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CURRENTS OF SINGLE-PHASE INDUCTION MOTORS SUPPLIED WITH VOLTAGE CONTAINING INTERHARMONICS

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Abstract: In real power systems, the voltage waveform is not a perfect sine, but contains various additional frequency components, like harmonics, and in some power systems also subharmonics and interharmonics, which are components of a frequency less than the fundamental frequency or not being its integer multiple. This paper deals with the effect of voltage interharmonics on currents of a single-phase induction motor with a permanently connected capacitor. It was found that the current characteristics are different from the analogical ones determined for a 3-phase induction motor.

Keywords: interharmonics, power quality, single-phase induction motor, voltage waveform distortions.

1. INTRODUCTION

In real power systems, the voltage waveform is not a perfect sine, but contains various additional frequency components, like harmonics [Bollen and Gu 2006], and in some power systems also subharmonics and interharmonics [Xie, Zhang and Liu 2017; Nassif 2019; Xu et al. 2025] that are components of a frequency less than the fundamental frequency or being not its integer multiple.

Subharmonics and interharmonics are generated by power electronic equipment, renewable energy sources and variable power loads, among others. Frequency converters and high-voltage DC links are particularly significant sources of subharmonics and interharmonics [Testa et al. 2007; Nassif 2019]. Both types of this equipment are used to interconnect systems that vary in frequency using rectifiers, DC links, and output inverters [Testa et al. 2007]. If a DC link contained a capacitor of infinite capacitance or an inductance of infinite value, there would be no voltage or, respectively, current ripple [Testa et al. 2007]. In practice, there are voltage/current pulsations in DC links. Consequently, subharmonics and interharmonics of significant magnitude can occur in both the mains and the output voltage [Tripp et al. 1993; Zhang, Xu and Liu 2005]. For example, [Nassif 2019] found that a 45 Hz subharmonic and interharmonics at 135 Hz, 225 Hz and 405 Hz were simultaneously present in a system with a rated frequency of 60 Hz, and the values of these harmonic types were 0.9%, 1.17%, 0.89% and 0.931 respectively.

Wind turbines [Bollen and Gu 2006; Xie, Zhang and Liu 2017; Verma et al. 2023] and photovoltaic plants [Ravindran et al. 2020; Zhong et al. 2021; Umadevi, Lakshminarasimman and Sakthivel 2023; Xu et al. 2025] are another significant source of subharmonics and interharmonics, especially during emergency conditions. For example, in [Xie, Zhang and Liu 2017], a subharmonic of 1–2% and a frequency of about 8 Hz were recorded during a subharmonic resonance event.

Subharmonics and interharmonics are also generated by loads that consume time-varying power, such as synchronous and asynchronous motors driving devices with variable resistive torque – like reciprocating compressors [Zhiyuan et al. 2017; Arkkio et al. 2018; Avdeev et al. 2021]. In [Zhiyuan et al. 2017], a 7.5 kW motor driving a reciprocating compressor produced voltage subharmonics of up to 0.5%, with interharmonics of up to approximately 0.4%.

Note that periodic voltage fluctuations [Gallo et al. 2005; Bollen and Gu 2006; Kuwałek 2021a,b; 2022] can be regarded as a case of simultaneous subharmonics and interharmonics [Gallo et al. 2005; Bollen and Gu 2006; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2021a,b; Gnaciński et al. 2022, 2024;].

Subharmonics, interharmonics and associated voltage fluctuations disturb various electrical loads [Gallo et al. 2005; Bollen and Gu 2006; Gil-de-Castro, Rönnberg and Bollen 2017; Kuwałek 2021a,b; 2022].

A type of load particularly sensitive to these disturbances is asynchronous squirrel-cage motors. In these motors, subharmonics and interharmonics cause effects that include increased power losses and higher winding temperature [Gallo et al. 2005; Ghaseminezhad et al. 2017a,b; 2021], local saturation of the magnetic circuit [Tennakoon, Perera and Robinson 2008; Gnaciński et al. 2019a,b; 2021, 2023; Pepliński et al. 2017a,b; 2021; 2022; Pepliński and Gnaciński 2024], torque pulsation [Gnaciński et al. 2019a; 2021, 2023; Ghaseminezhad et al. 2021], speed fluctuations [Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2017a; 2021a,b; Gnaciński et al. 2021a,b; Zhang, Kang and Yuan 2021], and excessive vibration and torsional oscillation [Tripp, Kim and Whitney 1993; Gnaciński et al. 2019; 2021; 2023; 2024], which – in extreme cases – lead to failure of the drive unit.

