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Research Article

Investigating the Effect of EMI Generated by Random Gauss and Random Linear Modulations Controlled SiC Mosfet Based DC-DC Converter on G3-PLC

Murat Sen[1], Seda Ustun Ercan[2*]

[1]Ondokuz Mayis University, Department of Electrical and Electronic Engineering, Samsun, Türkiye. (e-mail: murat.sen@omu.edu.tr).
[2*] Ondokuz Mayis University, Department of Electrical and Electronic Engineering, Samsun, Türkiye. (e-mail: sedau@omu.edu.tr).

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Corresponding author: *Seda Ustun Ercan*

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ABSTRACT

High frequency switching elements that cause electromagnetic interference (EMI) are widely used in low voltage power distribution grid when considering todays smart grid components. One of these high frequency power electronic switching devices is the DC-DC converter.

EMI emissions from DC-DC converters directly affect the wired communication method known as power line communication (PLC), which can carry the communication signal from the transmitter point to the receiver point using the existing power lines of the distribution grid.

In this experimental research, the frame error rates (FER) of G3-PLC corresponding to Random Gauss and Random Linear Spread Spectrum Modulation (SSM) indexes were measured in real time, and the effect of EMI emissions of the Random SSM controlled silicon carbide mosfet based DC-DC converter on G3-PLC performance was revealed. The modulation index points that cause acceptable FER for G3-PLC were determined for Random Gauss and Random Linear SSM.

1. INTRODUCTION

Presently, conventional electricity distribution grids are undergoing a transformation into smart grids, encompassing the integration of communication technologies, along with the activation of components such as photovoltaic systems, energy storage systems, electric vehicles, and charging stations. The accelerated proliferation of these novel components has precipitated the substitution of traditional mechanical switches with state-of-the-art high-frequency semiconductor switches and power converters [1]. One such component is the DC-DC converter. The utilization of DC-DC converters has been demonstrated to result in an elevated rate of change in voltage and current (dv/dt, di/dt) during the processes of switching on and off. This phenomenon, known as switching, has been observed to generate electromagnetic interference (EMI) [2,3]. It is imperative that the EMI values generated by the DC-DC converter be mitigated and maintained within the limits specified by the established standards. Ensuring electromagnetic compatibility (EMC) is crucial to prevent uncontrolled EMI values from adversely impacting the power converter equipment itself, the operation of neighboring components, and the functionality of communication systems in the vicinity [4]. EMI emissions are classified under two subheadings. These are conducted EMI and radiated EMI. The propagation path of conducted EMI is cable connections and is effective in lower frequency switching (9 kHz-30 MHz), while the propagation path of radiated EMI is space and is effective at high frequencies (30 MHz-40 GHz) [5]. In the case of investigating the EMI effects emitted by DC-DC converters in the distribution grid, it is essential to note that conducted EMI is more likely to create a disruptive effect, especially in wired communication systems. Therefore, it should be given priority consideration. EMI measuring devices employ the International Special Committee on Radio Interference (CISPR)-16 standard to address the EMI parameters of electrical and electronic devices for conducted emissions between 9 kHz and 30 MHz. In addition, the utilization of a switching frequency between 9 and 150 kHz in the CISPR-16-A band is widespread among most DC-DC converters [6].

Power line communication (PLC) is a wired communication technology that is widely used especially in low voltage distribution grids. PLC could transmit data signals from the transmitter point to the receiver point using existing power lines. It is one of the most frequently preferred communication methods in remote smart meter reading implementations, which are smart grid operations [7,8]. PLC provides a number of advantages when utilized as a communication technology in smart grids. These advantages include a simplified installation process and a favorable cost-benefit ratio due to the utilization of existing power lines. Additionally, PLC exhibits broad coverage, reliability, and stability, along with measurability and flexibility. Its versatility extends to its compatibility with multiple smart grid applications and its ability to ensure cyber security through the implementation of internal protocols [9]. In addition to the advantages, the most significant parameter that directly affects PLC performance is EMI emissions. The source of these EMI emissions is periodic and non-periodic, synchronous, and asynchronous pulse noise in electrical grids [10]. One of the reasons for the formation of these pulse noises is the high-frequency irregular switching of SiC mosfet based DC-DC converters. Consequently, EMI emissions resulting from these converters must be considered when evaluating PLC performance. The performance of PLC can be determined by evaluating several parameters, including the received signal strength indicator (RSSI), the signal noise ratio (SNR), the bit error rate (BER), and the frame error rate (FER). Although RSSI, SNR, and BER provide valuable insight into the raw channel and physical-layer behaviors, FER serves as a holistic, MAC-layer–centric indicator that succinctly encapsulates link quality, error-correction effectiveness, and ultimately user-perceived reliability in G3-PLC networks. As a result, academic and standardization organizations generally present FER as the key performance indicator when evaluating narrowband PLC systems.

