FAST EMISSION MEASUREMENT IN TIME DOMAIN

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Abstract: According to the standards, emission measurements are carried out in the frequency domain using a test receiver. In this paper the setup and algorithm of a measuring system in the time domain is presented. The advantage of this system is, that measurements can be done approximately 10 to 20 times faster. The paper shows a proposal for the use of the system in standard EMC tests. Since EMC tests are quite expensive, this measuring system offers an easy possibility to reduce EMC related costs of product development.

1. Introduction

Emission measurements for the EMC check of a device must be carried out (according to the standards [3],[4]) in the frequency domain with e.g. a test receiver. It is necessary to execute a frequency sweep and to measure the emission at each frequency. This method has the disadvantage that the measurement lasts, depending on the selection of the parameters, for a quite a long time (typically 10 to 30 min). Since a long measurement always implies high costs, it is profitable to look up for possibilities to shorten the measurements without a loss of quality.

In particular, the measurement in the time domain provides a good possibility to save time. Instead of measuring in the frequency domain with a test receiver several single shots are recorded with an oscilloscope. From these data a comparable spectrum can be calculated by using the Fourier transformation and several corrections and filterings. In this paper the time domain measuring system FEMIT (**F**ast **E**mission **M**easurement **I**n **T**ime Domain) is described in detail and compared with the test receiver on the basis of two EUTs.

2. Measurement setup

When measuring in the frequency domain the signal is directly recorded with the test receiver, which executes a frequency sweep. This measuring setup in comparison to FEMIT is shown in Fig. 1.

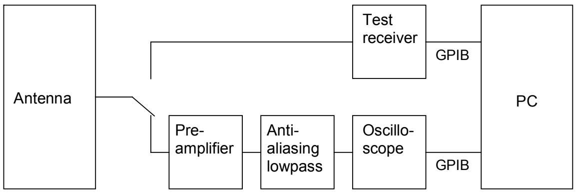

Fig. 1: Measurement setup

With FEMIT it is, depending on the level of the measuring signal, often necessary to use a preamplifier if the lowest measuring range of the oscilloscope is not sensitive enough. To make sure, that the sampling theorem is kept, an appropriate anti-aliasing lowpass should be connected in series to the oscilloscope. The data records are transmitted via GPIB bus from the oscilloscope to the PC.

3. Fourier transform

The transition from the time domain into the frequency domain is carried out via the Fourier transform:

$$X(\omega) = \int_{-\infty}^{+\infty} x(t)\, e^{-j\omega t}\, dt \tag{1}$$

Since a discrete data vector is obtained from the oscilloscope, it is necessary to use the Discrete Fourier Transform (DFT),

$$X_{DFT}(k) = \sum_{n=0}^{\mathrm{N}-1} x(n)\, \mathrm{e}^{-\mathrm{j}\,2\pi k n/\mathrm{N}} \tag{2}$$

where $x(n)$ are the input values and $X_{DFT}(k)$ gives the complex frequency domain waveform. To approximate the Fourier transform of a continuous, periodic signal $X_{kont}(k)$ by the DFT, the result of the DFT has to be normalized on the number of points N:

$$X_{kont}(k) = \frac{1}{\mathrm{N}} X_{DFT}(k) \tag{3}$$

The energy of the signal at a frequency k is distributed equally between the first and second halves of the spectrum. However, the energy at frequency zero is completely contained in the zero term. Therefore, only the first half of the spectrum up to the Nyquist frequency is kept and (except the DC component) doubled. Subsequently, the absolute value of the spectrum is determined to get data comparable with measurement data of the test receiver. The complete transformation used in FEMIT is given in equation (4) :

$$X_{FEMIT}(k) = \frac{2}{\mathrm{N}} \left| \sum_{n=0}^{\mathrm{N}-1} x(n)\, \mathrm{e}^{-\mathrm{j}\,2\pi k n/\mathrm{N}} \right|, \; k = 1 \ldots \frac{\mathrm{N}}{2} - 1 \tag{4}$$

$$X_{FEMIT}(0) = \frac{1}{\mathrm{N}} \left| \sum_{n=0}^{\mathrm{N}-1} x(n) \right|$$

4. Algorithm of evaluation

4.1 Overview

To increase the precision of the algorithm, two sets of oscilloscope measurements are acquired. The first set is captured with trigger level zero, the second set with maximum trigger level.

