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High Precision and Fast RF Power Measurement using Linear Regression Technique over FPGA

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Abstract **– Fast and precise power measurement of RF frequency in VHF and UHF band is important and can be used in multiple applications like characterization of high-power amplifier (HPA) and solid-state power amplifier (SSPA), fast interlocking system for plasma process control and feedback diagnostics. Good research has been done on measurement and interlocking amplifier systems using analog devices, flip-flops and hardware logic gates, calorimeter and bolometer. There are several limitations like this paper describes a novel technique in which prediction of RF power dBm by measurement of voltage across monolithic RF power detector IC and fast interlocking system. We have got best accuracy of 0.04% and speed of the acquisition is less than 1uSec.**

Keywords **– RF Power Measurement, SSPA Characterization, Fast Interlocking System, FPGA Based Power Measurement, Python Based Linear Regression, Machine Learning, Prediction from Regression, Data Cleaning, RF PCB Design.**

I. INTRODUCTION

Accurate power measurement is essential in tele-communication, satellite communication, plasma re-search, atomic research and in many other applications. For transmitters power measurement is most critical in the communication industry as radiated power must be limited as per the guidelines described from nation wise regulatory committees [3]. In many radar systems solid state power amplifiers and high-power amplifiers and their stages are being used in amplification of RF signals. In some cases, as per the requirement of RF power in-rush current of element exceeds the safety limits and may tend to damage the element and hence it gets crucial to measure the RF power fast and take instant necessary action [4]. Again, to ensure the efficiency at each amplification stage continuous monitoring of input power, output power and their ratio is very important. [5] [12]. For the Satellite communication accurate measurement of multi carrier FDMA efficiency is important because it impacts multi-tone intermodulation and intermodulation distortion [13].

For accurate and reliable RF power measurement the principle of the principle of calorimetry [2] was being used for primary standards from DC to High frequency ranges in GHz also. Micro-Calorimeters have been evolved with suitable bolometers which are calibrated with secondary standard. In the micro-calorimeter effective efficiency is assessed by continuous measurement of dissipated RF power and substituted DC power delivered by auto equilibrium Wheatstone bridge [5]. This methodology has some limitations like it needs corrections in determining the effective efficiency and speed of the measurement is slower, hence it needs to be improved [2]. In earlier methodologies simple coplanar technology on alumina substrate with thermistor have been used [5]. For lower frequency range less than 2GHz it provides good accuracy approximately 5% of error but while going to higher frequency ranges at 4 GHz its accuracy gets reduced to 30% error [5]. For the higher frequency greater than 10 Gym / Sec and faster measurement from 23.6pS to 50pS chromatic dispersion (CD)-insensitive first-order polarization mode dispersion (PMD) monitoring method have been developed experimentally [6] [8].

For compact setup for the measurement of Power amplifier of RF frequencies envelope tracking operation have been carried out for nearly 40MHz of bandwidth in which 5MHz for WCDMA and 20MHz for LTE signals at 838MHz frequency. For the calibrated sensing National Instruments NI PXIe-5645 with 40 MHz of bandwidth have been used with vector signal analyzer. This system can be used with RF input power shall be greater than -10dBm [10] [11]. For Optical fast communication CD-PMD based system can be useful at some level but limitation of it is that it gets inaccurate at lower frequencies. Along with accuracy a detector shall be rated by dynamic range, size and power consumption. Where time varying amplitude measures in peak to average envelope detector [3]. Micro fabricated flow calorimeters for better accuracy also have been used which are capable of measurement in 100 microwatts to 200 milliwatts till 4GHz of higher frequencies. The principal to measure RF Power measurement in micro fabricated flow calorimeter is 50ohm load heating transferred to micro channel of fluid and temperature change in the fluid channel measured by thermistor that is connected one lag of Wheatstone bridge [9]. The typical achieved resolution of this device is 50uW and measured reflection coefficient is range of -25dB.

There are chances of source mismatch in the RF Power measurement, which can be substituted by reflection coefficient of attenuator terminated with load. While working with RF attenuated power measurement this method can work well when attenuation factor of power is high to improve the accuracy [14] With improvement in accuracy a new method of 1/f measurement with field programmable gate array (FPGA) has been evaluated. Here five main modules have been used: whitening, wavelet decomposition, denoising, signal recovery and power estimation which have 1.74% percentage of error at 10 dBm signal power and 60.85 dB SNR [15]. For fast pulsed measurement of small duty cycle of RF power transistors design of bias network using of-the-shelf components and using source and measurement unit (SMU) have been carried out [16].

