The MSE of the Fig.(13) and Fig. (14) was calculated using the equation (5).

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(\hat{Y}_i - Y_i\right)^2 \qquad (5)$$

Where:
N - Is the total number of samples.
$\hat{Y}_i$ - n-th output value of the model solar.
Y_i - n-th output value of the FPGA.

And the correlation coefficient of Pearson R was calculated using the equation (6).

$$R = \frac{N\sum_{i=1}^{N} X_i Y_i - \sum_{i=1}^{N} X_i \sum_{i=1}^{N} Y_i}{\sqrt{N\sum_{i=1}^{N} X_i^2 - (\sum_{i=1}^{N} X_i)^2}\sqrt{N\sum_{i=1}^{N} Y_i^2 - (\sum_{i=1}^{N} Y_i)^2}} \qquad (6)$$

Where:
N - Is the total number of samples.
X_i - n-th output value of the model solar.
Y_i - n-th output value of the FPGA.

Table 3. Resource used for the FPGA

Slice Logic Utilization	Used	Available	Utilization
Number of Slice Registers	977	54576	1%
Number of Slice LUTs	2857	27288	10%
Number of occupied Slices	1029	6822	15%
Number of bonded IOBs	41	218	18%
Number of RAM B16BWERs	2	116	1%
Number of RAM B8BWERs	2	232	1%
Number of BUFIO2/BUFIO2_2CLKs	1	32	3%
Number of OLOGIC2/OSERDES2s	36	376	9%
Number of DSP48A1s	36	58	62%
Number of PLL_ADVs	1	4	25%

VI. RESULTS

As can be observed, considering an electrical analog model defined in Spice as that shown in Fig. (1), it was possible to emulate the behavior of an ST5 solar panel from Siemens, which represents 33 serially connected cells from which the electrical parameters could be extracted (short circuit current and open circuit voltage). The architecture of the proposed ANN is shown in Fig. (3) from which the best results were found, from an evaluation of the error between the input to the ANN and the expected value of the solar cell panel. Also it can be observed that the ANN architecture is a good function aproximator since it could effectively abstract any proposed profile. Also the Levenberg Marquardt algorithm is suitable for this sort of architectures, in which a minimum number of neurons is required to have a faster processing, obtaining a training time of around 3 seconds. As can be seen from Fig.(13) and Fig. (14) there is a good approximation between the measured results of the solar panel and those expected from the ANN digital implementation, from which an error of MSE = 2.0182E-07 and a factor of correlation R = 0.9998 for the current were obtained and a MSE = 10E-04 and a R=0.9972 for the voltage were obtained.

In the Table (3) we can see the small amount of resources used for the device FPGA, where the number of DSP's was considerable, because the implementation used 18 DSP's to perform the product between the input and the weight and other 18DSP's were used to evaluate the equation (4) in each neuron.

VII. CONCLUSIONS

It was possible to implement a solar panel in a digital device FPGA, only needing two environmental parameters (irradiance, temperature) having in this way a low computational effort, besides this emulator can operate in real time being a, reason why this type of devices are very useful to make the analysis of a solar module in a research laboratory, in addition that the FPGA used for this application is very viable due to the low consumption of resources which were used and to its type of architecture which allowed the parallelism with which the biological neural networks work, giving therefore the flexibility to make the implementation of a whole photovoltaic system in the future.

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REFERENCES

[1] L. Castañer, S. Silvestre "Modelling photovoltaic systems using PSpice". University Politecnica of Cataluña, Barcelona, Spain 2002; pp. 77 - 94.

[2] M.T. Hagan, H. B. Demuth, M. Beale "Neural Network Design" Oklahoma State University pp. 11-1 – 12-28

[3] A. Mellit, H. Mekki, A. Messai, H. Salhi "FPGA - based implementation of an intelligent simulator for stand- alone photovoltaic system". Expert Systems with Applications 2010; 37: 6036-6051.

[4] H. Mekki, A. Mellit , S. A. Kalogirou, A. Messai, G. Furlan "FPGA - based implementation of a real time photovoltaic module simulator". Progress in photovoltaics: Research and Applications 2010; 18: 115 - 127.

[5] H. Mekki, A. Mellit, H. Salhi, B. Khaled "FPGA - based implementation of multilayer perceptron for modelling of photovoltaic panel". In American Institute of Physics (AIP) Conference Proceedings 2008; 1019: 211 - 215

[6] E. Koutroulis K. Kalaitzakis, V. Tzitzilonis "Development of an FPGA-based system for real-time simulation of photovoltaic modules". Microelectronics Journal 2009; 40: 1094 - 1102.

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