073	0.00	Pass
26	0.001						
27	0.007	0.049	14.6	0.008	0.073	0.00	Pass
28	0.001						
29	0.003	0.049	5.2	0.003	0.073	0.00	Pass
30	0.001						
31	0.002	0.049	4.1	0.002	0.073	0.00	Pass
32	0.001						
33	0.003	0.049	6.7	0.003	0.073	0.00	Pass
34	0.001						
35	0.003	0.049	5.6	0.003	0.073	0.00	Pass
36	0.001						
37	0.003	0.049	5.6	0.003	0.073	0.00	Pass
38	0.001						
39	0.003	0.049	6.6	0.003	0.073	0.00	Pass
40	0.000						

Table-3: Test Report on Power Quality of ECPS 100 (5V, 15V, 24V) at full load

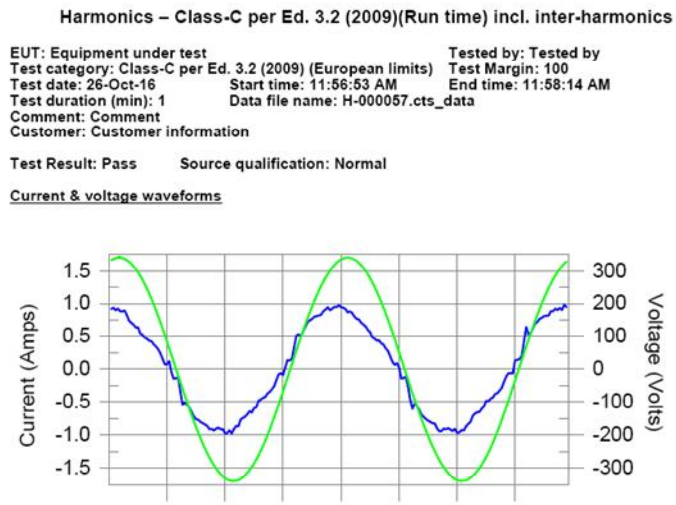
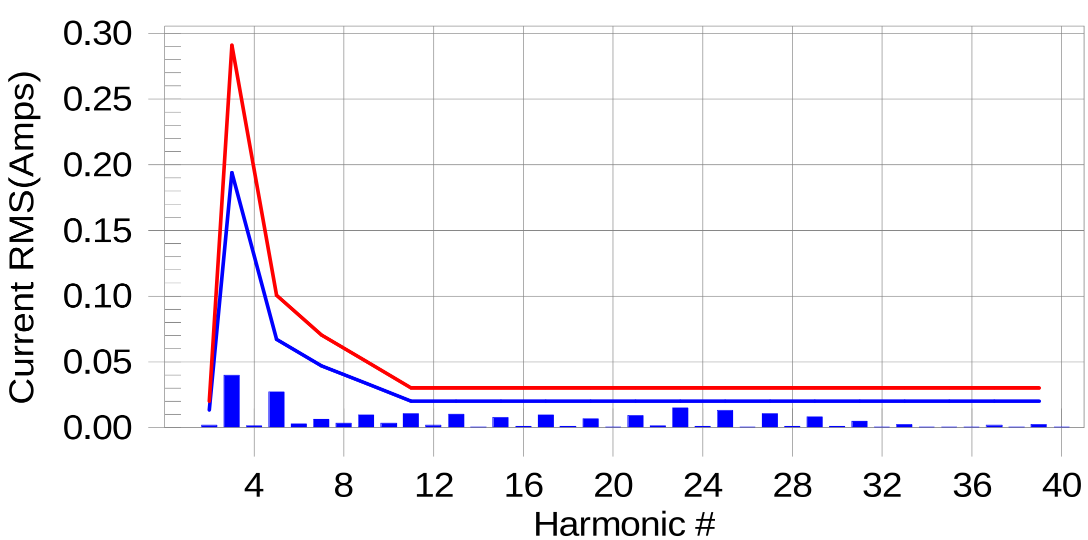


Fig-23: ECPS 100 (15V) two sharing load together Input Voltage Current Record for load current 16A shared by both

Harmonics and Class C limit line **European Limits**



Test result: Pass Worst harmonics H23-76.82% of 100% limit, H23-51.75% of 150% limit.

Fig-24: Harmonic current level display for ECPS 100 (15V) two sharing load of 16A total

Conclusions

In this short note we presented the brief result of Electro Magnetic Interference Tests and the power quality tests done for a developed new product ECPS100 to be used in NPCIL-PHWR700MW, as per CISPR22 standard and IEC 61000-3-2. Here we comment that if we want to do CE, RE tests as per say some special standards or MIL –STD, then accordingly measurements will also be different for different ranges of frequencies. The mitigation methods of use EMI filtering shielding etc used here may be stringent for the other standards. So those solutions need be different. Also packing the developed circuit onto a different PCB, with different enclosure, and internal wiring and assembly will give different results. We have qualified the equipment that is ECPS 100, with active PFC circuitry, to improve input power factor and reduce the harmonic current contents; that gives a qualified system as per latest IEC standard.

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