IJE TRANSACTIONS A: Basics Vol. 34, No. 1, (January 2021) 90-96

International Journal of Engineering

Journal Homepage: www.ije.ir

Employing the Empirical Mode Decomposition to Denoise the Random Telegraph Noise

A. Moshrefi, H. Aghababa*, O. Shoaei

School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran

PAPER INFO

Paper history:
Received 06 August 2020
Received in revised form 11 October 2020
Accepted 13 November 2020

Keywords:
Electronic Devices
Empirical Mode Decompositio
Noise
Random Telegraph Noise

ABSTRACT

Random Telegraph Noise (RTN) is a stochastic phenomenon which leads to characteristic variations in electronic devices. Finding features of this signal may result in its modeling and eventually removing the noise in the device. Measuring this signal is accompanied by some noise and therefore we require a method to improve the Signal to Noise Ratio (SNR). As a result, the extraction of an accurate RTN is a remarkable challenge. Empirical Mode Decomposition (EMD) as a fully adaptive and signal dependent method, with no dependency to the specific function, can be an appropriate solution. In this paper, we evaluate the most recent methods and compare them with our proposed approach for the artificial and actual RTN signals. The results show the higher accuracy and efficiency by about 54%, 61% and 39% improvement in SNR, Mean Square Error (MSE) and Percent Root mean square Difference (PRD) respectively for the optimized wited method. Finally, an indicator to evaluate the reliability in digital circuits is introduced.

***doi**: 10.5829/ije.2021.34.01a.11*

1. INTRODUCTION

In recent years, the noise issue has attracted the attention of semiconductor industry. This phenomenon can decrease the quality of the valuable data and negatively impact the results of analysis and modeling. There are some methods to improve the quality of measuring the noise and data. However, if the noise and data are combined together, their discrimination will be tough. In addition, we have some limitations for our instruments which cannot accurately capture the desired data. Meanwhile, providing a solution by the software analysis would be helpful to obtain the data accurately [1–3].

In the other side, as the scaling of transistor geometries towards only a few tens of nanometers continues, we find that small devices face new challenges regarding their operation reliablity. Random Telegraph Noise (RTN) is one of these challenges which happens by trapping and detrapping of the carriers in the transistor channel and it would make some variations on the drain current. RTN is one of the most important time variation sources having a prominent effect on the reliability of memories, digital and analog circuits [4, 5]. Therefore, capturing the features of RTN and its modeling is of great importance. If we can measure the RTN accurately, we can obtain an appropriate model for it. However, this measurement is usually affected by some noise and error and it calls for a method to improve the signal to noise ratio.

In this area, Karatsori et al. [6] have characterized and measured the low frequency noise in InAs MOSFET. Stampfer et al. [7] has characterized the noise produced by individual defects for MoS2 field-effect transistors. Waltl et al. [8] employed an advanced algorithm based on cumulative summation to detect the step levels in RTN. Jech et al. [9], Lai et al [10] and Ullmann et al. [11] have extracted and measured the low frequency noises in MOSFET and also they have introduced a model for the noise features. Feng et al. [12] investigated the effect of RTN on the drain current variations as a Model for the introduced FETs. Matsumoto et al. [13, 14] have evaluated the impact of RTN on the CMOS logic circuits for low supply voltages. Compagnoni et al. [15, 16], Veksler et al. [17], Ling et al. [18] have analyzed the

*Corresponding Author Institutional Email: *Aghababa@ut.ac.ir* (H. Aghababa)

Please cite this article as: A. Moshrefi, H. Aghababa, O. Shoaei, Employing the Empirical Mode Decomposition to Denoise the Random Telegraph Noise, International Journal of Engineering, Transactions A: Basics, Vol. 34, No. 1, (2021) 90-96

reliability of RRAM and Flash memory under the impact of RTN to estimate the accuracy of data loss.

