A Cost-Effective High-Performance Conducted Emission Test Solution to Comply with MIL-STD-461F/G Standard

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***Abstract*—The TDK's MIL-STD-461F/G CE102-compliant test is a semi-automatic solution using the leading edge standards-compliant MXE EMI test receiver Keysight N9038A and the authorized TDK®Emission Labs 9.68 software package. This however still results in longer measuring time and inferior measuring performance. Hence, a novel fully automatic test scheme in accordance with control software integrating suitable compensation algorithms is proposed to surmount these disadvantages. The proposal though uses less advanced models such as the low-cost X-Series N9000A CXA, or the high-performance X-Series N9030A PXA Keysight signal analyzers yet creates higher measuring performance in a shorter time. The test configuration with related problems are investigated and resolved then the experimental results are presented to compare with that of the TDK's solution showing the proposal's advantages.**

Keywords—Electromagnetic interferences; conducted emissions; MIL-STD-461F/G; CE102; compensation algorithm.

I. INTRODUCTION

Electromagnetic compatibility (EMC) or electromagnetic interference (EMI) testing is required to demonstrate that the equipment under test (EUT) will operate in its proposed operational electromagnetic environment, if that equipment has acceptable safety limits or if it satisfies required regulatory levels of immunity and/or emissions. MIL-STD-461 is an US military standard series that describes how to test equipment for electromagnetic compatibility. Various revisions of MIL-STD-461 have been released, of which, the latest ones are MIL-STD-461F (2007) [1] and MIL-STD-461G (2015) [2].

Conducted emissions (CE) are the noise currents generated by the ETU that propagate through the power lines to other components, systems or power grid. Levels of conducted emissions are regulated because electromagnetic energy coupled to an electrical equipment's power cord can find its way to the entire power distribution network where the equipment is connected to, and use the larger network to radiate more efficiently than the equipment could by itself. Other electronic devices could hence receive the electromagnetic interference through a radiated path (or, much less frequently, a direct electrical connection). The frequency range where CEs are regulated is typically lower than the frequency range where radiated emissions are regulated.

CE measurement on power lines with frequency range from 10 kHz to 10 MHz (CE102 applicability) of the MIL-STD-461F/G standard is applicable to all power leads, including Neutral wires (returns), which might obtain power from other sources not part of the EUT. Conducted emission requirements on power lines for general electronic equipment (used in the military field or other fields specified by the authorities) should not exceed threshold values specified in this standard as illustrated in Fig 1.

The TDK's CE102-compliance test solution exploits the dedicated leading edge signal analyzer N9038A MXE in accordance with the licensed TDK®Emission Labs 9.68 software package [3]. This solution is semi-automatic because the transfer of measurements between the Line and Neutral wires is carried out manually, complicating the operation, lengthening the time to measure and degrading the measurement performance. Moreover, the TDK Emission Labs 9.68 software package does not support control for other signal analyzer models such as N9000A CXA, N9030A PXA, hindering alternative low cost yet high performance measurement solutions.

To the best of our knowledge, there are not so much discussions relating to this studying topic. Recently, [4] demonstrated a test setup for the CE measurement using the Hameg Instruments®SW 5012E-V153 software package. However, this work concerned only on the measurement results and suggested a method to minimize the unwanted electromagnetic perturbations, namely to place an EMI filter in the test setup. Thus, the academic contributions are limited.

Based on these facts, and in order to improve the EMC/EMI testing capabilities (reducing measurement execution time and manipulations, lessening errors caused by testers, improving the measurement performance, and overcoming difficulties in result post-processing that are currently carried out manually), we propose a comprehensive solution to fully automate the CE102 test of the military standard MIL-STD 461F/G. In addition, the contributions of this proposal are:

+ An accurate attenuation compensation solution for the 20 dB attenuators, connection cables and insertion losses of line impedance stabilization networks (LISN) involved; This improves the test accuracies;

+ An automatic measuring solution for the Line and Neutral wires; This reduces the measuring time and guarantees the stable test conditions, hence increases the test reliability;

+ An automatic solution to extract measurement results into the Certification sheet currently in use; This minimizes the manipulation and time to report results and guarantees the test confidence.

