Saturation of Active Loop Antennas

Alexander Kriz
EMC and Optics
Seibersdorf Laboratories
2444 Seibersdorf, Austria

***Abstract*—The EMC community is working towards shorter test distances for radiated emission measurements in the frequency range from 9 kHz to 30 MHz. This would reduce the cost for testing dramatically since typical absorber lined shielded rooms can be used for magnetic field strength measurements. The reduction of the test distance will lead to higher emission limits. In combination with pulsed signals commercially available active loop antennas are not suitable due to insufficient dynamic range. Measuring a 2 % duty cycle signal will increase the dynamic range by 30 dB. Pulsed signal have to be taken into consideration because pulse width modulation is one of the possibilities to control power in wireless charging applications.**

Keywords*—*magnetic field measurement; active loop antenna;amplifier saturation; emission measurement; saturation indication

I. INTRODUCTION

Active loop antennas are widely used for radiated emission testing in the frequency range from 9 kHz to 30 MHz; applicable standards are CISPR 11 [1], CISPR 14-1 [2] and ANSI C63.4 [3]. They are required since emission limits are low due to a historical test distance of 30 m. This large test distance is inconvenient for the test labs due to large required space outside the building. The use of anechoic environments is established for emission measurement since more than two decades with several good reasons. So the EMC community is seeking for a test distance of 10 m or even 3 m with the advantage that emission tests are carried out in facilities which are built for the range above 30 MHz. Ongoing activities in several committees of CISPR support this demand. With decreasing distance the emission limits have to be increased to protect radio services at the same level.

In principle an active antenna is a combination of a passive antenna and a preamplifier. For EMC measurements preamplifier are generally not recommended due to overload. In CISPR 16-1-1 [4] extensive discussion of advantages and disadvantages can be found. In the relevant standards no specification of loop antennas can be found, except a maximum size requirement. Overload and saturation effects of active antennas are barely mentioned; only a reminder that saturation indicator lamps shall be observed is found.

Typical equipment with emissions below 30 MHz is induction cooking appliances, but the number is growing with large TV sets and wireless charging devices.

II. EQUIPMENT UNDER TEST

Although induction cooking appliances and wireless charging stations serve completely different purposes, the systems have a similar topology, see Fig. 1. After the AC power from the mains is rectified to DC, high frequency power is generated by an inverter. A strong magnetic field is generated by the working coil. In case of an induction cooking appliance the magnetic field is absorbed by a suitable pan and transformed into heat. Wireless charging systems have a second coil, which feeds the charger for the batteries. Depending on the application the transferred power reaches from a few watts for smart phones to several kilowatts for electric vehicle. The frequency range of the inverter ranges from 24 kHz for induction cooking [5], 85 kHz for Wireless Electric Vehicle Charging (WEVC) [6] to 100 kHz to 205 kHz for wireless power transfer (WPT) for smart phones [7].

Common for all systems is a control functionality of the transferred power. There are several possibilities to perform this task:

- Change of the DC output voltage of switched-mode power supply.
- Change of the inverter frequency in resonant systems. By detuning the circuit the current in the working coil and so the power is reduced.
- Pulse-width modulation of the inverter.

Pulse-width modulation is the most interesting in the view of an EMC engineer. This means the generated disturbance is not a CW signal with harmonics but a pulsed signal. WPT systems [7] specify a duty cycle from 2 % to 50 %.

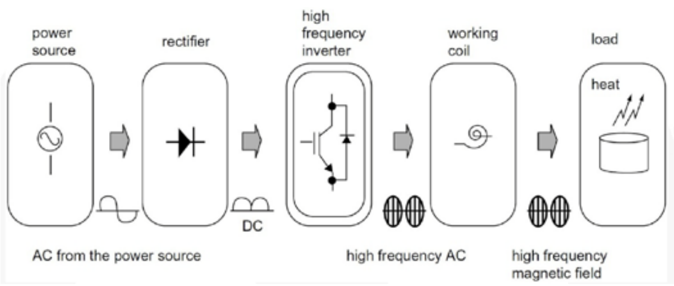


Fig. 1. System topology of EUT from [5]

III. AVAILABLE ANTENNAS

A. Specification

Since decades several manufacturers offer active loop antennas. They differ in diameter and in dynamic range, see Tab. 1. Specifications of the antenna diameter can be found at CISPR 16-1-4 [8]. The loop antenna shall fit into a square with 60 cm diameter. Requirements on dynamic range are not given.

Typically the upper end of the dynamic range is defined by the 1 dB compression point. Most of the antennas have an indication for saturation.