Imamoto et al. [19], Forbes and Miller [20], Chen et al. [21], Ioannidis et al. [22], Pirro et al. [23] have tried to decrease the level of RTN noise by changing some parameters in the structure of MOSFET devices. Although these methods can be effective, they might be so expensive. Thus, they require the nanometer instrument technologies and they are difficult to implement. Islam et al. [24], Seo et al. [25], Kushwaha et al. [26], Tanaka et al. [27] have considered the circuit noise as a deterministic process and have introduced a model based on the oxide trap density and energy level. Gokcen and Demir [28], Mohanty et al. [29] have considered the noise as a non-stationary and stochastic process. For de-noising the drain current from the RTN, some studies have been conducted. Diaz-Fortuny et al. [30, 31] have introduced a method to remove the RTN based on the detection and comparison of trace levels between the fast and slow defects. However, this method is consuming and cannot be implemented for real-time applications. Gao et al. [32], Vaseghi [33], Petrychuk et al. [34], Higashi et al. [35], Tega et al. [32–36] have analyzed and extracted RTN using the Fast Fourier Transform (FFT) and the Short Time Fourier Transform (STFT). However, Fourier analysis cannot determine the short-time variations of signal because it can only decompose the signal to same infinitive sinus and cosine series wherein all of the time information will be removed. Du et al. [37], Principato and Ferrante [38], Hendrickson et al. [39] have employed Wavelet decomposition to separate the data and 1/f noise. They have compared the shape of mother waves and introduced the Haar function as the best Wavelet to decompose the RTN. Then they have employed the universal threshold to de-noise the RTN by the Wavelet thresholding method. However, the Wavelet transform depends on the mother wave function and is not adaptive for every type of signal. Hence, it is not considered as a useful tool. In this paper, Empiricl Mode Decomposition (EMD) method is introduced which is the basis of the adaptive orthogonal functions and can be appropriate for non-stationary signals. This method is applied to diverse RTN signals and its capability is shown in decomposing the desired and undesired data.

2. METHOD

In this section, the proposed method for RTN signal is introduced.

2. 1. Empirical Mode Decomposition

In recent years, Empirical Mode Decomposition has been considered as one of the most practical and efficient approaches in signal processing area. As opposed to the Wavelet and FFT which use the specific orthogonal parametric basis, this method decomposes the signal based on the signal harmonics and is completely adaptive. Therefore, it has a strong capability to decompose non-stationary signals. This method creates some Intrinsic Mode Functions (IMFs) and a residual signal. The procedure to produce the IMFs is based on the subtraction of the baseline function from the main signal. The process continues untill the residual signal becomes constant. Baseline function is considered as the average of local extremum of the signal. The IMFs must satisfy the two following conditions:

1. The number of the extremums and zero-crossings must be equal or differ by at most one.
2. In each point, the average value of the defined envelope by the local extremums must be zero. In another word, IMFs must be symmetric functions around zero.

The algorithm can be considered as follow:

1. Find the upper and lower envelops of the signal x(t).
2. Subtract the average of envelopes (m(t)) from the signal (d(t)=x(t)-m(t)).
3. If d(t) can satisfy the two conditions of IMFs, d(t) can be saved as the first mode, otherwise re-calculate the algorithm from the 1st step for d(t).

Then, the residue signal r(t) obtained from the subtraction of the signal x(t) and the IMF_1 is considered to calculate the next modes.

To obtain the next residue, the current IMF must be subtracted from the previous residue which will be employed to obtain the mode. The summery of these relations are

$$\begin{aligned} &\mathbf{r}_1 - \mathbf{IMF}_2 = \mathbf{r}_2 \\ &\mathbf{r}_2 - \mathbf{IMF}_3 = \mathbf{r}_3 \\ &. \\ &. \\ &\mathbf{r}_{n-1} - \mathbf{IMF}_n = \mathbf{r}_n \end{aligned} \tag{1}$$

whenever the reside r_n does not have any extremum point with almost the uniform behavior, the algorithm will be finished.

Finally, the input signal x(t) can be expressed as the summation of the IMFs and a residue

$$x(t) = \sum_{i=1}^{n} \mathrm{IMF}(i) + r(t), \tag{2}$$

where n is the number of decomposition levels and r(t) is the residual signal at the end of the algorithm [40–43]. EMD method can be summarized in Figure 1.

This method is applied to show the decomposed levels on an actual noisy RTN in Figure 2.

For the first stage, because of the adaptive decomposition of EMD, we can propose the EMD thresholding instead of the Wavelet thresholding.

Another approach is that we can employ some weights for the decomposed modes since it is clear that our desired data has not been distributed in all IMFs uniformly.