PLC has become a globally accepted communication technology, with its use having become standardized. A notable example is the extensively implemented G3-PLC standard. The G3-PLC standard operates within the narrow band (NB)- PLC frequency range. The European Committee for Electrotechnical Standardization (CENELEC), the organization that regulates standards in Europe, has determined the 3–148.5 kHz frequency band range for the implementation of the G3-PLC standard. This frequency band is subdivided into four sub-bands by G3-PLC, with the aim of accounting for operational differences. For smart grid and smart meter reading implementations in the distribution grid, G3-PLC employs the CENELEC-A band (35.9 kHz–90.6 kHz) frequency range. G3-PLC employs the Orthogonal Frequency Division Multiplexing (OFDM) scheme. The OFDM configuration enables the PLC to defend the data transmission signal against external interferences and to optimize the utilization of the frequency band allocated for communication. Beside this The G3-PLC standard is predicated on the use of the phase shift keying (PSK) technique. This technique facilitates communication between receiver and transmitter points by differentiating the phase information of the data signal to be transmitted [11].

It is known that EMI emissions directly affect PLC performance. EMI emissions of DC-DC converter controlled by spread spectrum modulation (SSM) can be changed. In this research, SiC mosfet based DC-DC converter was controlled by using Random Gauss and Random Linear modulations which are SSM techniques. As a result of this control, the effect of EMI emitted from the converter on G3-PLC performance was measured with real-time experiments in laboratory environment.

2. SPREAD SPECTRUM MODULATION

SSM techniques are used to distribute concentrated energy in the spectrum by using different switching frequencies, which reduces EMI level [12]. SSM has the capacity to transform EMI spikes into multiple sideband harmonics, characterized by diminished amplitude. The generation of high EMI is attributed to the presence of concentrated energy. The SSM possesses the capability to redistribute the energy of EMI spikes, effectively shifting it from the peak to the lower zone. This process entails a transformation of the spectrum, characterized by a reduction in amplitude and an augmentation in continuity, while maintaining constant total spectral energy [13]. This situation is observed in Figure 1 [14].

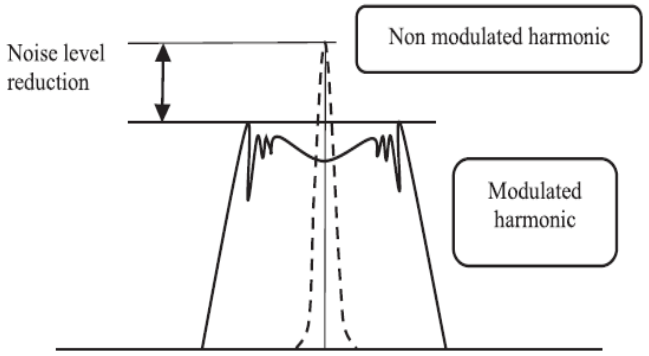

Figure 1. Spread spectrum modulation effect

SSM types are divided into periodic sine and sawtooth, aperiodic random gauss and random linear. Random gauss modulation is a technique in which the signal is modulated based on a gaussian distribution. Random linear modulation is a technique in which the signal is modulated as a linear function. In the SSM technique, there are major parameters that play a role in the process of reducing the amplitude of the interference signal by spreading it to a wider frequency band with variable frequency modulation. The parameters in question are listed as follows: modulation index (m), sampling frequency (f_m), spreading factor (α), and center frequency (f_c) value. In consideration of the Carson band rule, the mathematical relationship between these parameters is illustrated by equal 1.

$$m = \frac{\Delta f}{f_m} = \frac{(\alpha f_c)/2}{f_m} \tag{1}$$

Moreover Δf parameter defines the relationship between the (f_c) and (α) [15].

3. LABORATORY EXPERIMENTAL SETUP

In this section, the basic elements used in the experimental setup and their functions are explained. First, the SiC mosfet based DC-DC converter used in the experiments, then the PLC evaluation boards and finally the other experimental setup components will be introduced. The basic elements of the experimental setup shown in Figure 2 are variac, isolation transformer, LISN, DC-DC converter, microcontroller, coupling circuit for the effect of the DC-DC converter's high-frequency switching on the AC line, and Microhip PL360-Additional boards for G3-PLC FER measurements. All of these elements must be connected to a common ground point.