II. Hardware Design Description

Monolithic RF Power detector IC converts RF power in its operational frequency to millivolts that can be measured. Response time of these ICs are very fast (typically less than uS) and hence having ADC with sampling rate of MSPS would be preferable as it shall give output also faster. High speed ADC gives data to the FPGA. FPGA is brain of the system which can convert the measured voltage to RF Power in dBm using line equation.

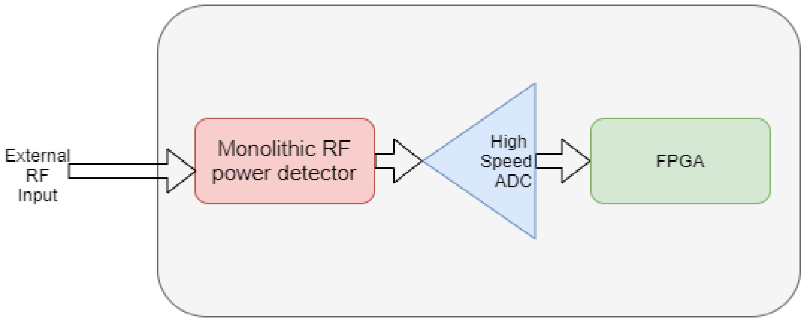

Fig. 1. RF Power measurement block.

Our hypothesis relies on below points.

1. Monolithic RF Power detector IC's output shall be linear with respect to frequency of operation and dBm of power.

2. Speed of measurement and control shall be at least comparable to previous development RF and high-speed digital system shall not create Signal integrity or EMI/EMC issues.

III. Overview of Characterization of System

LT5534 monolithic RF power detector is capable of measuring RF signals in frequency range of 50MHz to 3GHz over a 60dB dynamic range. Output of series of RF detectors and RF limiters are added to generate accurate DC voltage with respect to input RF signal in dB. With very good temperature sensitivity in order of +/-1dB detector IC provides output response in 40nSec.

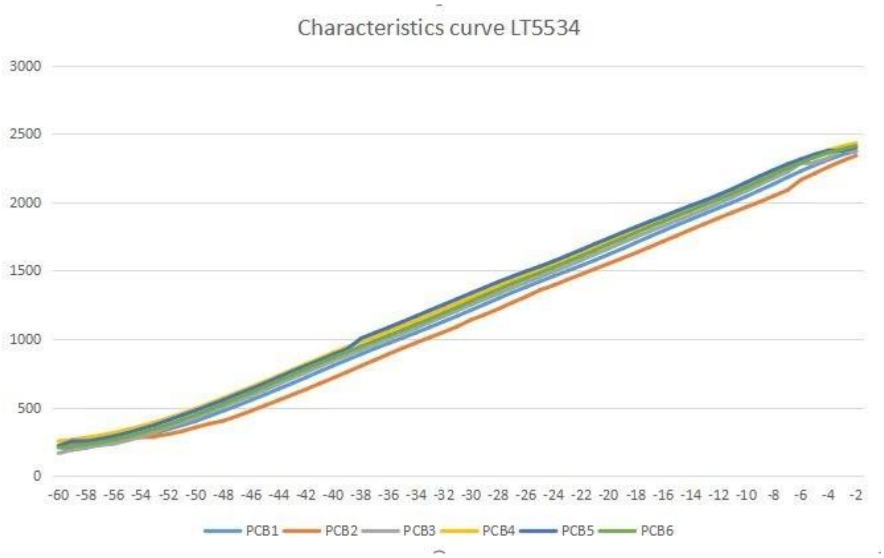

Fig. 2. Characterization curve of LT5534.

Above figure shows the characteristics curve of LT5534 ICs taken at different frequencies, we have characterized 6 numbers of LT5534 ENIG PCBs manufactured over Rogers RO4053b material substrate for better impedance matching. The PCB designer tool used is Zuken CADSTAR 18. For frequency generation we have used Tektronix AWG5000 series arbitrary waveform generator for different frequencies from 100MHz to 400MHz generated with power from -60dBm to -2dBm and measured voltage using 6 and ½ digit Fluke multimeter 8846A. The figure shows frequency response of LT5534 IC which shows linearity of power in dBm with respect to output voltage.