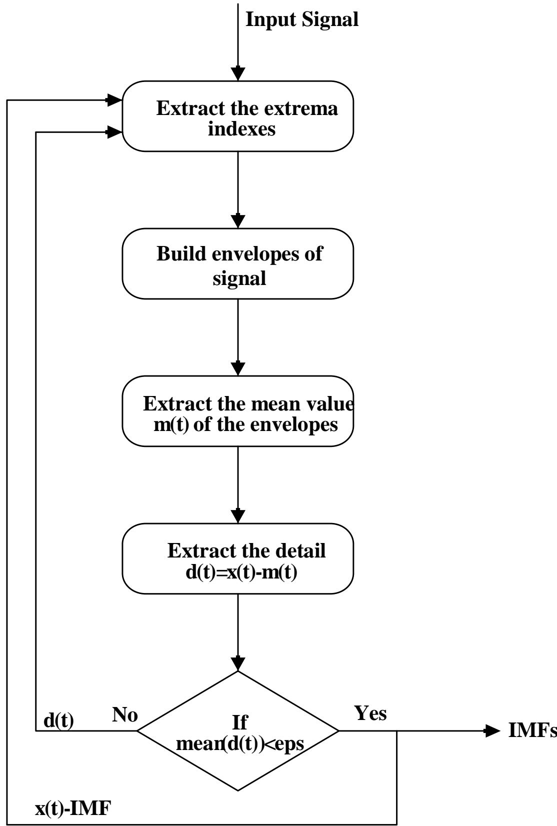

Figure 1. The EMD algorithm

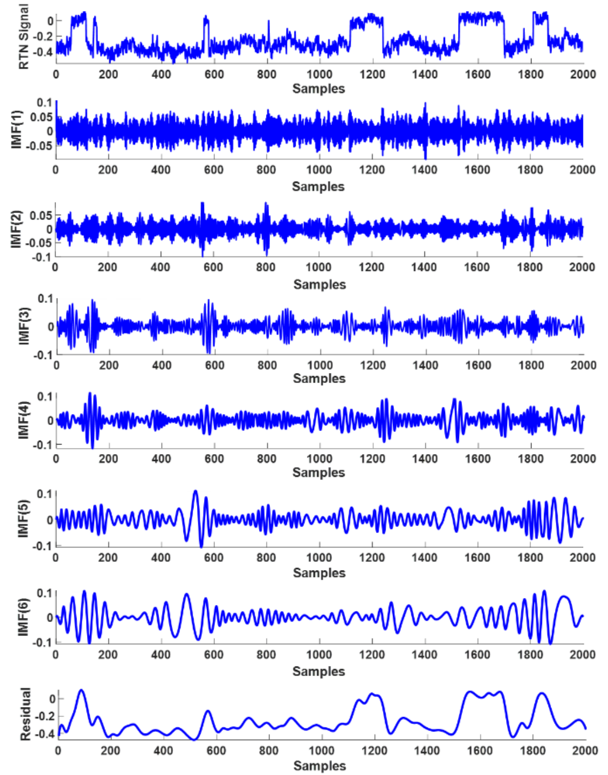

Figure 2. Employing EMD to an actual RTN in six levels

3. RESULTS

We considered two types of signals for our evaluation. Firstly, the actual signal which is extracted from an nMOSFET with Width = 0.16 µm and Length = 2 µm, which was biased by V_{GS}=2.2 V, in temperature of 50 °C based on the Measure-Stress-Measure (MSM) method and secondly, the artificial signal which is obtained from a stochastic defect modeling based on the Markov chain to simulate the RTN signal according to Grasser [44]. For the validation of our proposed methods, we applied our methods on the artificial and actual RTN signals.

For the EMD thresholding, six levels of IMFs were extracted and then the method is applied by using the Universal thresholding and soft removing. The Wavelet transform using the Haar function with six levels is used in accompany with the Universal thresholding in this method. For the weighted EMD method, we analyzed the different combinations of IMFs to see which IMF is more similar to the pure data and has higher SNR. Table 1 shows these results.