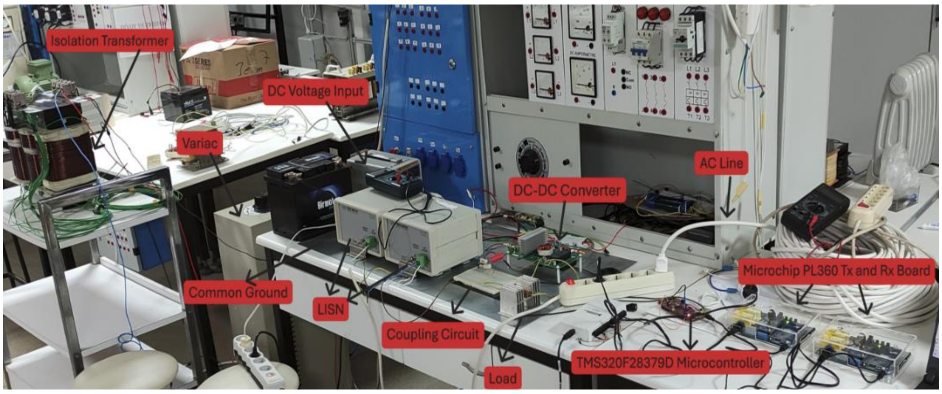

Figure 2. Experimental setup

3.1. SiC Mosfet Based DC-DC Converter

In all experiments, a SiC mosfet based DC-DC converter is utilized, as illustrated in Figure 3. The emission of EMI is dependent upon the type of semiconductor used in the DC-DC converter. This dc-dc converter was operated in buck mode in all experiments and used at 50 % duty cycle. It was controlled by Random Gauss and Random Linear SSM at center frequency of 63 kHz as f_c according to Carson rule. 4 Ω ohmic load was used at the output of the DC-DC converter [16]. The generation of a 14 V DC output was achieved through the utilization of 28 V DC at the DC-DC converter input. In addition, SiC based Mosfet maximum switching frequency is 100 kHz. Buck mode circuit diagram is shown in Figure 4 [17]. The center frequency 63 kHz as $f_c$will be changed by the amount of Δf within the SSM operating frequency band using the spreading factor α. Various modulation index m values will then be generated by comparing them to different f_m sampling frequencies, and the effects of EMI generated by different high-frequency DC-DC converter switching on FER values will be measured in real time.

Figure 3. SiC mosfet based DC-DC converter

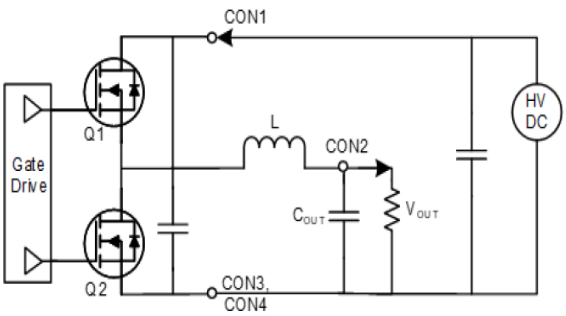

Figure 4. Buck mode circuit diagram

3.2. PLC Evaluation Board

Two Microchip PL360-Ek evaluation boards were used for experiments. One positioned at the transmitter point and the other at the receiver point, as depicted in Figure 5 [18]. These boards were employed to facilitate data transmission with the PLC method on the AC line and to assess the performance of the PLC. The Microchip PL360-Ek evaluation boards have been programmed to operate in accordance with the G3-PLC standard in the CENELEC-A band. The G3-PLC standard utilizes Quadrature Phase Shift Keying (QPSK), modulation for data transmission between transceivers. The Microchip PHY Tester Tool program, which is part of the boards in these experiments, transmitted 4000 frames containing data from the transmitter to the receiver. The program then measured the number of successfully transmitted and received frames between the transmitter and receiver and calculated the %FER value of the PLC performance.

In addition to the DC-DC converter and PLC evaluation board equipment, other elements and their functions in the experimental setup are listed as follows. TMS320F28379D microcontroller was used to manage DC-DC converter switching with Random Gauss and Random Linear SSM control blocks created in Matlab/Simulink environment. Isolation transformer and Line Stabilization Impedance Network (LISN) filtered the impacts originating from the distribution grid and ensured that only the EMI effects emitted by the DC-DC converter remained in the experimental setup where PLC performance was measured. The coupling circuit consists of series-connected resistance and capacitance. DC-DC converter transfers the EMI effects resulting from high-frequency switching to the AC line where PLC performance is measured via the common ground line created in the experimental setup.