TABLE I. COMMERCIALLY AVAILABLE ANTENNAS

Model	Specifications		
	Loop diameter [cm]	*Maximum field strength [dBµA/m]*	*Saturation indication*
#1	50	78.5	No
#2	30	82.5	Yes
#3	60	88.5	Yes
#4	49	78.0	Yes
#5	60	88.5	Yes
#6	59	88.5	No

In this paper measurements with model #1 and #2 are presented.

B. Calibration

Antenna calibration procedures can be found at CISPR 16-1-6 [9], ARP 958 [10] and IEEE Std. 291 [11]. All of them use CW signals for calibration and do not contain procedures to quantify saturation effects. Also methods to proof the effectivity of saturation indicators are not present.

IV. PROPERTIES OF PULSED SIGNALS

The properties of pulsed signals can be derived from the shape, see Fig. 2. The duty cyle D is the ratio between the active part T and the period P

$$D = \frac{T}{P} \qquad 0 < D < 1 \tag{1}$$

Since loop antennas are not sensitive to static magnetic fields, signals do not have a DC component.

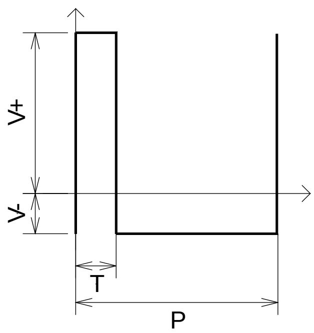


Fig. 2. Shape of a pulsed signal

So the area below the positive and negative pulse must be equal

$$V_+ D = V_-(1 - D) \tag{2}$$

The RMS power is calculated by

$$P_{RMS} = \sqrt{V_+{}^2 D + V_-{}^2 (1 - D)} \tag{3}$$

EMI receivers display the spectrum of the output voltage of the antenna. The fourier transformation is used to calculate the frequency domain X_k from the time domain x_n.

$$X_k \stackrel{\text{def}}{=} \sum_{n=0}^{N-1} x_n \cdot e^{-j2\pi kn/N}, \quad k \in \mathbb{Z} \tag{4}$$

The fundamental frequency is the spectral line where k=1.

To plot the power versus duty cycle normalization is required. In active antennas typically class AB amplifier or instrumentation amplifier are used. Their output swing is symmetrical around ground. Compression effects influence the output signal if V+ or V- overruns the output swing.

Fig. 3 shows the RMS power and the power of the fundamental frequency versus duty cycle of a pulsed signal of V+ = 1 V. Additionally the power of the sine wave with 1 V peak magnitude is plotted.

The RMS power is always larger than the power of the fundamental frequency. This is obvious because the harmonics contain the difference in power. At 50 % duty cycle both are above the CW power. The reason for this is that a rectangular signal contains more energy than a CW signal of the same peak voltage. With decreasing duty cycle the RMS power drops with 10 dB per decade while the power of the fundamental frequency drops with 20 dB per decade.

For a duty cycle of 2 % the fundamental is 28 dB below the CW signal. This fact is important if pulsed emissions are measured, because this relation is also valid at the compression point. This means if the EMI receiver shows a moderate signal magnitude, the active antenna can already be overloaded. This fact could be easily overlooked by the operator. Fault measurement can occur, if the antenna does not have a saturation indication or if this feature is not used.

V. SATURATION EFFECTS

Typically the 1 dB compression point is published in the datasheet of an active loop antenna. This property is measured with CW signals where the input power is increased until the gain of the internal amplifier drops by 1 dB. The same procedure can be applied with a pulsed signal. In this case the power of the fundamental frequency of the output is measured.

Fig. 4. shows the result of a simulation to investigate this effect. The output voltage of the simulated amplifier is limited by a defined voltage. If the voltage is below that the amplifier works in the linear range and no error occurs. Above this