IV. Linear Regression Technique Over FPGA

All PCB shows similar response with respect to different frequencies and very less change in linearity with respect to frequency change as shown in above figure. The standard techniques to convert this voltage into respective power value is being done using op-amp based offset removal and gain multiplier circuits. This circuit is giving good response but have several disadvantages associated with it which can be listed as

1. Complete circuit would have multiple slow analog components along with high frequency electronics components which creates signal integrity, power integrity and EMI EMC issues even with good isolation.
2. For analog circuit as per the measured data there are two available options from which one is to have calculated permanent resistor but that does not provide accurate results as per the standard available values and other is to have variable resistor whose value needs to be set every time for different frequency ranges.

3. For more channels of RF measurement circuit becomes too complex and hence RF loops gets generated which create inter channel interference.

A. *Linearity Equation*

From linearity been observed at different PCBs which is at different frequencies we have come up with applying traditional regression

Where

$$y = \alpha + \beta * x \tag{1}$$

β is multiplier of input or slope of the regression line is also known as gradient.

α is additive constant or intercept.

$$\beta = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{2}$$

$$\beta = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2 * \frac{(y_i - \bar{y})}{(x_i - \bar{x})}}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{3}$$

From Equation 3 implemented plot is represented in below image,

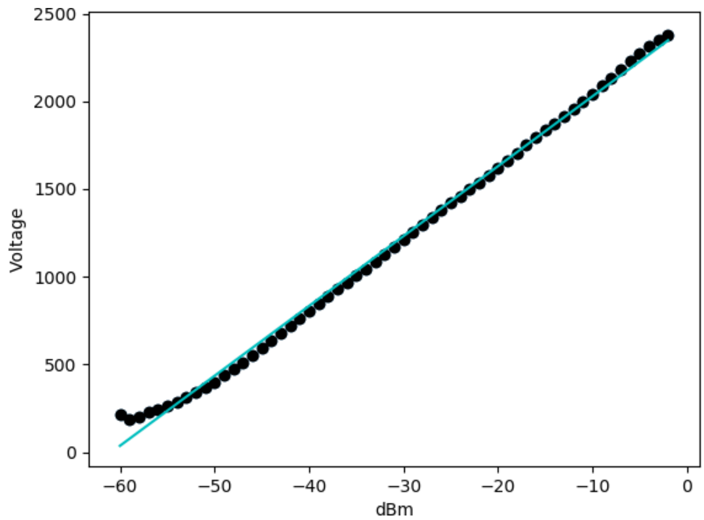

Fig. 3. Linearity from Linear regression of LT5534.

Above figure 3 is the plot from matplotlib library of python where points represent actual data whereas line represents predicted slope and intercept values, here the measured actual data are represented in points and line is our predicted line equation output.

For testing and measurement instrument the measurement accuracy is the most significant parameter. Measurement accuracy and measurement errors helps to understand the reliability of the measurement instrument. There are two kind of errors [1]

1. Those which cannot be calibrated and act as a noise in the system.
2. Those which can be taken into account for the calibration and can be removed.
3. Hence to check the reliability of the system we have developed two type of testing.

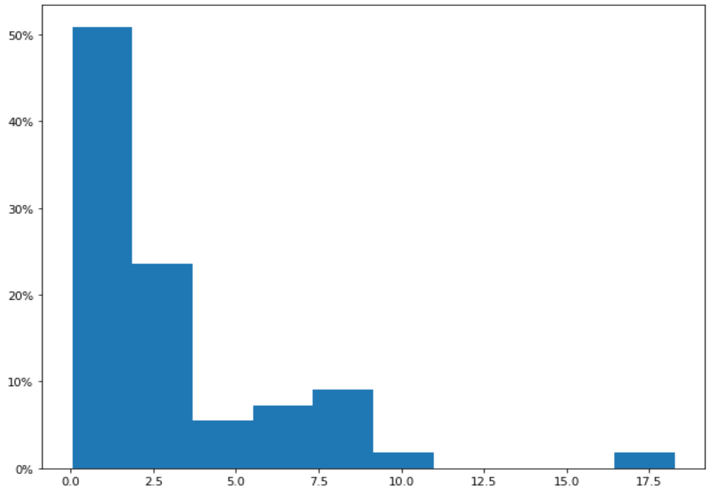

Fig. 4. Error Histogram.

