Experimental Comparison between Two Different Radio-Frequency Delivery Methods

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***Abstract*—For EMC and E-field probe calibration measurements, power delivery system is needed to monitor the net power at the input of the antenna or TEM cell. Typically, the power delivery system introduced in [1] with dual directional coupler is used in most scenarios for its accuracy and predicted uncertainty. In practice, another power delivery method can also be used by terminating the reverse power probe with a load. This paper focuses on the simulation model and experimental comparison between these two different radio-frequency power delivery systems.**

Keywords—EMC measurement, E-field probe calibration, net power delivery system, dual directional coupler

I. INTRODUCTION

In EMC and E-field probe calibration measurements, net power delivery system is usually used to monitor the input power of the antenna and TEM cell which are necessary instruments to construct a standard E-field strength[1]. Typically, a four-port dual directional coupler is the preferred choice to accomplish that task. Motohisa Kanda et al proposed a thorough measurement model based on scattering parameters of four-port dual directional coupler and validated its accuracy in the usage of net power delivery in [2]. Zhong Chen et al in [3] proposed a practical measurement method based on the model in [2], and evaluated the uncertainty of this method compared to Kanda's model via simulation and measurement data. Dabo Li et al in [4] proposed another method to determine net power based on a power transfer standard and compared with the method using only scalar coupling coefficients of the forward and reverse ports. In this paper, we proposed a method by measuring the reflection coefficient of antenna and/or TEM cell and replacing the reverse monitoring probe with a 50Ω load. This method requires power monitoring only for the forward direction, which is more economical compared to the dual directional method in [1] and [4]. Finally, we validate the proposed method against the results from [2] through simulation and experimental data.

II. THEORETICAL AND SIMULATION MODEL

Kanda et al provided a thorough theoretical model for a four-port net power delivery system using dual directional couplers. A net power delivery system model equation was derived based on scattering parameters. A brief summary is shown in equation (1)

$$P_{net} = \frac{P_{fwd}}{1-\left|\Gamma_{fwd}\right|^2}|g|^2 - \frac{P_{rev}\left|\Gamma_{ant}\right|^2}{1-\left|\Gamma_{rev}\right|^2}|h|^2 \quad (1)$$

Where P_{net} is the net power delivered to the load,

P_{fwd} is the power read by forward power probe,

P_{rev} is the power read by reverse power probe,

Γ_{fwd} is the reflection coefficient of forward power probe,

Γ_{rev} is the reflection coefficient of reverse power probe,

Γ_{ant} is the reflection coefficient of antenna/TEM cell,

$g = \frac{FB+AE}{DA-FC}$

$h = \frac{BF+AE}{BD+EC}$

$A = S_{13}\left(1 - S_{22}\boldsymbol{\Gamma}_{rev}\right) + S_{12}S_{23}\boldsymbol{\Gamma}_{rev}$

$B = S_{23}\left(1 - S_{11}\boldsymbol{\Gamma}_{fwd}\right) + S_{12}S_{13}\boldsymbol{\Gamma}_{fwd}$

$C = (S_{13}S_{24} - S_{14}S_{23})\,\boldsymbol{\Gamma}_{ant}$

$$D = S_{13}\left(1 - S_{44}\Gamma_{ant}\right) + S_{14}S_{34}\Gamma_{ant}$$

$$E = S_{34}\left(1 - S_{11}\Gamma_{ant}\right) + S_{13}S_{14}\Gamma_{ant}$$

$$F = (S_{13}S_{24} - S_{12}S_{34})\,\Gamma_{rev}$$

For couplers with high directivities, the vector equation can be approximated with a scalar representation, as shown equation (2). Because of the simplicity of equation (2), it is the most commonly adopted method in practical applications.

$$P_{net} = \frac{|S_{34}|^2}{|S_{13}|^2}\frac{P_{fwd}}{1-\left|\Gamma_{fwd}\right|^2} - \frac{1}{|S_{24}|^2}\frac{P_{rev}}{1-\left|\Gamma_{rev}\right|^2} \quad (2)$$

As shown in equation (1) and (2), a power sensor is needed to monitor the reverse power because of the finite return loss of antenna/TEM cell. Therefore, if the reverse power probe is replaced by a standard 50Ω load with reflection coefficient of Γ_{load}, and assuming 100% of power that actually input the load has been dissipated by the load, which is reasonable, equation (2) can then be modified to equation (3)

$$P_{net} = \frac{|S_{34}|^2}{|S_{13}|^2}\frac{P_{fwd}}{1-\left|\Gamma_{fwd}\right|^2} - \frac{\left|\Gamma_{ant}\right|^2}{1-\left|\Gamma_{load}\right|^2} \quad (3)$$

Equation (3) forms the basis for the proposed method, in which only the forward power and the reflection coefficient of the load are needed to monitor the net power delivered.