It is clear that the last IMFs are more related to the pure RTN. The results in Table 1 were obtained for noisy RTN with zero SNR. By analyzing, we understand that some IMFs have less similarity to the pure RTN and have less SNR when considered alone. However, if we add it to other IMFs, we obtain a higher SNR. Therefore, removing an IMF would not be correct and we should better consider a weight for each of the decomposed levels as below.

$$S = a*IMF_1 + b*IMF_2 + c*IMF_3 + d*IMF_4 + e*IMF_5 + f*IMF_6 + g*r \quad (3)$$

For the next stage, we employed an optimization method to reach a reasonable weights for 1000 RTN signals to reach the highest level of SNR. The input data were selected from diverse signal records with different levels of noise. The data were collected in an excel file and based on the genetic optimization algorithm with 0.8 mutation, the data were processed one by one in MATLAB software. In Table 2 the weight results are presented.

Finally, all of the mentioned methods are evaluated, and samples of this analysis have been shown for artificial and actual RTNs in Figure 3 and Figure 4 respectively.

For a better evaluation, three indicators, namely, SNR, Mean Square Error (MSE) and Percent Root mean square Difference (PRD) are calculated for the different methods.

$$\mathrm{SNR} = 10\log\left(\frac{\sum_{t=1}^{N} x^2(t)}{\sum_{t=1}^{N}\left(\tilde{x}(t) - x(t)\right)^2}\right) \quad (4)$$

$$\mathrm{MSE} = \frac{1}{N}\sum_{t=1}^{N}\left(\tilde{x}(t) - x(t)\right)^2 \quad (5)$$

TABLE 1. SNR for different combination of IMFs

IMFs	1	2	3	4	5	6	r	$\sum(1:5)$	$\sum(1:6)$	$\sum(2:r)$	$\sum(3:r)$	$\sum(4:r)$	$\sum(5:r)$	$\sum(6:r)$
SNR	1.3347	0.2310	1.6905	1.4088	2.5321	2.9312	3.7918	1.4381	1.9105	4.8923	4.2648	5.3968	5.2189	4.4283

TABLE 2. Weights for the different decomposed levels

Factor	a	b	c	d	e	f	g
Value	0.0291	0.0467	0.3277	0.2809	0.5297	0.7384	0.9271

$$\mathrm{PRD} = 100\sqrt{\frac{\sum_{t=1}^{N}\left(\tilde{x}(t)-x(t)\right)^2}{\sum_{t=1}^{N}\left(x^2(t)\right)}} \quad (6)$$

where $x(t)$ is the clean signal and $\tilde{x}(t)$ is the de-noised signal.

The results of SNR, MSE and PRD have been reported for the mentioned method for the various SNRs in different RTNs in Tables 3, 4 and 5 respectively. The results were obtained by averaging on 50 simulations. By considering an indicator to evaluate the improvement rate of the methods, we can define

$$\text{Indicator \%} = \frac{\left|\sum_{i=1}^{N}\mathrm{SNR}_{EMD} - \sum_{i=1}^{N}\mathrm{SNR}_{DWT}\right|}{\sum_{i=1}^{N}\mathrm{SNR}_{DWT}} * 100 \quad (7)$$

where tN is the number of the calculated SNRs. This indicator can be utilized as well for the MSE and PRD to evaluate the results.

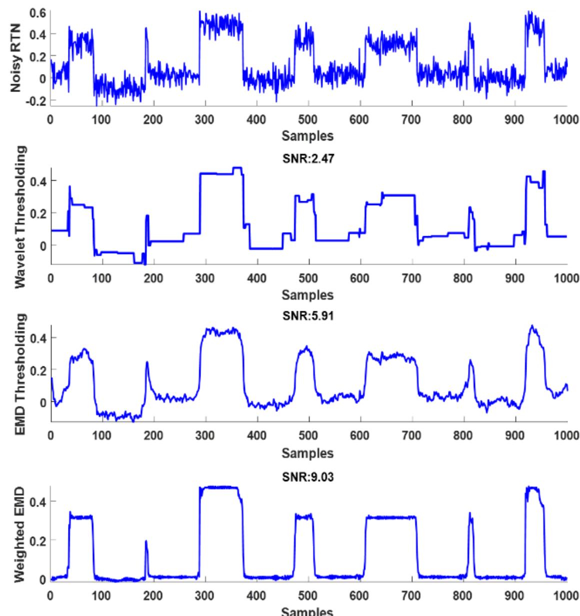

Figure 3. The results of the mentioned methods for Artificial RTN signal: a) Noisy RTN b)Wavelet thresholding c) EMD thresholding d) Weighted EMD

