

Research on Secure Communication of Electric Power IoT in Shore Power Scenarios

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Abstract. In the complex electromagnetic environment of port shore power systems, the operation of various power electronic devices generates both persistent interference within fixed frequency bands and transient narrowband pulse interference. To address this challenge, this paper proposes a novel frequency-hopping sequence generation method that integrates a lightweight encryption algorithm with the dual-band method. The generated sequences not only satisfy stringent wide-interval requirements but also exhibit excellent randomness characteristics.

Keywords: shore power; the dual-band partitioning method; wide-Interval frequency-hopping sequence.

1. Introduction

In the complex electromagnetic environment of port shore power systems [1, 2], various power electronic devices, as shown in Fig. 1, generate continuous interference within fixed frequency bands and transient narrowband pulse interference during operation. Traditional frequency-hopping communication systems [3,4] using sequences with small frequency intervals between adjacent channels are prone to situations where multiple consecutive hopping frequencies simultaneously fall into interference bands. This phenomenon leads to persistent communication link interruptions, severely compromising system reliability. To address this issue, wide-interval frequency-hopping technology incorporates strict minimum interval constraints between adjacent channels, ensuring that when interference occurs at a specific frequency, the system can rapidly switch to "clean" frequency bands far removed from the current interference range. This large-span frequency switching strategy not only effectively avoids consecutive communication interruptions but also significantly enhances the system's anti-interference capability and communication reliability in complex electromagnetic environments.



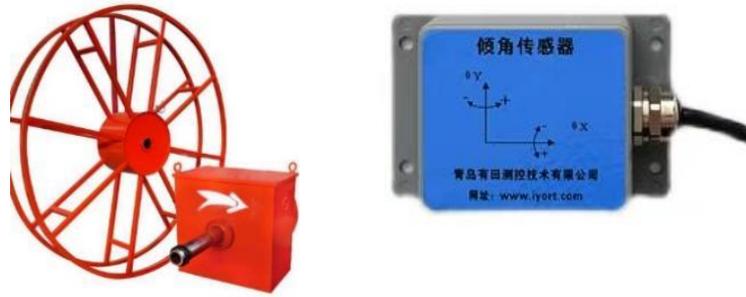


Fig. 1 Common Equipment in Shore Power Terminals

2. Definition of Wide-Interval Frequency-Hopping Sequences

2.1 Comparison Between Narrow-Sense and Generalized Wide-Interval Frequency-Hopping Sequences

Fig. 2 and Fig.3 respectively demonstrate the topological characteristics of narrow-definition and broad-definition wide-interval sequences from a spectral distribution perspective. Comparative analysis of the graphical structures clearly reveals their topological distinctions:

In the narrow-definition wide-interval model, the system configures the geometric relationship between spectral extremes (maximum and minimum values) as adjacent elements, forming a closed-loop frequency-domain association. Conversely, the broad-definition model employs an endpoint distribution strategy for extreme frequencies, positioning the maximum and minimum frequencies at polar opposite ends of the spectral set to establish an open-loop frequency-domain topology.

This spatial visualization distinctly illustrates the fundamental differences in topological relationships between frequency extremes: the narrow-definition model achieves frequency concentration through adjacent extreme values, while the broad-definition model enhances spectral discreteness via endpoint distribution of extremes.

The frequency-band partitioning design methodology comprises two primary steps:

1. Dividing the frequency band into multiple sub-segments while ensuring each satisfies the wide-interval constraint
2. Mapping codewords to sub-bands using predetermined rules, with typical approaches including: the mid-band elimination method [5] and the dual-band method [6][7]

This study adopts the dual-band method for generating wide-interval frequency-hopping sequences.

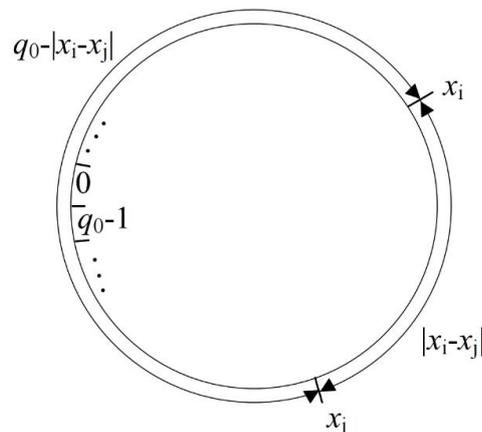


Fig. 2 Schematic of narrow-definition wide-interval sequence

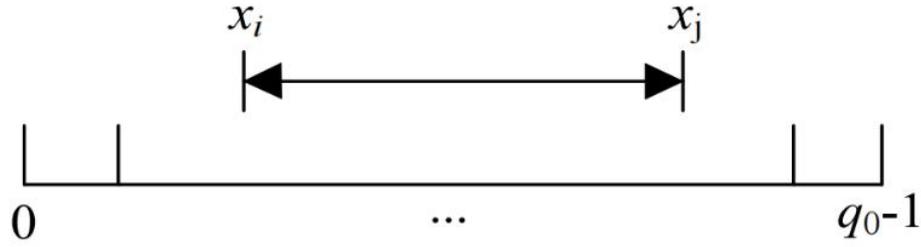


Fig. 3 Schematic of broad-definition wide-interval sequence

2.2 The Dual-band Partitioning Method

The specific implementation process of the dual-band partitioning method is as follows:

First, given the frequency-hopping interval d and the frequency band F , partition it into two dual bands F_1 and F_2 containing an equal number of frequency-hopping slots. The expressions for F_1 and F_2 are as follows:

$$F_1 = \{f_i, 0 \leq i < \lfloor q/2 \rfloor\} \quad (1)$$

$$F_2 = \{f_i, q - \lfloor q/2 \rfloor \leq i < q\} \quad (2)$$

The dual frequency point pairs on F_1 and F_2 can then be expressed as $(f_i, f_{i+q-\lfloor q/2 \rfloor})$, where $0 \leq i < \lfloor q/2 \rfloor$.