Particularly significant oscillations occur during torsional vibration resonance of a rigid body [Arkkio et al. 2018; Gnaciński et al. 2019a,b; 2021; 2024]. On the other hand, during torsional vibration resonance of a deformable body, there can be a torque amplification by up to 100 times [Tripp, Kim and Whitney 1993], which can lead, for example, to coupling rupturę. Torsional vibration resonance (of a rigid or deformable body) occurs when the frequency of the torque pulsation matches the natural frequency of the rotating masses [Tripp, Kim and Whitney 1993; Arkkio et al. 2018; Gnaciński et al. 2019a,b; 2021; 2024].

Note that the harmful phenomena occurring in an asynchronous motor supplied with a voltage containing the disturbances of interest are generally related to the flow of a current subharmonic and interharmonic through the motor windings.

The prevailing voltage quality standards, PN-EN 50160 [PN-EN 50160] *Voltage Characteristics of Public Distribution Systems* and *IEEE Standard for Harmonic Control in Electric Power Systems* [IEEE Standard 519] do not specify any acceptable levels of subharmonics and interharmonics. Only the information section in [IEEE Standard 519] indicates two proposals to limit the level of these harmonics to about 0.3% and about 0.5%, respectively. The standardisation of voltage subharmonic and interharmonic limits requires further in-depth research into things like the effects of the considered disturbances on asynchronous motors.

The research into asynchronous motors supplied with voltages containing subharmonics and interharmonics to date has been focused on three-phase motors [Tripp, Kim and Whitney 1993; Gallo et al. 2005; Tennakoon, Perera and Robinson 2008; Ghaseminezhad et al. 2017a,b; 2021; Gnaciński et al. 2019a,b; 2021; 2023; 2024; Pepliński 2021; Zhang, Kang and Yuan 2021; Pepliński et al. 2022; Pepliński and Gnaciński 2024]. The problem of the effect of the disturbances of interest on a single-phase asynchronous motor is mainly the focus of these authors' previous works [Pepliński 2021; Pepliński, Adamczak and Gnaciński 2022; Pepliński and Gnaciński 2024]. Note that the subject of the works was a single-phase motor under cyclic voltage fluctuations and a motor supplied with a voltage containing subharmonics and interharmonics at a frequency below 100 Hz.

This paper is an analysis of the currents in a single-phase asynchronous motor supplied with a voltage containing interharmonics ranging from 100 Hz to 400 Hz. This research was experimental.

2. DESCRIPTION OF THE TEST SETUP

The test setup comprised a single-phase induction motor with a permanently online capacitor, a programmable voltage source, a digital oscilloscope, and a voltage quality monitor.

The induction motor under test was coupled to a type PKBa12a/101 DC machine. The motor originally tested was part of the JETW-B/800-50 pressure booster set [*Pumps and pressure boosters.Webermann pressure booster sets*], the ratings of which are listed in Table 1.

The motor was powered by a Chroma 61512+A615103 programmable voltage source [*Programmable AC Power Source 61511/61512*], through which the test setup was able to force various voltage quality disturbances, like voltage harmonics, subharmonics and interharmonics, phase and amplitude imbalance, voltage dips, and frequency and RMS voltage fluctuations. Selected parameters of the programmable voltage source are shown in Table 2.

A Tektronix type TBS 2000B digital oscilloscope was used to record currents and voltages, and a PC-based power quality monitor was used to determine the sub- and interharmonic components in the recorded waveforms.

A simplified diagram of the test setup is shown in Figure 1.

Table 1. Ratings of the JETW-B/800-50 pressure booster set

Assembly type: motor-pump	**JETW-B/800-50**
Motor	single-phase
Nominal power [kW]	0.8
Nominal voltage [Hz]	230
Nominal frequency [Hz]	50
Pump capacity	50l/min.
Head	40 m
Insulation class	B

Source: Pumps and pressure boosters.Webermann pressure booster sets.