Each measurement in the time domain is transformed into the frequency domain by the Fourier transform. Then for both sets of spectra the maximum is calculated. Then, the data are smoothed and corrected. At last, the average of the two results is determined (Fig. 2).

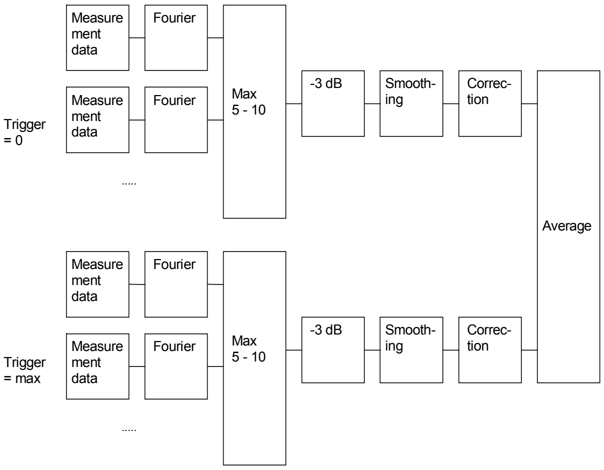

Fig. 2: Algorithm of evaluation

4.2 Data acquisition

The result of the Fourier transform depends on the settings of the oscilloscope. Two parameters have to be properly adjusted: the sampling frequency f_s and the capture time T.

4.2.1 Sampling frequency f_s

According to the sampling theorem the required sampling frequency equals twice the wanted maximum frequency (Nyquist frequency) of the calculated spectrum. To avoid aliasing errors it is recommended to set the sampling frequency 2 to 4 times higher.

4.2.2 Capture time T

The distance between the center frequencies of two neighbouring bins (frequency resolution) Δf depends on the capture time (duration of the time domain record) T :

$$\Delta f = \frac{1}{T} \qquad (5)$$

For two reasons it is important to make the Δf equal to the step size of the frequency domain measurement.

- *Narrowband signals*

The magnitude of the peak in the spectrum of a narrowband signal depends on its frequency. If the frequency corresponds to a frequency step of the DFT, the magnitude is calculated correctly. However, if the frequency is located between two DFT frequency steps, the magnitude is reduced by 3.92 dB. This is called “leakage”, the loss itself “scallop loss”. This effect can also be observed in frequency domain measurement with the test receiver if Δf is equal to the step size, as shown in Fig. 3.

If the frequency resolution of the DFT is doubled, the narrowband signal between two frequency steps, would again meet a frequency step and would therefore not be reduced. Theoretically, this result is correct, but since the measurement of the test receiver is interpreted as a reference, the reduction of 3.92 dB is the wanted result.

Therefore, the capture time T has to correspond to the frequency step size according to equation (5).

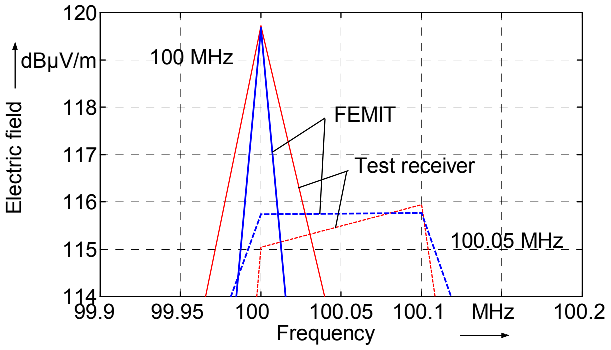

Fig. 3: Scallop loss (100 MHz and 100.05 MHz sine, Δf = 100 kHz)

- *Broadband signals*

Another reason for the described selection of T is the processing of broadband signals in the DFT. If the frequency bins Δf become smaller (wider), the DFT collects less (more) signal energy in each bin, which leads again to a differing result.

4.2.3 Typical settings

Taking this into consideration the following settings for a standard radiated emission measurement are obtained:

	Sampling rate	Capture time	Number of points
biconical antenna (... 230 MHz, Δf = 100 kHz)	1 GS/s	10 µs	10 000
log. per. antenna (... 1 GHz, Δf = 100 kHz)	4 GS/s	10 µs	40 000

Table 1: Settings for typical frequency bands (radiated emission measurement)

4.3 Fourier transform

The acquired data are transformed via the DFT into the frequency domain as described in equation (4).

4.4 Maximum of several measurements

The accuracy of the result can be increased, if the spectra of more than one measurement are considered.