Monte-Carlo Method is used to evaluate the uncertainty of this new net power delivery method, assuming random phase and same magnitude of parameters used in [1] (reflection coefficient is measured using a VNA), which are shown below. Figure 1 shows the uncertainty distribution.

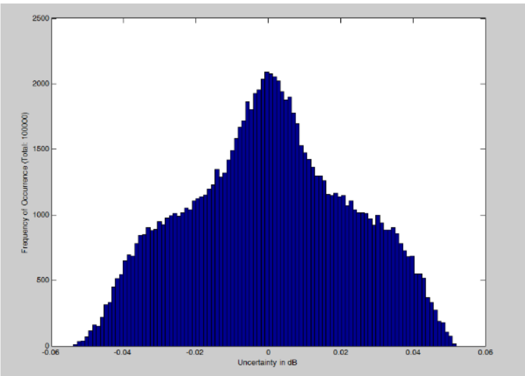

Figure 1 Uncertainty of the new method (Kurtosis 2.2991, Skewness 0.0041, Standard Deviation 0.0223)

$$|S_{11}| = |S_{22}| = |S_{44}| = 0.05$$

$$|S_{13}| = |S_{24}| = 0.1$$

$$|S_{14}| = |S_{23}| = 0.001$$

$$|S_{12}| = 10^{-6}$$

$$|S_{34}| = 0.95$$

$$\Gamma_{fwd} = \Gamma_{rev} = 0.05$$

$$\Gamma_{ant} = 0.05$$

$$\Gamma_{load} = 0.06$$

Comparison can also be made to the method in [2]. Figure 2 shows the result.

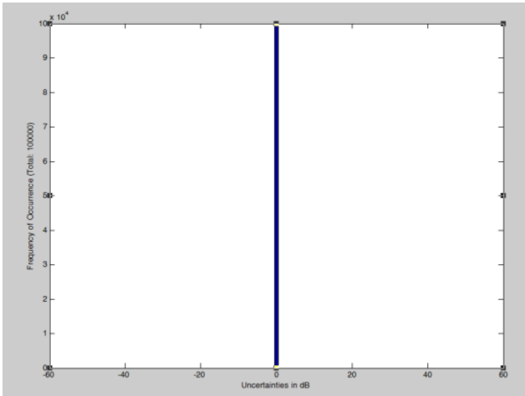

Figure 2 Uncertainty between the new method and the one in [2] (Kurtosis 1, Skewness -1, Standard Deviation 1.3650*10^{-16})

From Figure 1, it can be concluded that most results are distributed within 0.05dB which means the uncertainty of the new method is within 0.05dB. Through Figure 2, it can be shown that the standard deviation of comparison to the method in [2] is very small, which means the difference between the two methods is very small.

III. EXPERIMENTAL COMPARISON

Practically, the method of the power delivery system in [2] is mostly used, according to Section 2, it has been proved that the uncertainties of the new method is very close to the one in [2] through simulation. In this Section, the net power will be measured using a calibrated power probe and comparison will be made between the new method and the one in [2] through actual measurement.

Figure 3 is the block diagram of the experimental system. We took measurements by using these two methods from 2500MHz to 3000MHz with frequency step of 100MHz and took 10 times measurements at 3GHz to make sure the repeatibility.

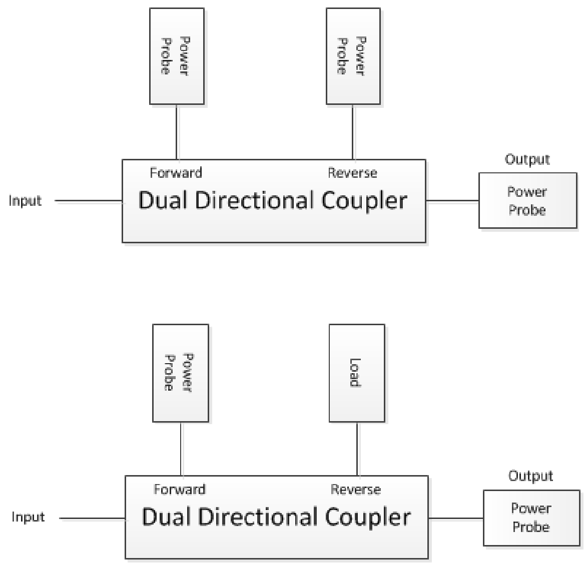

Figure 3 Block Diagram of Experiments

Table 1 shows the results (the net power corresponds to the target power to generate a standard E-field of 10V/m using a specific antenna) and Table 2 shows measurement results which have been repeated 10 times at 3GHz