Table 2. Selected parameters of the Chroma 61512+A615103 programmable voltage source

Rated power [kW]	36
Output line voltage range [V]	0–150/0–300
Output frequency range [Hz]	DC, 15–1500
Output voltage accuracy [%]	0.2+0.2 full range
Output voltage phase accuracy of [%]	0.8 at 50/60 Hz
Output frequency accuracy [%]	0.15
Output voltage distortions [%]	0.3 at 50/60 Hz

Source: Programmable AC Power Source 61511/61512.

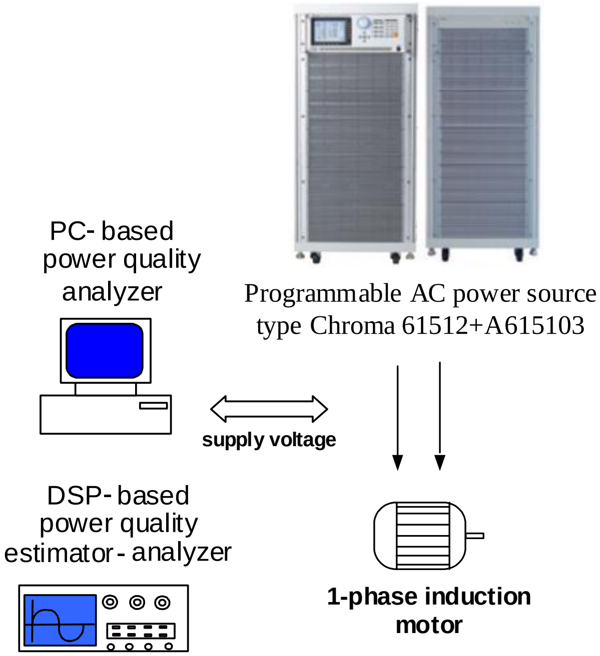

Fig. 1. Diagram of the test setup

Source: [Pepliński 2021].

3. RESULTS

The following are experimental results of a single-phase asynchronous motor supplied with a voltage containing a single interharmonic at 1% of the frequency between 101 Hz and 399 Hz. Figures 2 to 7 are for the idling motor, while Figure 8 is for the motor under load.

Figures 2 to 4 show an example of the current drawn by the motor (Fig. 2), the current spectrum (Fig. 3), and the test voltage spectrum (Fig. 4) for a supply voltage containing an interharmonic at 160 Hz. The voltage interharmonic resulted in an interharmonic current flow of 0.17 A (approximately 12% of the fundamental current harmonic), and no current subharmonics were present. Note that both interharmonics and subharmonics of current are usually present in the current drawn by a three-phase motor supplied with a voltage containing an interharmonic at a frequency not higher than double the frequency of the fundamental component [Tennakoon, Perera and Robinson 2008; Gnaciński et al. 2021]. Low current subharmonics were also found for a three-phase motor supplied with a voltage containing an interharmonic at a frequency higher than double the fundamental frequency [Gnaciński et al. 2023].

In addition to the interharmonic, the spectrum in Figure 3 contained harmonics associated with the non-linearity of the magnetic circuit, i.e. the 3rd and 5th current harmonics were equal to 0.42 A and 0.13 A, respectively.

For comparison, the following figures (Fig. 5 and 6) show the spectrum of the motor current draw for a supply voltage containing an interharmonic at 220 Hz (Fig. 5) and for a supply voltage without an interharmonic (Fig. 6).

Figure 7 shows the characteristics of the current interharmonic as a function of the voltage interharmonic frequency. The current interharmonic had its highest values at a frequency of approximately 160 Hz, which was likely related to resonance phenomena. There was also a local maximum (0.12 A) at 280 Hz. For other frequencies, the interharmonic generally did not exceed 0.1 A. Note that the characteristics discussed above differ significantly from the analogous plot made for an example three-phase motor rated at 3 kW [Gnaciński et al. 2023]. For the frequency range considered and the three-phase motor, the current interharmonic is approximately inversely proportional to the voltage interharmonic frequency, revealing only low local maximum values and a local minimum.

The characteristics of the interharmonic current as a function of the interharmonic voltage frequency for the loaded motor are shown in Figure 8. As with the zero-load motor (Fig. 7), the interharmonic current reached its maximum value (0.19 A) at a frequency of 160 Hz. In summary, the current interharmonics assumed their highest values at 160 Hz, which was probably due to resonance phenomena.