II. Test configuration

The CE102 test is performed to verify that electromagnetic emissions from the EUT with AC or DC power inputs do not exceed the specified requirements for power input leads including returns. The required limits are based on the EUT's source voltage. This is a medium frequency voltage (dBμV) measurement test. Emission levels are determined by using an EMI receiver to measure the voltage presenting at the output port of the LISN. Thus, attenuators and pulse limiters are essential for protecting the EMI receiver, and also providing a better impedance match between the LISN output and the EMI receiver input.

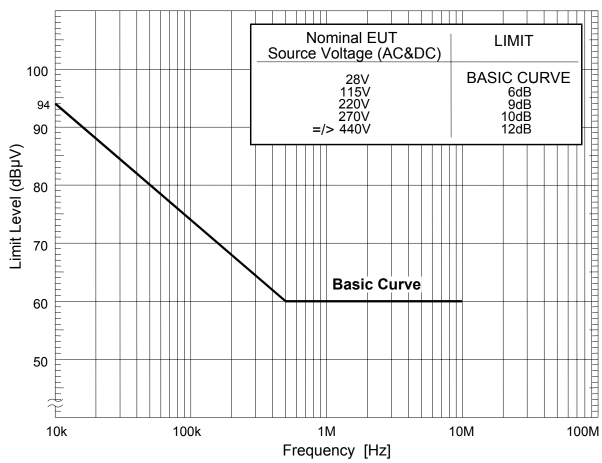

Fig. 1: CE102 limit (EUT power leads, AC and DC) for all applications [1].

A. *TDK's CE102 test solution*

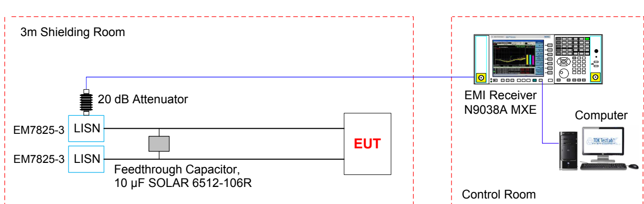

Fig. 2: TDK's CE102 test setup.

As illustrated in Fig. 2, the TDK's setup for measuring CE102 conducted emissions from 10 kHz to 10 MHz includes:

+ The dedicated Keysight signal analyzer N9038A (EMI receiver) with operating frequency range of 3 Hz to 26.5 GHz being used to measure the conducted emissions propagating through the power lines of the operating EUT;

+ The Electro-Metrics LISN 7825-3 having 03 main functions as follows:

- Providing a clean power source with stabilized impedance (50 Ω) and inductance (50 μH) for EUT to operate;
- Isolating the unwanted interferences from the power source not to affect the EUT;
- Providing a port for the measurement of conducted emission generated during the operation of the EUT;

+ The Fairview 20 dB 10 W attenuator (frequency range from DC to 3 GHz) being responsible for protecting the input of the signal analyzer N9038A from overvoltages;

+ Interconnecting cables, connectors and accessories involved in the test setup for connecting the system from the 3m shielding room to the control room;

+ A computer with the TDK®Emission Labs 9.68 software package being installed to control and perform the semi-automatic measurement process for the CE102 test; The software allows users to divide the measuring frequency range into 2 bands to set up the analyzer's parameters satisfying the MIL-STD 461F standard requirements, specifically:

- Band 1: from 10 kHz to 150 kHz, 6-dB frequency bandwidth: 1 kHz, frequency step: 500 Hz, scanning time: 1 second, number of scans: 15 times/second;
- Band 2: from 150 kHz to 10 MHz, 6-dB frequency bandwidth: 10 kHz, frequency step: 5 kHz, scanning time: 1 second, number of scans: 15 times/second;
- Detection type: peak detection (used for both bands);
- Selection of signal analyzer's measurement channel input: Could be AC or DC; However, in this test, the maximum measurement frequency is 10 MHz, so to ensure accurate measurement results, the signal analyzer input should be selected as DC Input.