Figure 5. Microchip PL360-Ek evaluation board

4. RESULTS AND DISCUSSION

The Results and Discussions section presents graphs with real time measured G3-PLC FER values corresponding to m obtained for α=0.1, 0.3, 0.6, 0.8 and 1 deploying SSM Random Gauss and Random Linear techniques for DC-DC converter control. In addition, the highest and lowest G3-PLC %FER values of SSM Random Gauss and SSM Random Linear methods, which are of critical importance for each α parameter, measured in real time at different modulation indexes are presented in Table I. Beside this the text goes on to discuss other common SSM types, and the importance of SSM-controlled DC-DC converters, EMI and the relationship between G3-PLC is revealed.

When Figure 6 is examined, it is seen that Random Linear modulation reaches the highest FER value for m =3.15 and this is 6.60% FER. On the other hand, Random Gauss modulation achieves only 1.52% FER for m=3.15. The maximum FER value for Random Gauss is determined as 5.88% for m =18.9. For this m value, Random Linear FER continued its decreasing trend and was read as 2.37%. Random Gauss modulation converged to zero in the transmitted data error rates with FER values 0.12% - 0.15% in the range of m=6.3-12.6 and presented a suitable control range for the success of G3-PLC. After reaching the maximum FER values, both modulation types exhibited a decrease in error rates and approached each other with 0.87% FER and 0.95% FER for m=47.25.

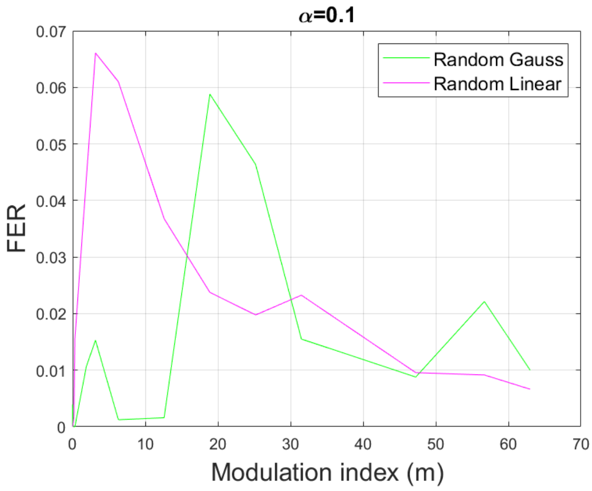

Figure 6. Random gauss-random linear modulation for $\boldsymbol{\alpha}$=0.1

In case of comparing Random Gauss and Random Linear modulations for α =0.3 in Figure 7, the first notable detail is that the FER parameter of the Random Linear modulation increases rapidly from the initial m values and reaches a very high point of 41.66% for m=56.7. The Random Linear modulation FER parameter started to decrease for other m values and then the lowest FER was recorded as 12.78% at m =189. Random Gauss modulation clearly has a positive difference in terms of G3-PLC performance compared to Random Linear modulation. The highest FER value reached by Random Gauss modulation was only 9.98% for m =75.6. Also, Random Gauss modulation provided two different control ranges that would not deteriorate G3-PLC performance with 3.34% FER and 3.58% FER in the range of m =5.67 and m =37.8, 2.86%FER and 2.98% FER in the range of m =170.1 and 189.