Frequency (MHz)	New Method (dBm)	Method in [2] (dBm)
2500	16.23	16.31
2600	17.96	17.95
2700	17.59	17.61
2800	17.84	17.37
2900	17.03	17.10
3000	16.75	16.86

Table 1 Measurement Results in [2.5GHz, 3GHz]

Time	New Method (dBm)	Method in [2] (dBm)
1	16.74	16.84
2	16.74	16.84
3	16.75	16.85
4	16.76	16.86
5	16.74	16.88
6	16.74	16.87
7	16.74	16.87
8	16.75	16.86
9	16.75	16.87
10	16.74	16.87

Table 2 10 times Measurement Results at 3GHz

From Table 1 and Table 2, the difference in the net power varies within -0.47dB and 0.11dB from 2.5GHz to 3GHz, and is very stable through repeated measurements at 3GHz. This illustrates the stability and repeatability of the experiment.

It should be mentioned that in a case such as TEM cells or near field measurements, the reflection coefficient of the load can be varied by the presence of the probe and is under evaluation.

IV. CONCLUSION

From simulation results in Section 2 and experimental results in Section 3, conclusions can be drawn that the uncertainty of the proposed method is similar to that can be obtained in [2]. Experimental results show that the power difference varies from -0.47dB to 0.11dB through 2.5GHz to 3GHz. The measurement uncertainty analysis of the experiment is still under evaluation and is not included in this paper. The method in this paper can be used in scenarios where only one power sensor is available, with very limited impact on measurement uncertainties. A comparison study is also being conducted at the time of the writing to show the effects of coupler directivity on measurement uncertainties from these two methods.

V. APPENDIX

coupler_comparison.m

```
clc;
clear all;

nsample=1e5;
s11=0.05*complexmp(1, 360*rand(nsample, 1));
s22=0.05*complexmp(1, 360*rand(nsample, 1));
s44=0.05*complexmp(1, 360*rand(nsample, 1));
s13=0.1*complexmp(1, 360*rand(nsample, 1));
s24=0.1*complexmp(1, 360*rand(nsample, 1));
s14=0.001*complexmp(1, 360*rand(nsample, 1));
s23=0.001*complexmp(1, 360*rand(nsample, 1));
s12=1e-6*complexmp(1, 360*rand(nsample, 1));
s34=0.95*complexmp(1, 360*rand(nsample, 1));
gamma1=0.05*complexmp(1, 360*rand(nsample, 1));
gamma2=0.05*complexmp(1, 360*rand(nsample, 1));
gamma3=0.06*complexmp(1, 360*rand(nsample, 1));
gamma4=0.05*complexmp(1, 360*rand(nsample, 1));

A=s13.*(1-s22.*gamma2)+s12.*s23.*gamma2;
B=s23.*(1-s11.*gamma1)+s12.*s13.*gamma1;
C=(s13.*s24-s14.*s23).*gamma4;
D=s13.*(1-s44.*gamma4)+s14.*s34.*gamma4;
E=s34.*(1-s11.*gamma1)+s13.*s14.*gamma1;
F=(s13.*s24-s12.*s34).*gamma2;
g=(F.*B+A.*E)./(D.*A-F.*C);
h=(F.*B+A.*E)./(D.*B+E.*C);
p1net=(abs(s13).^2+abs(s34).^2.*abs(gamma4).^2.*abs(
s14).^2);
p2net=(abs(s23).^2+abs(s34).^2.*abs(gamma4).^2.*abs(
s24).^2);
Pnet=p1net.*abs(g).^2-
p2net.*abs(gamma4).^2.*abs(h).^2;

Pnet0=abs(s34).^2./abs(s13).^2.*p1net-
1./(abs(s24)).^2.*p2net;
Pnet1=abs(s34).^2./abs(s13).^2.*p1net-
abs(gamma4).^2./(1-(abs(gamma3)).^2);
Diffpercent=(Pnet-Pnet1)./Pnet1;
Diffpercent1=(Pnet0-Pnet1)./Pnet1;
DiffdB=10*log10(1+Diffpercent);
DiffdB1=10*log10(1+Diffpercent1);
avg_dB1=mean(DiffdB);
stddev_dB1=std(DiffdB);
kurt1=kurtosis(DiffdB);
skew1=skewness(DiffdB);
avg_dB2=mean(DiffdB1);
stddev_dB2=std(DiffdB1);
kurt2=kurtosis(DiffdB1);
skew2=skewness(DiffdB1);
subplot(1,2,1);hist(DiffdB,100)
subplot(1,2,2);hist(DiffdB1,100)
function c = complexmp(mag,angle)
c=mag*(cos(angle*pi/180)+1i*sin(angle*pi/180));
```

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