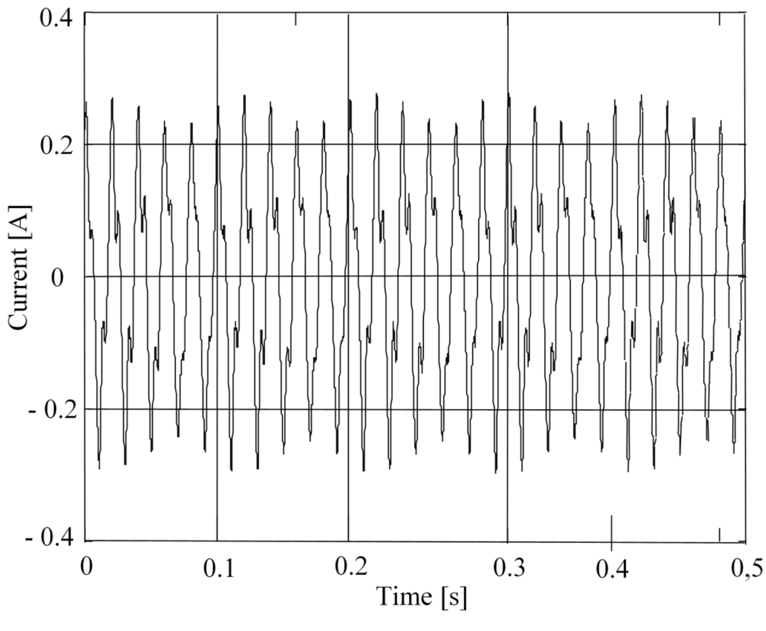

Fig. 2. Registered current waveform of the unloaded motor fed with a supply voltage containing a 160 Hz interharmonic