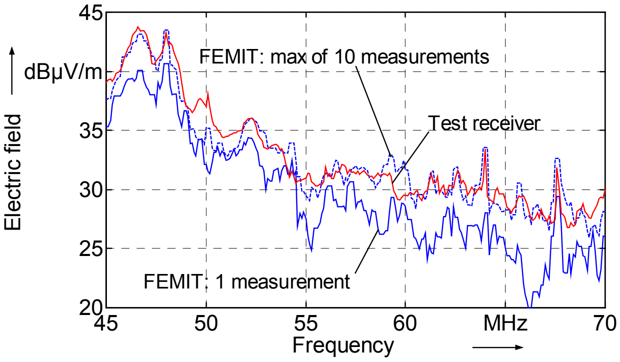

Fig. 4: Effect of maximum determination

Therefore, it is necessary to calculate the spectra of several measurements and to calculate for each frequency the maximum value of the spectra. Thus, the spectrum becomes smoother. It is meaningful to use the maximum (and not for example the average value) because it is better to get the worst case then to underevaluate the EUT.

Comparative investigations have shown, that it is best to use approximately 5 to 10 measurements. As shown in Fig. 4, the maximum of 10 spectra is close to the test receiver measurement. If less than 5 measurements are taken, the signal is being underestimated. Are more measurements used, the time requirement for the computation rises without substantial improvement of the quality of the result.

4.5 Smoothing

In particular within the area of broadband disturbances the calculated spectrum is noisy. In order to find the best approach to the test receiver measurement it is advisable to smooth the spectrum. Therefore, a window of odd point length is shifted over the curve. At each frequency the maximum of the neighbouring values in the window is determined. Thus, each value is replaced by the maximum value from its environment and the curve is thereby smoothed. The average value from the window must not be used since the amplitudes of narrowband peaks would be completely falsified. In Fig. 5 the smoothing effect using three points is shown.

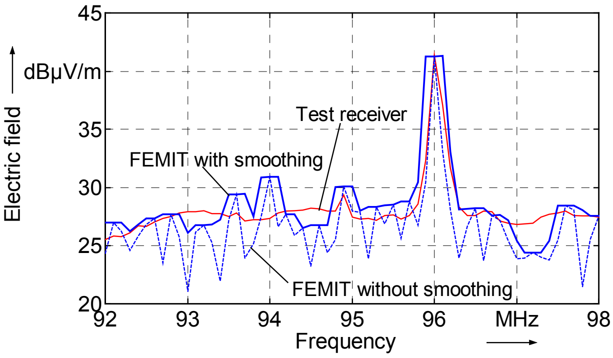

Fig. 5: Effect of smoothing with the 3-point-window

This algorithm shows the side effects that narrowband peaks are widened to the length of the smoothing window. An useful window is the 3-point window.

4.6 Correction

The test receiver always gives the RMS value of a signal. The DFT however calculates the peak values. In order to adjust this difference, the DFT results must be divided by $\sqrt{2}$ (or reduced by 3 dB). The spectrum determined up to this point represents the spectrum of the antenna base voltage. For the conversion into the field strength *E* the antenna factor provided by the antenna manufacturer is added. Finally, the gain of the amplifier is corrected.

A resulting correction curve containing all adjustments can also be obtained by calculating the difference between the FEMIT spectrum an a test receiver reference spectrum.

4.7 Averaging

4.7.1 Influence of the trigger level

If the signal is unknown, there are basically two possibilities of triggering. On the one hand side the trigger level can be set to zero. This produces coincidental triggering. On the other hand side the level can be set to maximum, so that triggering is still possible. With this method the part of signal with the highest amplitude is found. The best approximation to the reference spectrum of the test receiver can usually be achieved if the described measurement and analysis algorithm is applied on measurement sets with both trigger levels and the average value at each frequency is calculated. The corresponding background is described in 8.1 "Influence of pulse repetition rate".

4.7.2 Example

This effect is shown in Fig. 6 by means of the example of a robot cell. Besides the reference spectrum of the test receiver the FEMIT spectra resulting from zero triggering and maximum as well as their average value are shown.