The working principle of this test system is as follows.

+ When the EUT operates, it generates electromagnetics propagating along the power line; in order to quantify the level and frequency of the interference signal, it is necessary to use the N9038A signal analyzer combined with the LISN EM 7825-3 device to measure and evaluate;

+ Level of the conducted emission caused by the EUT is calculated according to the following formula:

$$EMI = Trace_{\mathrm{N9038A}} + CL + IL + ATT, \qquad (1)$$

where, $Trace_{\mathrm{N9038A}}$ [dBμV] is the noise level measured on signal analyzer N9038A; CL [dB] is the total loss of the connecting cables and connectors used in the setup; IL [dB] is the insertion loss of the LISN EM7825-3; ATT [dB] is the attenuator's value, normally being 20 dB in this case;

+ TDK Emission Labs 9.68 software, in addition to functions of configuring and controlling the N9038A analyzer, is also responsible for calculating the EMI value according to formula (1) for each frequency point in the measuring band 1 and 2, to draw a graph representing the relationship between measured conducted emission by frequency.

There are several disadvantages of the TDK's solution as.

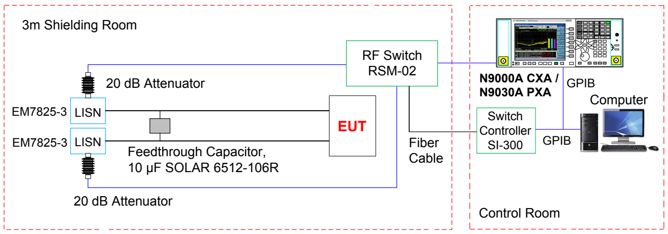

Fig. 3: The CE102 automatic test proposal.

+ Experimentally, using the standards-compliant MXE EMI test receiver N9038A results in higher background noise than the high-performance X-Series N9030A or even low-cost X-Series N9000A does (demonstration shown below);

+ Technically, there is no solution for compensating for the Fairview 20 dB 10 W attenuator's value that could fairly vary around the nominal value at different frequencies, significantly contributing to the total measuring error;

+ Importantly, the solution does not support in flexibly setting the number of signal points for each scan; This may cause the missing of concerned interferences at specific frequencies;

+ It also does not support in automatically switching the conducted emission measurements between Line and Neutral lines; This complicates the operation and lengthens the measuring time, and more adversely, increases the instabilities of the measuring conditions, causing unreliable results.

These shortcomings and limits motivate novel solutions that could utilize lower cost analyzers yet result in higher measuring performance.

B. The CE102 automatic test proposal

In order to completely overcome the problems as analyzed above, the authors propose a comprehensive solution for fully automatic test of CE102 as shown in Fig. 3. There are three main differences between the proposed measurement solution and the TDK's test scheme described above. First, the sooner uses signal analyzers N9000A CXA [5] or N9030A PXA [6] instead of the much higher price N9038A MXE. Second, the proposal's conducted emission measurement software can fully automatically control the measurement process of both Line and Neutral wires, reducing the testing time while giving more reliable measuring results than the TDK's software does. Last but not least, an accurate attenuation compensation algorithm is also integrated in the software, creating more precise results than what the TDK's software does.

Test setup

This test setup differs to the TDK's at the following items:

+ The high frequency Remote Switch Module RSM-02: having 6 input ports, 1 output port; Two input ports of the switch are connected directly to the 20 dB attenuators installed on each LISN;

+ The switching controller System Interface SI-300: being responsible for receiving commands from the computer via the GPIB port to control the output switching of the RSM-02 module; The connection between this module and the SI-300 controller is carried out using a fiber optic cable to avoid interference during the test.

Level of conducted emission caused by the EUT shown in Fig. 3 is calculated as:

$$EMI = Trace + CL + IL + ATT, \tag{2}$$

where $Trace$ is the noise level measured on signal analyzers N9000A, N9030A, or N9038A (all three models are supported in the test setup), while CL, IL and ATT have the same meanings as being in equation (1).