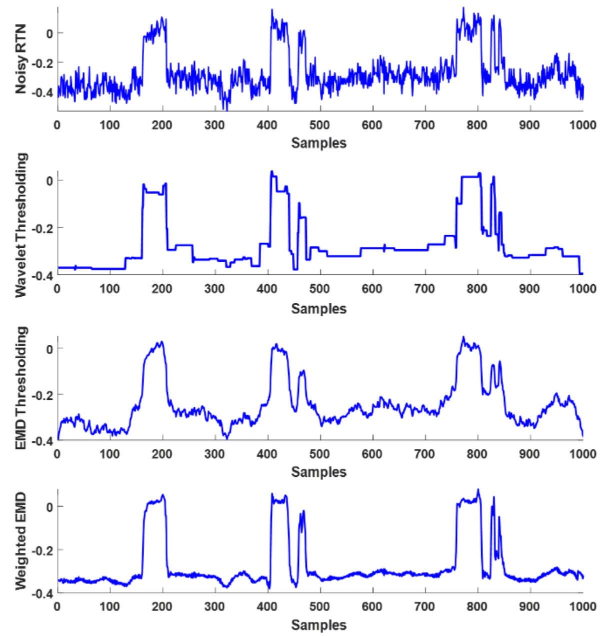

Figure 4. The results of the mentioned methods for Actual RTN signal a) Noisy RTN b)Wavelet thresholding c) EMD thresholding d) Weighted EMD

Summary of the results is shown in Figure 5. The results show 14%, 27% and 19% improvement in SNR, MSE and PRD for the EMD Thresholding, respectively. The results also show 54%, 61% and 39% improvement in SNR, MSE and PRD for the Weighted EMD, respectively.

In other side, we should consider the pros and cons of the proposed method.

TABLE 3. SNR results for the mentioned methods

Input SNR (db)	-5	0	-2.5	5	10
Method			**SNR**		
Wavelet Thresholding [39]	-2.141	2.3456	4.2704	6.8205	10.6842
EMD Thresholding	-1.034	3.0356	4.8875	7.2971	11.0345
Weighted EMD	1.629	5.1352	6.1970	8.3557	12.5159

TABLE 4. MSE results for the mentioned methods

Input SNR (db)	-5	0	-2.5	5	10
Method			**MSE**		
Wavelet Thresholding [39]	0.0281	0.0145	0.0092	0.0064	0.0043
EMD Thresholding	0.0188	0.0119	0.0073	0.0045	0.0032
Weighted EMD	0.0105	0.0061	0.0047	0.0026	0.0007

TABLE 5. PRD results for the mentioned methods

Input SNR (db)	-5	0	-2.5	5	10
Method			**PRD**		
Wavelet Thresholding [39]	98.21	70.44	56.75	42.11	36.08
EMD Thresholding	74.56	56.92	43.67	38.22	32.14
Weighted EMD	58.17	38.58	33.71	28.45	25.67

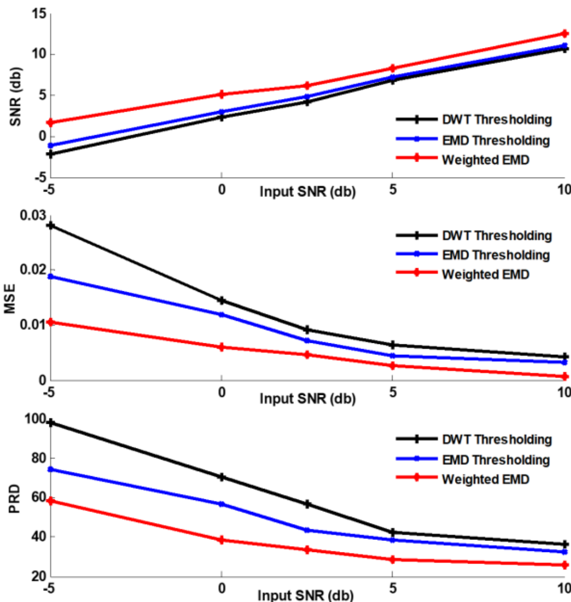

Figure 5. The results of SNR, MSE and PRD for three methods and in terms of different input SNRs

The computation time of the methods are evaluated in MATLAB by "tic toc" command and the average of the 50 runs of the algorithms is shown in Table 6. In order to obtain the computation time, we have employed a laptop with 2.2 GHz CPU clock frequency.