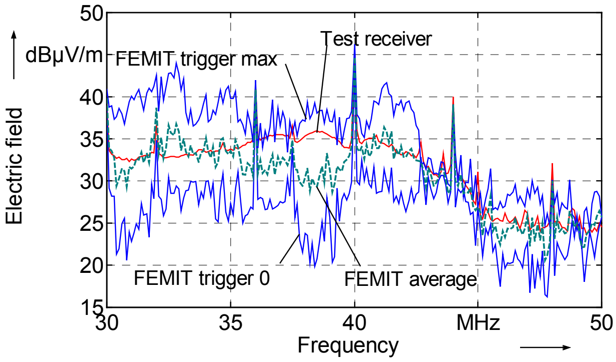

Fig. 6: Effect of averaging

5. Comparison: test receiver – FEMIT

In this section the quality of the measuring system FEMIT is demonstrated by the example of two different EUTs. The radiated emission in the frequency range of the biconical antenna (30 - 220 MHz) is measured. In the case of a complete measurement up to 1 GHz nothing changes in the methodology except for the increase of the sampling rate and the use of the logarithmic-periodic antenna.

For the test receiver measurements according to the standards the quasi-peak detector is used.

5.1 Robot cell

In co-operation with the IPR (Institute for process control and robotics) of the University of Karlsruhe, the emission of a robot cell was measured. The entire robot cell is illustrated in Fig. 7. In Fig. 8 the results of the two measurements are presented, in the following figure (Fig. 9) a zoom view (100 to 110 MHz) within the area of the highest peak is shown for a more detailed comparison of the spectra.

Fig. 7: EUT robot cell

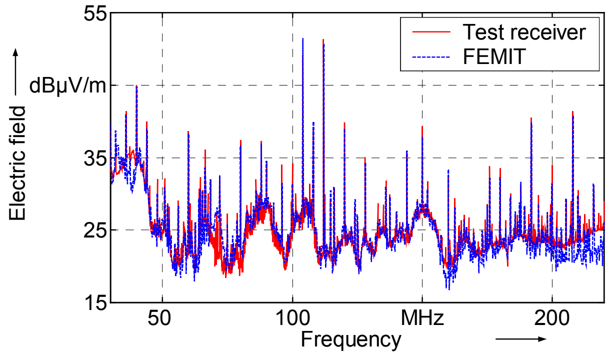

Fig. 8: Overview emission (robot cell)

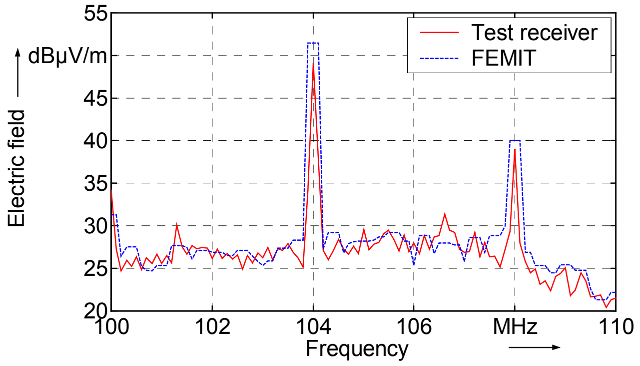

Fig. 9: Zoom emission (robot cell)

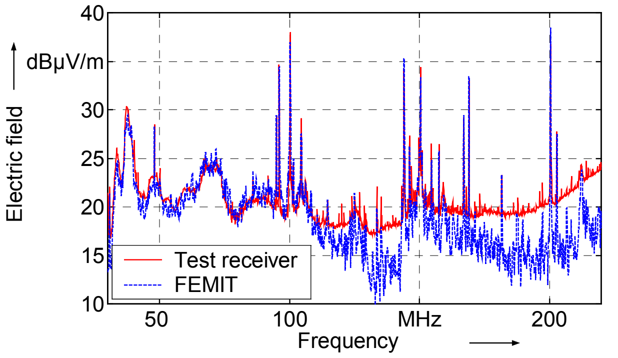

Fig. 10: Overview emission (PC)

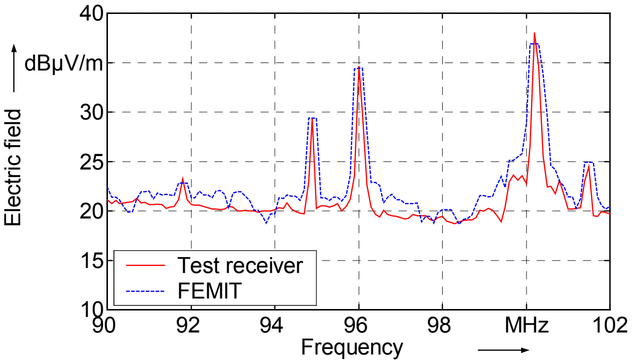

Fig. 11: Zoom emission (PC)

5.2 Personal computer

The second EUT is a commercial PC with 266 MHz clock frequency.