It can be seen from equations (1) and (2) that the accuracy of the test depends on the measurement accuracies of the involved signal analyzer, and value sets of CL, IL, ATT. In the TDK's test solution for the whole frequency range from 10 kHz to 10 MHz, the ATT value is always set to 20 dB at every measuring frequency point while the numbers of value points of CL and IL are relatively small (6 and 75 points, respectively). Therefore, it is possible to improve the accuracy of measurement by increasing the number of sampling points for CL and IL in combination with a compensation algorithm for the attenuator by examining its attenuation variations by frequency.

Software implementation

As suggested above, there are three problems to be solved in the implementation.

+ First, in formula (2), the value sets of $Trace$, CL, IL, ATT terms are different, so it is not possible to normally add these values. Indeed, as mentioned in the previous section, the CE102 test is divided into two measuring bands (band 1 from 10 kHz to 150 kHz, band 2 from 150 kHz to 10 MHz), each with different number of scanning points, N_p, given by:

$$N_p = \frac{f_{stop} - f_{start}}{\Delta f}, \tag{3}$$

where f_{stop} [MHz] is the ending point of the frequency band; f_{start} [MHz] is the starting point of the frequency band; Δf[MHz] is the frequency step. Consequently, the numbers of scanning points in band 1 and band 2 are 280 and 1970, respectively. Meanwhile, for the whole frequency range from 10 kHz to 10 MHz, it only needs at least 201 measuring points for each $Trace$, CL, IL, ATT that ensure the test's accuracy. Thus, the sets of $Trace$ values in measuring bands 1 and 2 have 280 points and 1970 points, respectively, while CL, IL, ATT all have 201 points in each band. To solve this problem, we propose using a linear interpolation algorithm as follows.

Representing the terms in formula (2) as a matrix, with $Trace$ being an $(n \times 2)$ matrix, of which the first column is the frequency vector of measuring points and the second column represents the measured $Trace$ value for each frequency; the remaining terms are matrices of the same size, $(m \times 2)$, in this case, $m = 201$ points. Then, formula (2) is recast as follows and is used in the software program to calculate:

$$\begin{aligned} EMI = Trace & \\ & + \text{interp1}(CL(:,1), CL(:,2), Trace(:,1)) \\ & + \text{interp1}(IL(:,1), IL(:,2), Trace(:,1)) \\ & + \text{interp1}(ATT(:,1), ATT(:,2), Trace(:,1)), \end{aligned} \tag{4}$$

where all terms now are matrices of the same size, $(n \times 2)$; $y_q = \text{interp1}(x, y, x_q)$ is the Matlab function for 1-D linear interpolation [8], interpolating sample points (x, y) to the coordinates of the query points (x_q, y_q). Thus, using a linear interpolation algorithm allows us to convert the terms/matrices in formula (2) originally of different sizes to terms/matrices of the same size as in (4) .

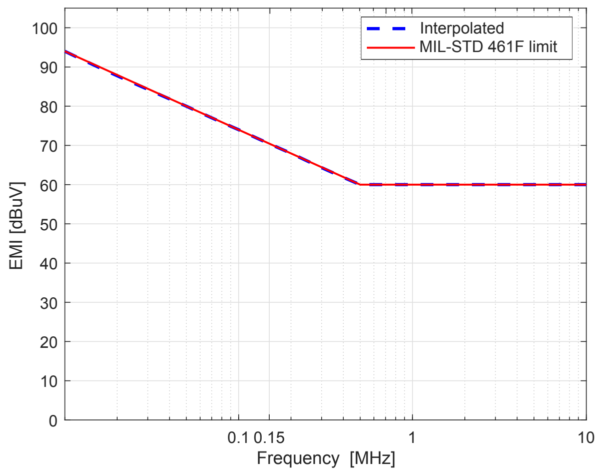

Fig. 4: MIL-STD 461F limit and its interpolated curve.