According to the results, Wavelet thresholding has the least computational time among the other methods, which is about 38 times faster than the weighted EMD method. However, the denoising approach is usually

TABLE 6. Computation time of the mentioned methods

Method	Computation-Time (s)
Wavelet Thresholding [39]	0.023246599
EMD Thresholding	1.152699315
Weighted EMD	0.902714652

analyzed after recording the data as an off-line processing. Furthermore, the cost of computation in the range of around one second will not be a critical challenge and the denoising performance would be more significant than the computational time.

The bottle neck of the weighted EMD would be the process of finding the weights using diverse signals with different levels before denosing. It is noteworthy that the only bottle neck of this approach is finding appropriate weights.

3. 1. RTN Intensity Indicator

Having de-noised the RTN signals, we can consider a criterion for finding out the energy level of RTNs to show the intensity of this phenomenon. In that regard, we can make use of the following equation.

$$I = \int_{t_0}^{t_1} s(t)dt \tag{8}$$

where I is the intensity, s(t) is the de-noised RTN signal and (t_0,t_1) is the desired interval. It is clear that de-noising would be necessary as sometimes noise might have a considerable intensity and it could potentially make an error.

This way, we can find out the quality and rate of the reliability for digital circuits. Therefore, one of the indicators to make comparison among the different circuits would be the intensity (I) of RTN and we can measure the circuits in diverse situations and capture RTNs to compare the reliability rate.

4. CONCLUSION

One of the most suitable analysis methods for RTNs as a non-stationary signal is EMD. In this paper, this tool and its application were introduced and a comparison among the existing methods was made. Firstly, we proposed the EMD thresholding method that could have a better result compared to the previous methods. Then, we analyzed the intrinsic modes for RTN and found the last modes are more similar to our desired data compared to the earlier modes. Therefore, we proposed to weight the modes in order to extract the pure RTN. The results show 14%, 27% and 19% improvement in SNR, MSE and PRD for the EMD Thresholding, respectively. Furthermore, the results also show 54%, 61% and 39% improvement in SNR, MSE and PRD for the weighted EMD, respectively.

5. ACKNOWLEDGEMENT

The authors would like to thank the Austrian Research Promotion Agency FFG, Institute for Microelectronics in TU-Wien and specially Dr. Tibor Grasser and Dr. Michael Waltl for their support in this research.

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Persian Abstract

چکیده

نویز تلگرافی تصادفی (RTN) یکی از پدیده‌های تصادفی ناخواسته در قطعات الکترونیکی است که باعث نوسانات در مشخصه‌های مدار می‌گردد. یافتن و استخراج مشخصه های این سیگنال می‌تواند در بدست آوردن مدل مناسب به منظور جبران سازی و بهبود پارامترهای افزاره مؤثر باشد. این اندازه گیری معمولاً همراه با مقادیری نویز و خطا همراه است و نیازمند روشی جهت بهبود نسبت سیگنال به نویز می باشد و بدست آوردن سیگنال RTN تمیز و دقیق از اهمیت زیادی برخوردار است. تجزیه مدهای ذاتی (EMD) به عنوان یک راهکار مناسب، کاملاً وفقی و وابسته به تغییرات سیگنال و بدون هیچگونه وابستگی به تابع خاص، می‌تواند در نظر گرفته شود. در این مقاله، روش‌های ارائه شده اخیر به همراه روش پیشنهادی برای سیگنال واقعی و مصنوعی RTN را جهت اطمینان از نتایج حاصل، ارزیابی کرده‌ایم. یافته‌های حاصل، دقت و عملکرد بالاتر روش وزن های بهینه شده را برای مقادیر نسبت سیگنال به نویزهای مختلف (SNR) و برای سیگنال‌های متنوع RTN تا ٥٤٪، ٦١٪ و ٣٩٪ به ترتیب بر اساس سه معیار SNR، MSE و PRD نشان می‌دهد. در پایان معیاری جهت بررسی و ارزیابی کیفیت و نرخ قابلیت اطمینان در مدارات دیجیتال معرفی گردیده است.