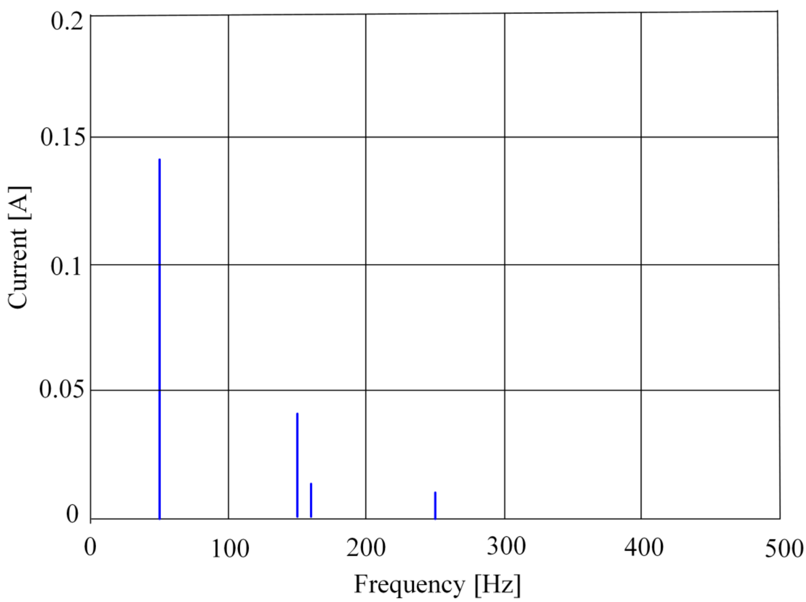

Fig. 3. Waveform spectrum for the current shown in Figure 2

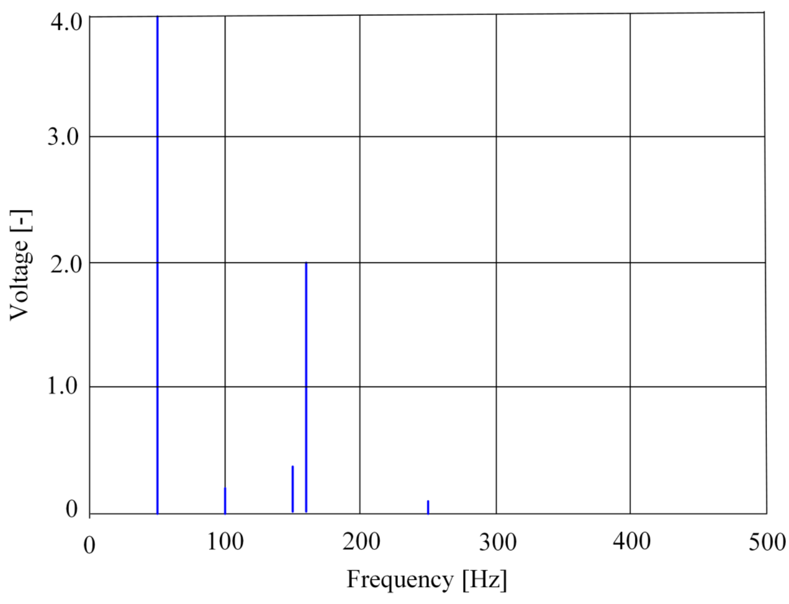

Fig. 4. Test voltage spectrum for the case shown in Figure 2 and Figure 3

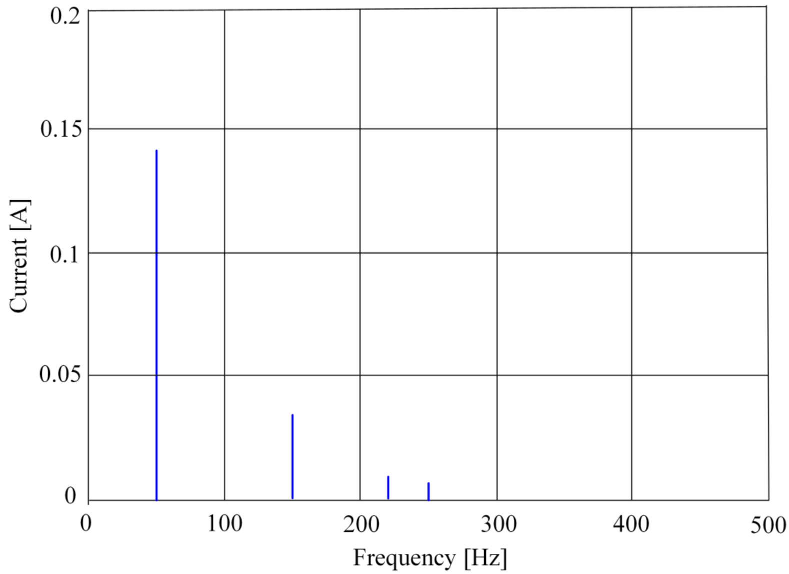

Fig. 5. Current waveform spectrum for the unloaded motor fed with a supply voltage containing a 220 Hz interharmonic

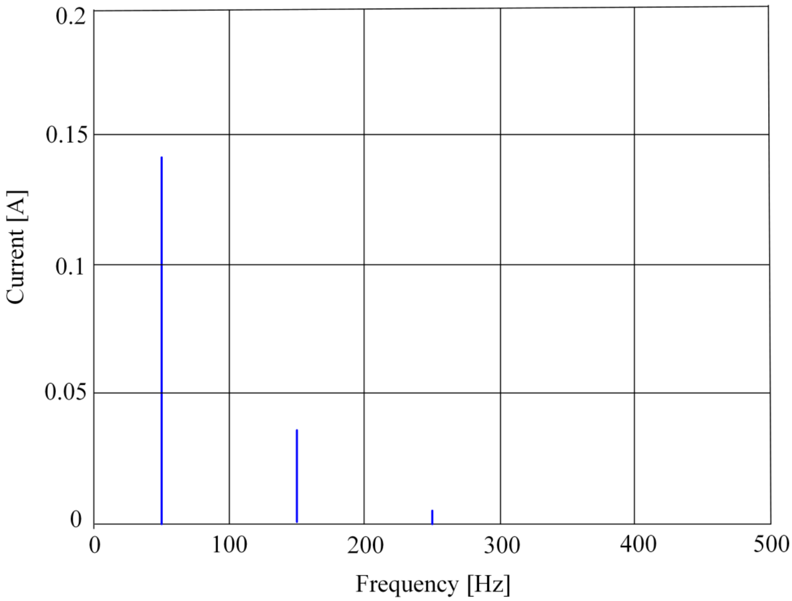

Fig. 6. Current waveform spectrum for the unloaded motor and a supply voltage free of interharmonics