+ Second, to determine the conducted emission limit according to the CE102 MIL-STD 461F standard shown in Fig 1 for the frequency range of 10 kHz to 500 kHz, we choose 06 marking sample points as: (0.01, 94); (0.03, 84.3); (0.05,80); (0.1,74); (0.2,68); (0.5,60). Then using the log-log linear interpolation algorithm to calculate the interpolated values for the limit in this frequency range as:

$$\begin{aligned} &EMI_{Lim} = 10^{A}, \\ &A = \text{interp1}(log(F_b), log(V_b), log(Trace(:,1))), \end{aligned} \tag{5}$$

where EMI_{Lim} is the interpolated conducted emission limit; (F_b, V_b) are coordinates of 06 sample points determined above; Fig. 4 illustrates the interpolated limit acquired by (5), showing the reasonableness of the proposed numerical implementation that will be used for the experiment below. Noting here that, referring to Fig. 1, when using the 220 V source voltage, a displacement of 9 dB should be added to this curve.

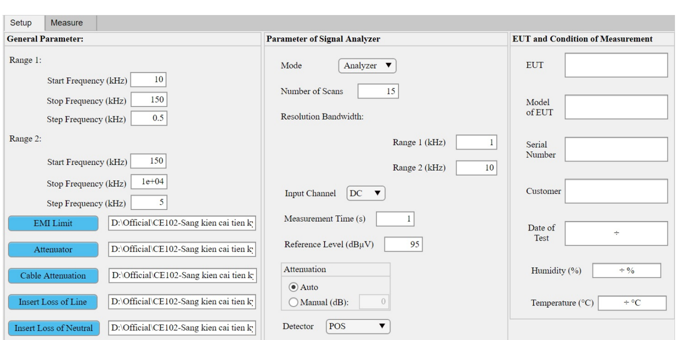

Fig. 5: Software interface for parameter setting and calibration.

+ Third, to increase the test accuracy, the software is supplemented with a tool set that allows to automatically determine and re-evaluate the insertion losses of attenuators, cables, connectors and LISNs in use. The software interface for this function is illustrated in Fig 5.

III. Experimental results and discussion

A. Measurement error analysis

This section concentrates on the evaluations of measurement errors of TDK's conducted emission test (shown in Fig. 2) and the proposed test (shown in Fig. 3).

For the TDK's test, the systematic error includes the following components: measurement error of the N9038A signal analyzer, error of the 20 dB attenuator, insertion loss errors of LISN EM7825-3 sets, cables, connectors in use.

+ For the N9038A signal analyzer: According to its data sheet, for the frequency range from 10 kHz to 10 MHz, there is a measurement error of ± 0.5 dB [7] (laboratory conditions);

+ For the set of 02 LISN EM7825-3 having been tested and calibrated by Keysight in 2019, measurement error is of ±0.66 dB;

+ For the Fairview SA3N10-20 20-dB attenuator: According to its data sheet, the error is of ± 0.6 dB;

+ For cables and connectors in the low frequency range from 10 kHz to 10 MHz, the attenuation value is about 0.3 dB at every frequency point, so their errors can be ignored;

Thus, the TDK test's systematic error would be

$$\Delta_{\text{TDK}} = \pm\sqrt{0,5^2 + 0,66^2 + 0,6^2} = \pm 1,02 \text{ dB}. \tag{6}$$

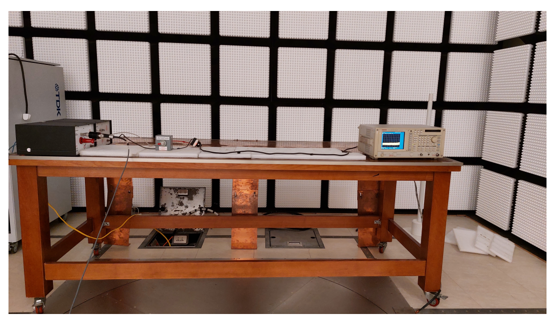

Fig. 6: The conducted emission test setup with spectrum analyzer R3162 as an ETU.