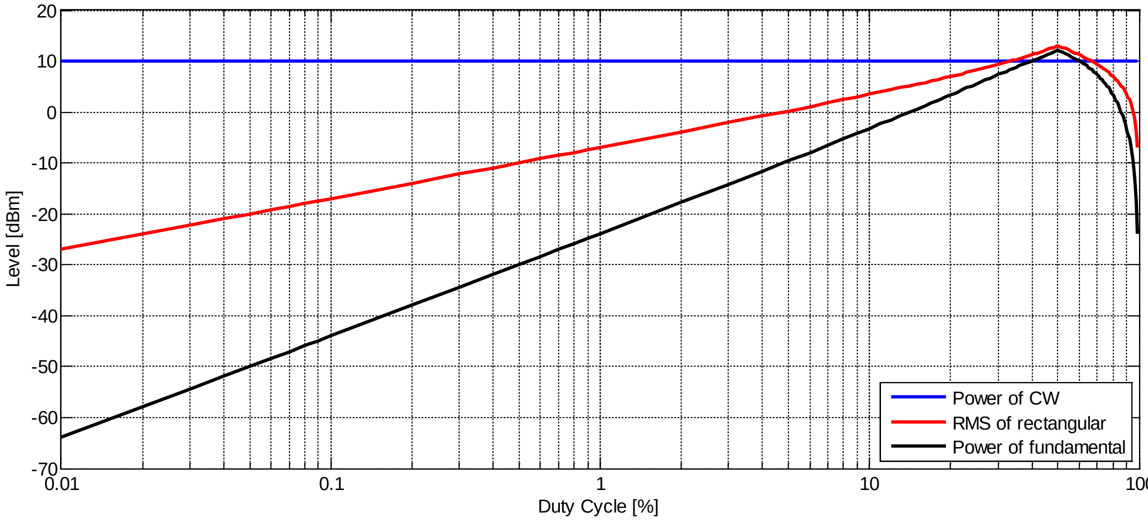


Fig. 3. Shape of a pulsed signal

threshold – normalized to 0 dB – saturation occurs.

For CW signals there is a smooth transition between linear range and compression. If a small part of the top of a sine is cut off, the power is not changed dramatically. For pulsed signals the effect of compression starts with a bend at the threshold. Above a linear trace can be observed.

To see a 1 dB compressed CW signal the voltage is 2 dB above the threshold. For a 1 dB compressed pulse the voltage is only 1.1 dB above the threshold. This behavior is independent from the duty cycle.

To eliminate the effect of saturation the maximum signal should be 2 dB below the 1 dB compression point. The instrumentation uncertainty of radiated emission measurements above 30 MHz is specified in CISPR 16-4-2 [12]. If this standard is extended to the range below 30 MHz, operation in the linear range is preferred to minimize the uncertainty. Otherwise an additional uncertainty contribution has to be taken into consideration.

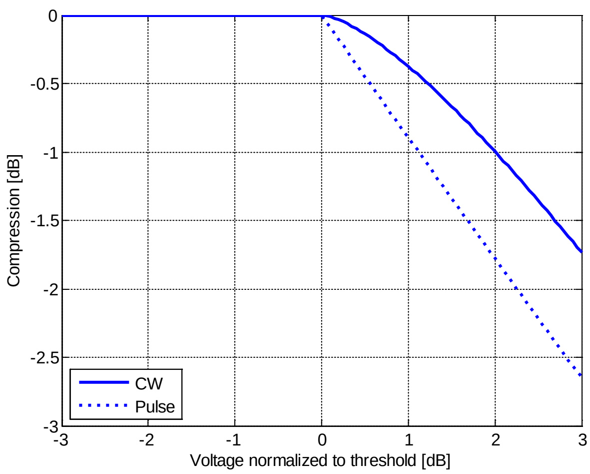


Fig. 4. Compression of signals

VI. Emission Limits

In CISPR 11 equipment is separated into groups and divided into classes with limits for each test distance, see Fig. 5. Due to this variety there are strong demands on the dynamic range of active loop antennas. The latest edition 6.0 from 2015 is responsible for wireless power transfer for instant power supply and charging purposes as group 2 equipment.

Even for CW signals not all products given in Tab. 1 are suitable for a test distance of 3 m, if a class A group 2 device is measured.

For a 2 % duty cycle pulsed signal the situation is worse. The saturation should be at least 28 dB above the limit, see Fig. 3. Furthermore amplifiers are more sensitive to compression for pulsed signals. To avoid saturation effects another 2 dB must be added, see Fig. 4. This means the antenna should have a dynamic range up to 112 dBµA/m, which cannot be fulfilled by any active antenna.

Induction cooking devices are covered by CISPR 14-1 and measured at 3 m distance. The largest limit for such devices is 69 dBµA/m in the frequency range 9 kHz to 70 kHz.