As demonstrated in Fig. 10, the noise level in the time domain measurement is lower (!) than in the test receiver measurement. The reason for this is the high quality of the used preamplifier.

6. Reduction of time consumption

6.1 Comparison: test receiver – FEMIT

As initially described, the main advantage of the emission measurement in the time domain is time saving. Table 2 shows the time required for a measurement with test receiver and with FEMIT by the example of the frequency range of the biconical antenna (30 - 220 MHz).

	Test receiver (quasi-peak)	Test receiver (peak)	FEMIT
Time required	40 min	9 min	0.5 to 1 min

Table 2: Comparison of time required

According to the standards it is obligatory to measure 1 s per frequency step with the quasi-peak detector, which adds up to a measuring time of approx. 40 min. An acceleration can be achieved by using the peak detector (100 ms/step). In this case still approximately 9 min are needed. However, it is necessary to recheck frequency ranges with quasi-peak detector where the result exceeds the limit line.

With FEMIT the time required is approximately 30 s to 1 min. In FEMIT this time is mainly needed for the analysis. The time consumption depends strongly on the computer and the used programming language. In case of exceeding the limit value a recheck with the test receiver is obligatory. Thus, measurements can be done 10 to 20 times faster using FEMIT!

6.2 Example

The following example shows, that it is possible to get even *more exact* results with smaller expediture of time using FEMIT. According to the standard it is prescribed to find the direction of the maximum emission and to measure from that direction. However, this is rarely done in practice for time reasons. The emission of the PC (266 MHz clock frequency) was measured from four directions by the test receiver and by FEMIT.

For both measurements the maximum and the minimum of the spectrum was formed. The maximum represents the maximum radiation of all directions and indicates thus the measurement required according to standard. The minimum represents the measurement obtained in the most unfavourable case, when the measurement is carried out only from one direction which happened to be the one of the lowest emission level.

A comparison of these spectra is given in Fig. 12. The difference between the maximum and minimum spectra of the test receiver (and therefore the error) amounts to 10 dB. However, the maximum spectrum of FEMIT is very close to the reference spectrum. Considering that even four FEMIT measurements require less time than one measurement with the test receiver, FEMIT provides not only a time but also *a quality advantage*.

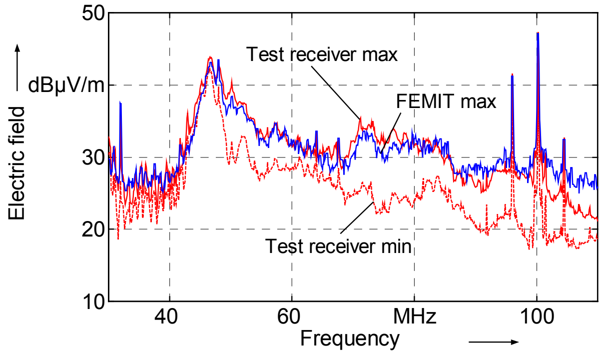

Fig. 12: FEMIT-max., test receiver max. and min. (over angle)

7. Accuracy

In this chapter the differences between FEMIT and the test receiver measurements are presented by the example of the robot cell and the PC. The results of the test receiver are interpreted as a reference. Therefore, the difference gives the error of FEMIT. The difference of the robot cell is shown in Fig. 13.

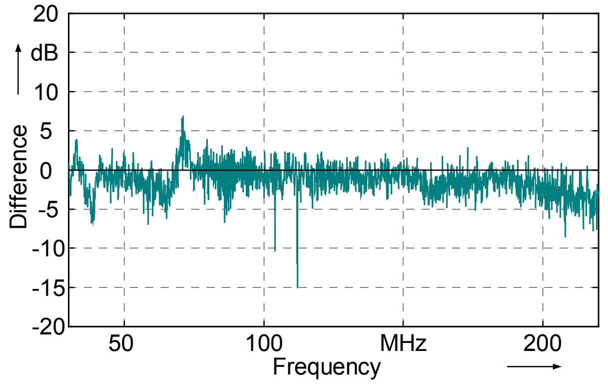

Fig. 13: Difference between test receiver and FEMIT (robot cell)

The recognizable peaks between 100 and 120 MHz do not represent deviations in the sense of an error. High narrow-band peaks with slightly different slopes (refer to Fig. 9) produce large deviations when determining the difference.