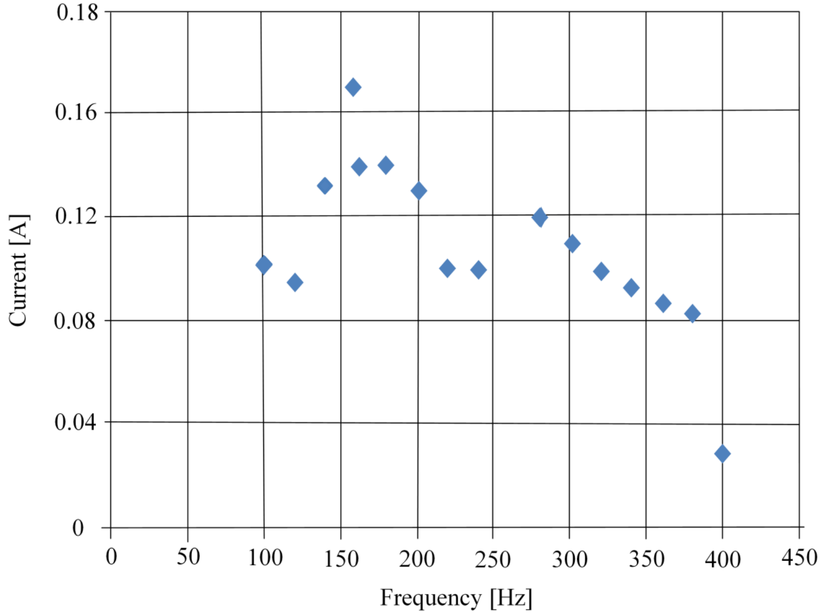

Fig. 7. Current interharmonics vs. voltage interharmonic frequency for the unloaded motor

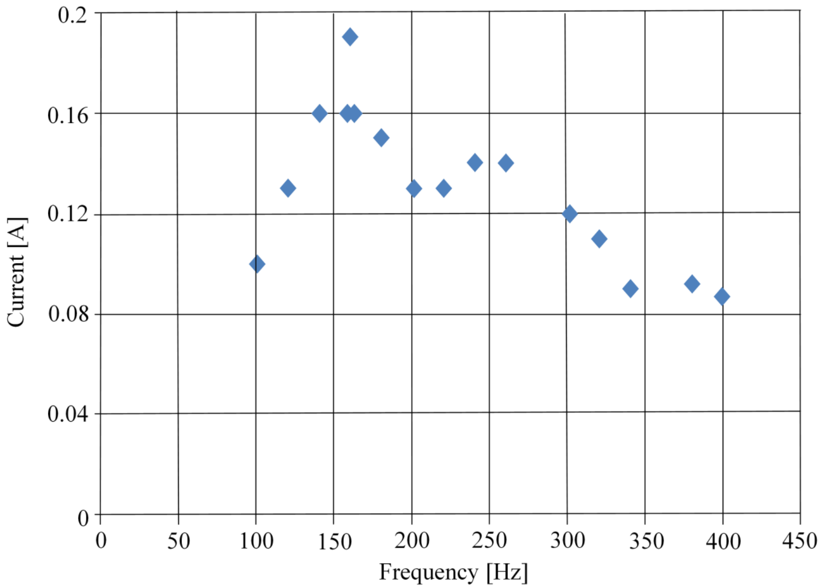

Fig. 8. Current interharmonics vs. voltage interharmonic frequency for the loaded motor

4. CONCLUSIONS

For the single-phase motor studied, the characteristics of current interharmonics as a function of the voltage interharmonic frequency differed significantly from the analogous characteristics determined for an example three-phase induction motor of low power [Gnaciński et al. 2023]. For the single-phase motor studied, the current interharmonics reached the highest value at a frequency of about 160 Hz and a local maximum at a frequency of about 280 Hz. In contrast, for the three-phase motor and the considered voltage interharmonic frequency range, the current interharmonic is approximately inversely proportional to the voltage interharmonic frequency, revealing only two local maxima and a local minimum [Gnaciński et al. 2023].

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