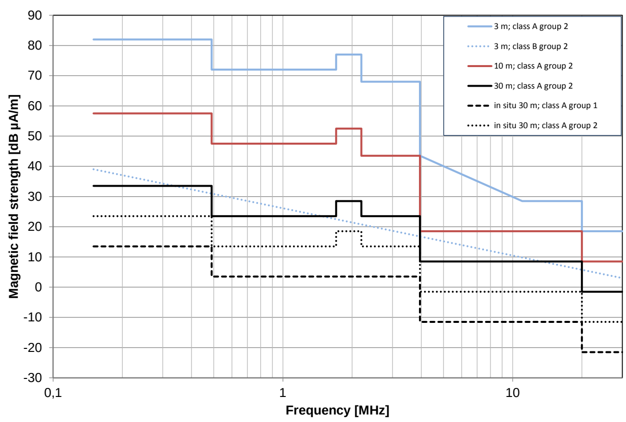


Fig. 5. CISPR 11 emission limits

VII. MEASUREMENTS

A test setup used for calibration of loop antennas is given in Fig. 6. An arbitrary waveform generator is used to generate a pulsed signal with a duty cycle from 1 % to 50 %. This signal is amplified and fed to a TEM cell. It is measured with an oscilloscope via attenuators from the cell output. The output of the active loop antenna is measured with an EMI receiver.

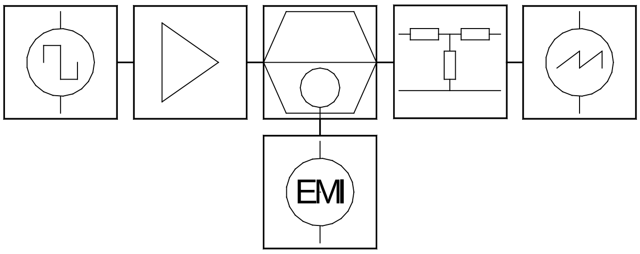
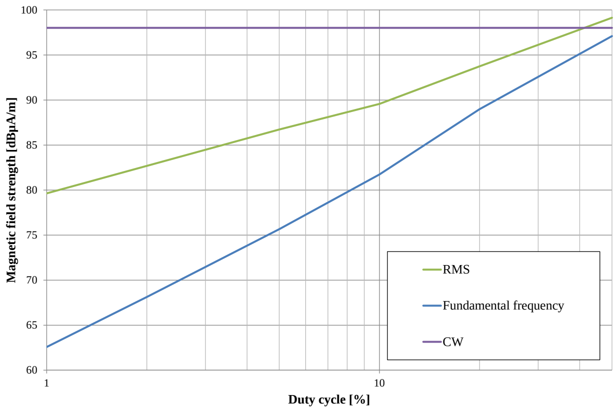


Fig. 6. Block diagramm of antenna calibration test setup

With this setup the 1 dB compression points are measured for the active antennas #1 and #2 of Tab. 1, see Fig. 7. The diagram shows the RMS power measured with the oscilloscope and the power of the fundamental frequency measured with the EMI receiver. Additionally the compression point for CW signals is plotted.

a)



b)

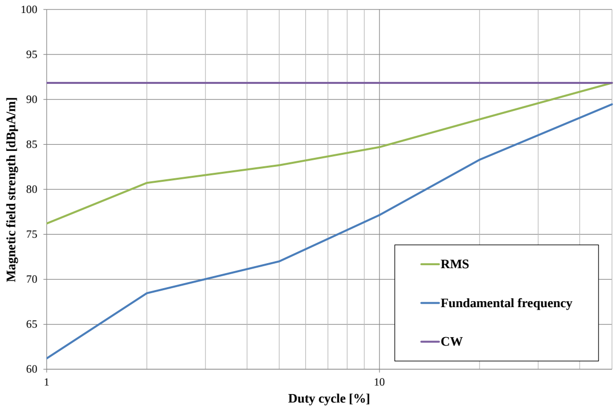


Fig. 7. Measured compression for pulsed signals of antenna a) #1 b) #2

Both diagrams look similar but have a difference in magnitude of approximately 7 dB. The reason for this is the difference in diameter and the gain of the internal amplifier. They show a good agreement with the calculated power in Fig. 3. Minor deviations occur due to measurement uncertainty and due to ringing close to the compression point of antenna #2. So the estimation of the requirement for additional dynamic range, if pulsed signal are measured, is valid.

VIII. SATURATION INDICATORS

Another important issue is the saturation indicator of active loop antennas. Although the majority of antennas are equipped with such indicators little information is present. Several important questions are not answered by their manufacturers in the data sheets:

- At which magnetic field strength does the indicator alert the operator?
- Is there a frequency dependency of this magnetic field strength?
- When the indicator alerts is the antenna still in the linear range or does compression already occur?
- Is the indicator sensitive to peak, average or RMS power?
- How long after a single overload does the indicator show the alert?

So the manufacturers are requested to give further information on the principle of the saturation indicator and the proper use.