Next, by processing F_1 , we obtain the frequency-hopping sequence $\{w_u(j)\}$. Based on the dual frequency point pairs, we construct the corresponding frequency-hopping sequence $\{w'_u(j)\}$ in band F_2 as follows:

$$w'_u(j) = w_u(j) + \lfloor (q + 1)/2 \rfloor \quad (3)$$

Finally, using $\{w_u(j)\}$ on F_1 as the initial sequence: when encountering a frequency point that doesn't meet the wide-interval criterion, immediately switch to $\{w'_u(j)\}$ on F_2 to obtain the corresponding frequency point. When another non-compliant frequency point is encountered, switch back to the corresponding point in $\{w_u(j)\}$ on F_1 . Through this alternating selection method, we gradually obtain a frequency-hopping sequence that satisfies the wide-interval requirements.

3. Wide-Interval Frequency-Hopping Sequence Generation Method

The proposed scheme in this paper primarily generates a base sequence $BS = \{bs_i, i = 0, 1, 2, \dots\}$ by encrypting the input time of day (TOD) and cryptographic key (KEY) through a lightweight block cipher algorithm. Subsequently, the frequency-hopping base sequence BS is remapped according to the required number of frequency-hopping slots q_t and hopping interval d_t in the current environment to obtain the wide-interval frequency-hopping sequence. This study adopts the dual-band method to generate the wide-interval frequency-hopping sequence.

4. Performance Analysis

The study validates the algorithm's compliance with fundamental spacing requirements by testing frequency-hopping sequences under rigid constraint conditions with intervals set to $d_t = 10, 15, 20, \text{ and } 25$, as shown in Table 1. All generated wide-interval frequency-hopping sequences meet the specified performance criteria, with the minimum interval consistently satisfying $d_{\min} \geq d_t$ and the average interval exceeding the required d_t value. These results demonstrate that the proposed method successfully generates frequency-hopping sequences with excellent wide-interval characteristics across all test cases.

Table 1. Wide-interval frequency-hopping sequence spacing value table

| Minimum Interval | Average Interval |
|------------------|------------------|
| 10 | 15.3541 |
| 15 | 23.8542 |
| 25 | 47.8542 |

Periodicity serves as a core evaluation metric for the security of frequency-hopping sequences, characterizing the minimum repeating unit of frequency symbols that recur at specific time intervals or in particular patterns. The length of this period directly determines the system's anti-interception capability and anti-jamming performance. Long-period sequences significantly increase the difficulty for attackers to capture complete periodic samples by extending the temporal span of repeating units, while short-period sequences, due to their higher risk of exposing repetitive patterns, are more vulnerable to having their key pattern features intercepted within limited observation windows, thereby enabling targeted jamming.

Fig 4 displays the frequency-hopping sequence pattern generated by the algorithm described in this paper, observed within the system clock range $TOD \in [2500, 3000]$, with the following characteristics:

The frequency distribution exhibits an aperiodic arrangement, with no fixed order or arithmetic spacing patterns appearing across consecutive hopping cycles.

No repetition of local frequency combinations occurs within 2500 clock cycles.

There is no discernible mathematical correlation between frequency hops in adjacent time segments, making it impossible to extract periodic patterns using conventional analytical methods.

Experimental results demonstrate that this sequence avoids periodicity flaws, making it extremely difficult for attackers to deduce the global frequency-hopping pattern through time-frequency analysis or pattern-matching techniques, even if partial communication data is intercepted. This significantly enhances the wireless communication capability of shore power systems in complex electromagnetic environments.

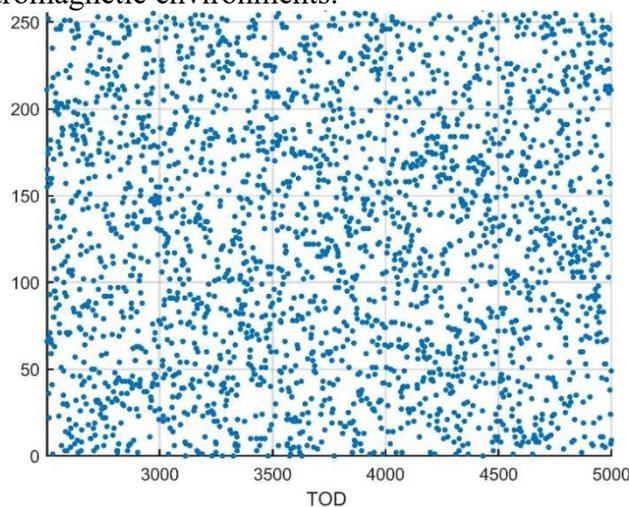


Fig. 4 Frequency-hopping pattern

5. Summary

Therefore, the wide-interval frequency-hopping sequence generation method proposed in this study not only meets the wide-interval requirements but also maintains both uniformity and randomness of the hopping sequences, serving as an effective solution for secure wireless communication in shore power systems.

6. References

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