B. *Accuracy Measurement*

We have measured accuracy of predicted data by error histogram image shown below, Figure represents error (%) vs its spread in histogram which clearly shows that our prediction model gives 50% correct data in less than 1% of error while 75% of correct data with less than 2.5% of error. Now to verify that our model works the same while in running mode we have developed a hardware descriptive language (VHDL) code which simply multiplies the gradient to the input from ADC. We have used Texas Instruments high speed ADC having sampling rate capabilities till 130 MSPS ADC16V130 and 16-bit resolution.

Xilinx Artix 7 series FPGA has been interfaced with ADC and data has been sampled, gradient which we have measured from the formula shown above is been multiplied and intercept is been added using VHDL code. We have displayed final data on the LED. We compared over measured data displayed over LED with the actual dB level that was fed as an input to the system from arbitrary waveform generator. Further we have compared the results which is explained further in subsequent section.

V. Results and Conclusion

We have measured data at different frequencies ranging from 100MHz to 400 MHz and also on different PCB and com- pared with actual dBm power. Error from the measured RF power and actual input power can be shown using the figure 5.

A. *Error and Outliers*

Description of error can be measured as below.

- Median: 1.80777739
- Minimum: 0.046736233
- Maximum: 10.95411488
- First quartile: 0.818603173
- Third quartile: 3.56890801575

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- Interquartile Range: 2.75030484275

Box plot results can be described as the best accuracy we have got is 0.04% and worst accuracy is 10.95% further it explains about data as 25% of measured values has errors less than 0.8%.

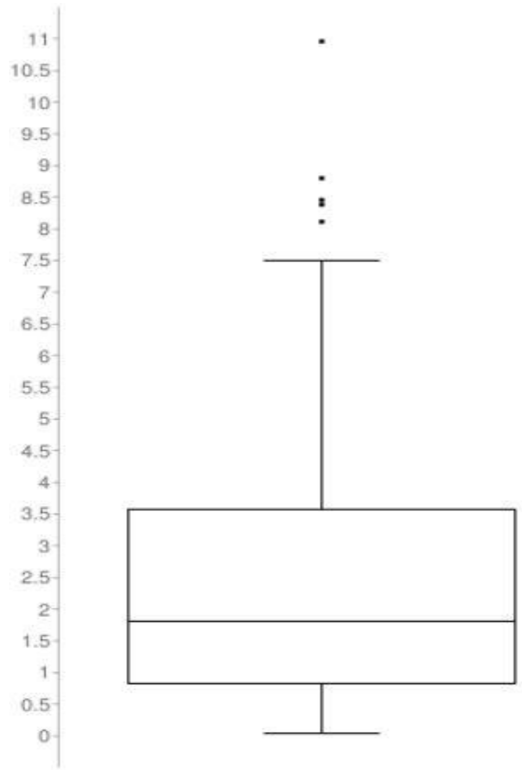

Fig. 5. Error Box Plot.

There are four Outliers:

- 10.95411488
- 8.790458796
- 8.447461897
- 8.386932849
- 8.123972507

Outliers are more near to lower dBm which were less than -55dBm.

B. *Test and Measurement System*

Frequency generation from arbitrary waveform generator of PCB and result measurement in oscilloscope is shown in figure 6.

We have achieved the good results in the required frequency and we have obtained results at high speed also interlocking is also possible with less than a microsecond as we have described in the timing diagram. This technology can replace old RF Power measurement and fast interlocking system as it requires very less time to calibrate and it is cost effective too. For different frequency ranges we can change the power measurement IC and with the same type of one-time calibration we can reproduce the entire development in very less time.

Fig. 6. Arbitrary waveform generator input.

Fig. 7. Oscilloscope measurements.

Hence, we conclude that this innovative system should be used and it shall replace the traditional analog based high cost and slow speed system.

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Abhishek Parikh received B.E. (Electronics and Communication) from GTU Ahmadabad in 2014, M.E. (Microprocessor System and Application) from MSU Baroda in 2016 and pursuing his Ph.D. in bio-medical signal processing from GTU. He has got 5 years of working experience as Product Development Lead in Product Engineering Services at Optimized Solutions Limited.

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