With the test setup of chapter VII it is possible to determine the effectiveness of the indicator. When measuring the compression point the magnetic field strength at which the indicator alerts is also recorded. For antenna #2 this measurement is performed and showed in Fig. 8. The diagram shows the level at which the indicator alerts relative to the 1 dB compression point. So the indicator responds at least 2 dB below the compression point which means in the linear range of the amplifier. It works wells for pulsed signals with a duty cycle between 1 % and 50 %. If the indicator is sensitive to single pulses was not tested. Also the frequency dependency is out of scope of this paper.

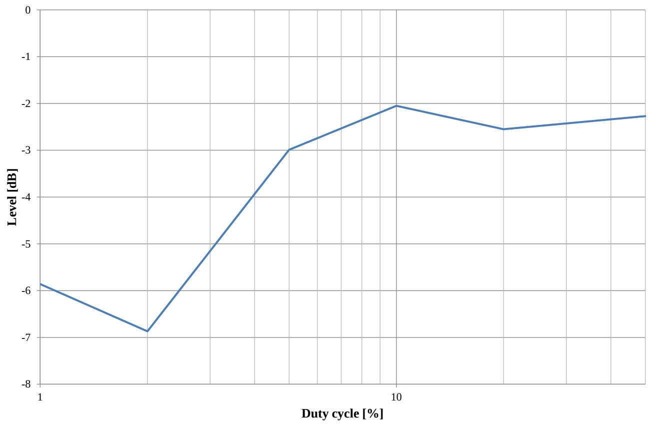


Fig. 8. Effectivity of saturation indication

IX. Compression Detection and Avoidance

The previous chapter showed that the saturation indication works effectively for pulsed signals. However observing a LED of an antenna inside a shielded room is inconvenient. Therefore the manufacturer offers a fiber optic extension to root the light outside the room. Other products increase the supply current of the antenna to alert the operator.

If an antenna does not have a saturation indication the wave shape of the emission must be known. If it is unknown an oscilloscope must be used to see if it is CW or pulsed signal and to determine the duty cycle.

There are limited methods to avoid compression. One is to increase the test distance but this is not an option for the majority of the operators. So switching to another antenna model with larger dynamic range or less sensitivity is one possibility. The easiest method to avoid saturation is to use a passive antenna.

The antenna factor of a passive antenna decreases with 20 dB per decade for lower frequencies and is flat for higher frequencies, see Fig. 9. Between 100 kHz and 200 kHz the antenna factor is approximately 10 dBS/m. The dynamic range of an EMI receiver in band B is typically from 10 dBμV to 137 dBμV. This leads to a dynamic range for magnetic field strength measurements from 20 dBμA/m to 147 dBμA/m since cable loss can be neglected in this frequency range. This fits well for class B group 2 equipment for a test distance of 3 m and 10 m. For a test distance of 30 m the dynamic range is insufficient. So passive as well as active loop antennas are required for a laboratory to serve all distances.

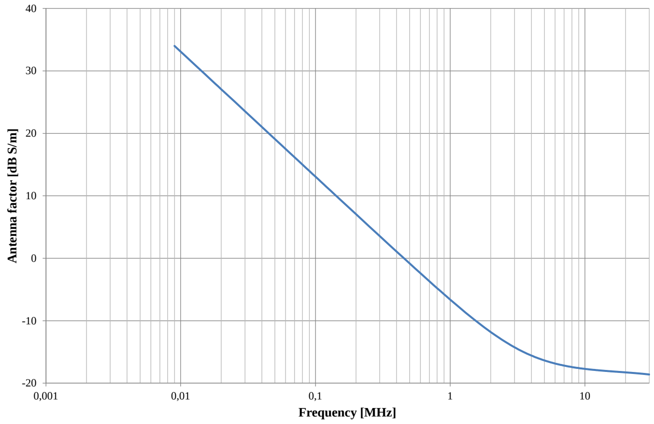


Fig. 9. Antenna factor of a passive loop antenna with 60 cm diameter

The operator has to keep in mind that a dynamic range up to 112 dBμA/m, see chapter VI, is still required even if a passive loop antenna is used. The reason for this is the design of the preselector of the EMI receiver. The specification of the design is not given by the relevant standard [4], instead the functionality is specified. However manufacturer use similar implementations with a fixed lowpass filter below 150 kHz and fixed or tuneable bandpass filter above. Since these bandpass filters are not narrowband, the pulsed signal with several of its harmonics lies on the input of the receiver. The same effect like for active antenna occurs, however it is easier to control the level with the step attenuator.

X. Outlook

Changes in the test distance for radiated emission measurements and emerging technologies like wireless power transfer will change magnetic field strength measurements in future. Active loop antennas with a large dynamic range are required to fulfill the demands. In future new designs will be switchable from active to passive. Also antennas with a complete front-end with preselector and step attenuator are possible [13].

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