For the proposed test, the attenuation variations by frequency of the 20 dB attenuator are compensated for by the software, thus the error of this attenuator could be considered as 0. Consequently, the proposed measurement system's error only includes insertion loss errors of LISN EM7825-3 sets and the measurement error of signal analyzers CXA N9000A (±0.6 dB [5]) / PXA N9030A (±0.19 dB [6]) / MXE N9038A (±0.5 dB [7]). Hence the systematic error for each case is as:

$$\Delta_{\text{N9000A}} = \pm\sqrt{0,6^2 + 0,66^2} = \pm 0,89 \text{ dB} \tag{7}$$

$$\Delta_{\text{N9030A}} = \pm\sqrt{0,19^2 + 0,66^2} = \pm 0,69 \text{ dB} \tag{8}$$

$$\Delta_{\text{N9038A}} = \pm\sqrt{0,5^2 + 0,66^2} = \pm 0,83 \text{ dB}. \tag{9}$$

Hence, using the compensation tool, our proposal outperforms the TDK's scheme in terms of measurement error, even with the low-cost X-Series N9000A CXA signal analyzer. This will be demonstrates right below.

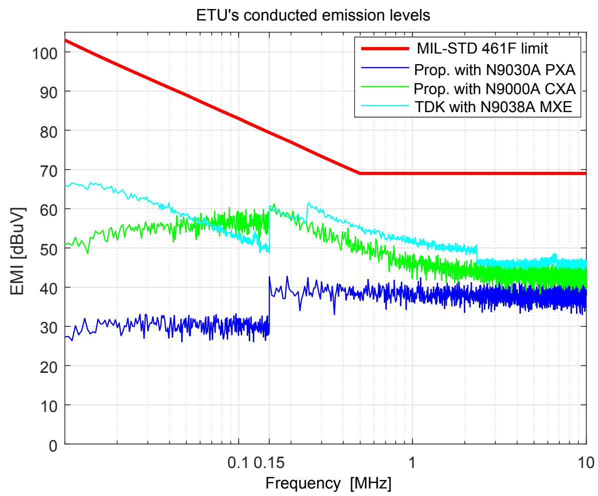

Fig. 7: Conducted emission test results.

B. *Test measurement results and discussion*

Using an Advantest R3162 spectrum analyzer as the EUT for all tests carried out in the same conditions, we compare effectiveness of the TDK's and proposed solutions by measuring the CE102 conducted emissions on the Line wire. The TDK's test uses N9038A while our proposed scheme utilizes N9000A, N9030A signal analyzers. Results shown in Fig 7 reveal that:

- For such EUT, the conducted emissions on the Line wire are relatively small, even almost non-existent; The measured results in the figure are mainly the background noises of the analyzers and the LISNs; On the other hand, as required in the calibration steps of the CE102 measurement, the better the noise level measured during calibration/background measurement is as far away from the limit curve as possible (the minimum requirement is 6 dB below the limit curve to ensure measurement conditions);
- The EMI measured by the proposed solution using the N9030A is the lowest, followed by the case of using the N9000A except in the frequency range from 50 kHz to 150 kHz being higher than that in the case of TDK's test using the N9038A; These results are achieved because the background noise of N9030A is the lowest among all analyzers used; The low-cost X-Series N9000A used in our solution could give more delighted results than what yielded by the high-price N9038A involved in the TDK's scheme.

IV. Conclusion

This work has proposed and successfully implemented a fully automatic system for measuring conducted emission on power lines, frequency range of 10 kHz to 10 MHz under the MIL-STD 461F Standard. The solution could supports multiple signal analyzer models (N9000A, N9030A, N9038A) to perform CE102 tests. This allows diverse measurement alternatives depending on the equipment availability or measuring performance requirement. Also, this solution fully automates the CE102 test from the selection control of the conducted emission measurement on the Line or Neutral wires to the extraction of processed results to the Certification sheet. This increase the stability, reliability and confidence of the test and vastly reduces the measuring and post-processing times. Last but not least, the solution also integrates a compensation algorithm for the losses of attenuator, connection cables and LISNs involved in the measurement to help in increasing the accuracy of the measured results compared to that of the TDK's solution.

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