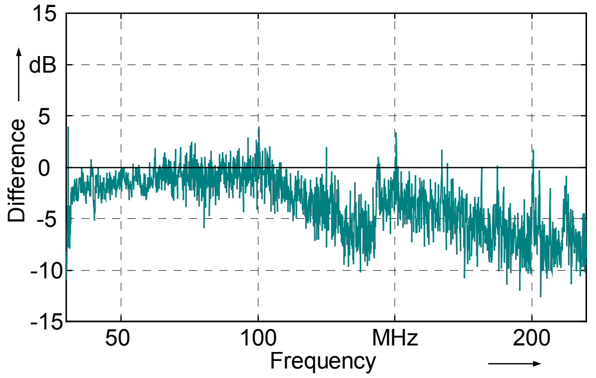

Fig. 14: Difference between test receiver and FEMIT (PC)

In Fig. 14 the difference for the PC is shown. Since in this measurement the noise level of FEMIT is lower (refer to Fig. 10), the deviations in the upper part of the spectrum represent no errors. These deviations result of the fact, that in these ranges FEMIT is more exact than the “reference measurement” of the test receiver.

The analysis of the measurements and differential curves shows that the typical error of FEMIT is mostly below 2 to 3 dB. Larger deviations are to be found when the signal contains pulses of low repetition rate as described in 8.1.

8. Limits

8.1 Influence of pulse repetition rate

Higher deviations between FEMIT and the test receiver can be found with pulses of a repetition rate lower than the frequency resolution $\Delta f = 100$ kHz. The lower the repetition rate of this signal, the more it is damped by the quasi-peak detector of the test receiver following the pulse response characteristic in Fig. 15 as prescribed in the standards [5].

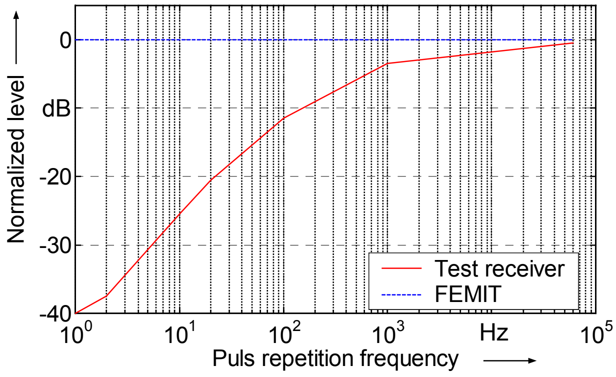

Fig. 15: Pulse response characteristic (quasi-peak detector, 30-1000 MHz, according to standards)

However, in measurements with an oscilloscope a pulse can always be found when the trigger condition is met, no matter how often it occurs. This means that all pulses with a repetition rate < 100 kHz (distance between two impulses > capture time *T*) result in the same spectrum. Due to this fact the "pulse response characteristic" of FEMIT is a line at 0 dB. The distance between the two curves equals the difference between the spectra of FEMIT and the test receiver. For instance, the test receiver spectrum of a 1 kHz-pulse is about 3 dB, the spectrum of a 100 Hz-pulse is about 11 dB lower compared with FEMIT. For this reason higher differences between FEMIT and the test receiver can be found if the signal contains pulses with high amplitude and low repetition rates.

In an EMC measurement primarily the highest levels in the spectrum are important. These are mostly represented by narrowband peaks. Thus, the error induced by the described pulses is only significant, if there are no dominating narrowband peaks in the spectrum (e.g. brush discharge of a motor or welding process). However, since FEMIT gives in this case higher levels the EUT is never underestimated. The averaging of measurements with different trigger levels (as described in 4.7) is a step to compensate this effect. If the trigger level in the second part of the measurements is set to zero, less pulses are found and thus the calculated spectrum is lower.

8.2 Dynamic range

The dynamic range of a digital oscilloscope is limited by the number of bits used for representing the signal. In Fig. 16 the spectrum of a 100 MHz sine measured by FEMIT is shown. For the measurement, the vertical gain of the 8 bit-oscilloscope was adjusted best to the amplitude of the sine. As to be seen in the figure, in this case the dynamic range amounts to approximately 55 dB.