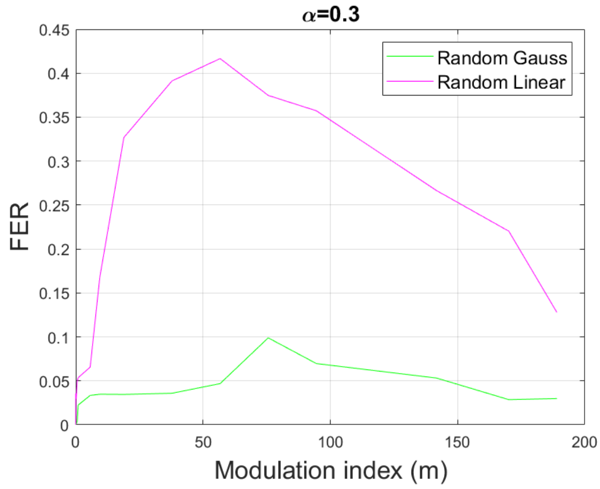

Figure 7. Random gauss-random linear modulation for $\boldsymbol{\alpha}$=0.3

As depicted in Figure 8, for α=0.6, the Random Gauss maximum FER value begins to approach notably high values, similar to those observed for Random Linear FER values. However, Random Linear modulation still demonstrates the highest error rates. Random Linear modulation reached 49.73\% peak FER for m=151.2. Then it decreased to 27.57% FER for m=378. Random Gauss modulation peak FER value was observed as 39.6% at m=113.4. There is a remarkable detail for Random Linear. Random Linear has zero FER value from the beginning to m=37.8. This means that the EMI value emitted by SiC mosfet based DC-DC converter is reduced by SSM Random Linear method without any error in G3-PLC operation even with a short control interval. Despite this situation, FER parameters remained at elevated levels throughout the m values for both SSM modulation types.

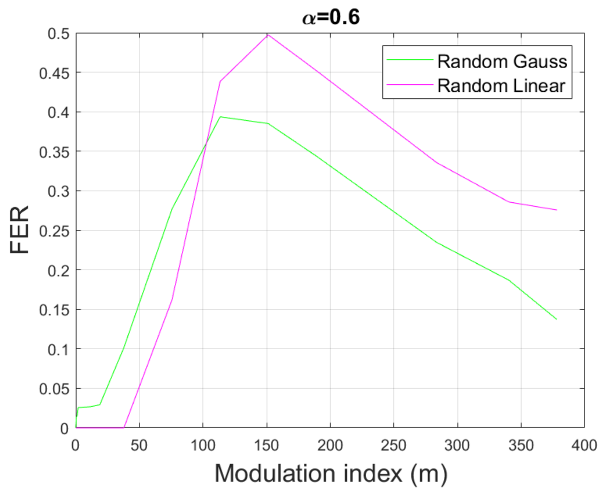

Figure 8. Random gauss-random linear modulation for $\boldsymbol{\alpha}$=0.6

The most critical outcome of employing the spreading factor α=0.8 in given Figure 9 is that, in contrast to the scenarios prior to α=0.8, the Random Gauss peak FER value exceeds the Random Linear peak FER value. The highest FER was obtained by Random Gauss with 44.80\% for m=252. For Random Linear, the maximum FER was recorded at m=252, with 31.58% of the total. The noteworthy finding is that both modulation types reach the maximum FER value at the same m value. Another notable observation is that Random Linear Modulation does not generate any erroneous data bits in G3-

PLC operation from the initial phase to the m=50.4 index, thereby data transmission resulting in zero FER.

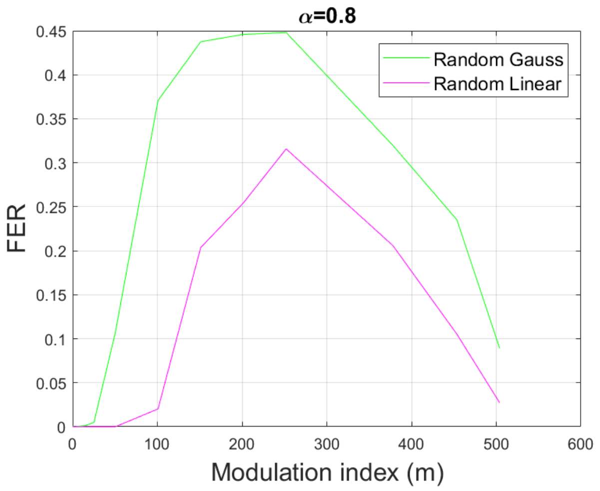

Figure 9. Random gauss-random linear modulation for $\boldsymbol{\alpha}$=0.8

Figure 10 indicates that the peak FER of Random Gauss modulation keeps rising as α increases, while the peak FER of Random Linear modulation continues falling. The Random Gauss modulation has been found to have the highest FER value, with 45.65% for m=189. On the other hand, Random Linear displays the highest FER value of 22.69% for m=315. Furthermore, after the Random Gauss modulation arrived at the maximum error rate, the FER value began to decline, reaching 8.92% for m=504. Initially, the Random Linear modulation had 0% FER value up to the index m=50.4, after which it experienced a slight increase, reaching 2.02% FER for m =100.8.