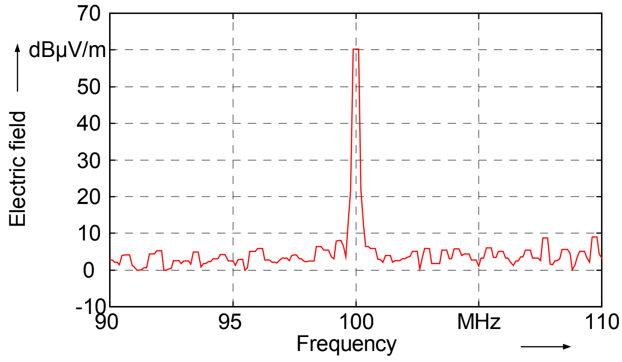

Fig. 16: Dynamic range

If the signal amplitude is lower, the signal is represented with less bits and the dynamic range decreases.

8.3 Widening of narrowband peaks

If a sine wave has a whole number of periods in the time domain record (sine frequency = DFT frequency step), the spectrum will have a sharp peak corresponding exactly to the frequency and amplitude of the sine wave. Otherwise the spectrum peak will be broader and lower (refer to 4.2.2).

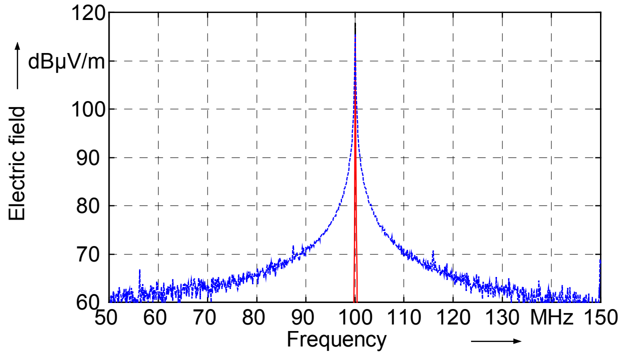

Fig. 17: Sine (100.05 MHz) between the center frequencies of two neighbouring bins

This effect is shown in Fig. 17. When measuring with the test receiver, this effect does not occur. However, this error is only noticeable, if the regarded peak stands out very far from the noise level (more than 20 dB).

8.4 Instrumentation

As described in 4.2 a digital oscilloscope with at least 1 GS/s sampling rate and 10 kBytes memory size is necessary (this allows measurements up to 250 MHz). For measurements up to 1 GHz 4 GS/s and 40 kBytes memory must be available.

9. Proposal for application

As stated above, FEMIT helps to save time. Since the time required for EMC emission measurements is quite high, it is possible to reduce costs by using this time domain measuring system. However, FEMIT cannot completely replace frequency domain measurements, because the latter measuring method is prescribed in the standards.

Here are several proposals for the use of FEMIT:

- *Critical frequency ranges*

In a standard emission measurement it is checked, whether the emission level of the EUT is below or above the permitted limit. With FEMIT a quick preview of the spectrum can be obtained. In frequency ranges, where the level is clearly situated below the limit line (e.g. at least 6 dB), this result can be accepted. Only in critical frequency ranges the exact emission level must be controlled with the test receiver. Depending on the emission level of an EUT, it is possible to save a lot of time using this measuring system.

- *Repeated emission checks*

In the process of reducing the emission of a device, the effects of different disturbance suppressions can quickly be observed and judged by using FEMIT.

- *Measurement of short phenomena*

The time domain measurement is the only possibility to determine the spectrum of a short phenomenon (e.g. flashover, switching impulse).

- *Direction of the highest radiation*

According to the standards, measurements must be carried out from the direction of the maximum radiation. FEMIT is adequate to find this direction quickly. As already mentioned, this is often omitted in practice. Here, FEMIT helps to improve the quality of emission measurement (refer to chapter 6.2). The same possibility of acceleration is given when executing the prescribed height scan.

10. Conclusions

The time domain measurement system FEMIT executes emission measurements approximately 10 - 20 times faster than a test receiver. The error of the result depends on the signal. Usually the error is lower than 2 to 3 dB. In the case of dominating pulses with high amplitude and very low repetition rate the error can be higher.

FEMIT is an adequate measuring system for quick previews and repeated checks of the emission of an EUT. Also, it could be used for standard emission measurements, if critical frequency ranges are rechecked with the test receiver.

11. References

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