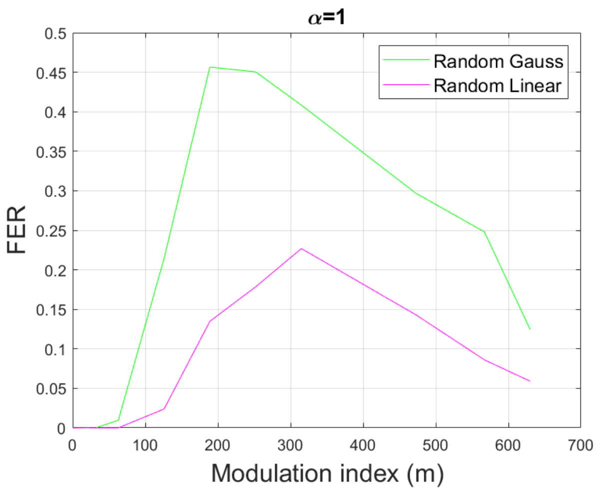

Figure 10. Random gauss-random linear modulation for $\boldsymbol{\alpha}$=1

The important FER values determined in the graphs for Random Gauss and Random Linear modulations are arranged in Table I according to α.

DC-DC converters are high-frequency switching elements that are frequently employed in essential smart grid components, including photovoltaic systems, energy storage systems, electric vehicles, and charging stations [19]. The EMI values emitted by these DC-DC converters have a direct impact on the success of PLCs, which are a method of enabling point-to-point data transfer in smart grid components. The objective of this study was to determine the modulation index points at which the G3-PLC exhibits the least error by controlling DC-DC converter EMI values using random Gaussian and random linear SSM methods. In addition to random Gaussian and random linear methods, there are also other SSM methods, such as periodic SSM, which uses sine and sawtooth signals [20]. It is also possible to exercise control over the DC-DC converter using these methods. PLC measurements, particularly in systems where the DC-DC converter is controlled with Sawtooth SSM, demonstrate that the FER value is lower than that of other SSM types [21].

TABLE I
COMPARISON OF RANDOM GAUSS AND RANDOM LINEAR FER VALUES

α	R. Gauss Min. FER%	R. Gauss Max. FER%	R. Linear Min. FER%	R. Linear Max. FER%
0.1	0.12	5.88	0.87	6.60
0.3	2.86	9.98	12.78	41.66
0.6	2.91	39.60	0.00	49.73
0.8	0.12	44.80	0.00	31.58
1	0.90	45.65	0.00	22.69

5. CONCLUSION

The performance of the G3-PLC was investigated in relation to the EMI values of a SiC mosfet based DC-DC converter switched with Random Gauss and Random Linear procedures, which are SSM approaches. Random Gauss and Random Linear modulations were compared and the SSM modulation parameters that achieved optimum results in terms of data transmission success with G3-PLC were defined. For α 0.1, both the Random Gauss and Random Linear modulation parameters reduced the EMI of the DC-DC converter, provided the lowest FER values, and created the most suitable operating mode for the G3- PLC. It has been determined that, for α value less than or equal to 0.6, Random Gauss modulation should be preferred to Random Linear modulation regarding achieving success in G3-PLC. However, this situation changes after α value greater than 0.6 are reached. It has been observed that the peak FER values for Random Gauss modulation exceed those for Random Linear modulation when α value are equal to 0.8 and 1. Furthermore, there exist m indices where the FER value is initially zero for spreading factors α=0.6, α=0.8, and α=1. These circumstances suggest that the Random Linear technique is the optimal choice for G3-PLC when α is greater than or equal to 0.6.

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BIOGRAPHIES

Murat Sen was born in Türkiye. He received the B.Sc. degree in electrical engineering from Kocaeli University, Türkiye in 2010 and the M.Sc. degree in electrical and electronic engineering from Ondokuz Mayis University, Samsun, Türkiye in 2021. He is currently Ph.D. student in the department of electrical and electronic engineering at Ondokuzmayıs University and works as a lecturer at Yesilyurt Demir Celik Vocation School Electronic Technology Program of Ondokuzmayıs University. His research interests include power line communication, electric distribution, smart metering and smart grid.

Seda Ustun Ercan was born in Türkiye. She received the B.S, M.Sc., and Ph.D. degrees in electrical and electronic engineering from Ondokuz Mayis University, Samsun, Türkiye, in 2005, 2009, and 2016, respectively. She was a Postdoctoral Researcher in electrical and electronic engineering with the University of Nottingham, Nottingham, U.K. She is currently an Associate Professor with the Department of Electrical and Electronics Engineering, Ondokuz Mayis University. Her research interests include power line communication and digital signal processing.