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Performance Analysis of Z-Source Fed Cascaded Multilevel Inverter

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Abstract*: Three phase multilevel inverters are frequently utilized in moderate and high power industries by minimizing the electromagnetic interference (EMI), enhancing the voltage profile and improving the power capacity. Although various converter topologies are developed for multilevel inverters (MLIs), Z-source MLIs are widely used for higher voltage applications. Z-source MLIs diminishes the total harmonic distortion (THD), and it has good stability and efficacy for various electrical power system applications. This paper aims to develop a three phase Z-source seven-level cascaded H-bridge (CHB) inverter with multicarrier PWM control techniques. The Z-source CHB inverter with multicarrier PWM control is modeled and its performance investigation with shoot through and non-shoot through modes is carried out in MATLAB/Simulink software platform.

***Keywords* : Buck-boost, CHB inverter, Multicarrier pulse width modulation, Total harmonic distortion, Z-source network.**

I. INTRODUCTION

In last decades, multilevel inverter (MLI) becomes more popular because of the increased power capacity, enhanced output voltage profile, and reduced electromagnetic interference (EMI). In specifically, switching semiconductor devices are correctly connected resulting in a topology capability of achieving higher voltage by employing high standard voltage components [1,2]. Three-level inverter has drawn increasing focus in industrial uses, for example in renewable energy systems, active filters and motor drives [3,4]. The most significant benefits of MLI over the conventional two-level voltage source inverter (VSI) are the stepwise waveform, higher power capacity, absence of demand for a transformer in a distribution voltage level, less switching losses and superior electromagnetic compatibility (EMC).

The seven-level cascaded H-bridge (CHB) inverter has lots of benefits when compared with low and medium level H-bridge inverters such as low harmonic distortion, reduced dv/dt, higher switching frequency and very low voltage stress across the switching devices. The shoot through the problem, which could be caused by mis-gating because of electromagnetic interference, is an issue related to the reliability of a converter. Thus the dead time to stop the cross conduction of the lower and upper switches has to be allowed in the VSI, which causes the harmonics and voltage distortion.

Voltage boost operation requires an additional DC/DC boost converter in the input stage, which makes the overall system costlier and harder to control. Meanwhile, the Z-source inverter (ZSI) proposed in [5] overcomes the limitations and problems of the traditional VSIs. Such a topology provides the boost function with the inherent short -circuit immunity [6].

The Z-source network with the ability of single stage power conversion [7], uses an X-shape structure with the symmetrical position of passive components to store inductive energy and after that discharge it to the load attained by using shoot and non-shoot through modes [7].

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II. Z-SOURCE NETWORK

Fig. 1 shows the schematic of a Z-source network, it has a DC source, Z-impedance with switch 'S' and diode 'D'. As shown, the Z-source network is made of-of an X shape LC structure that can boost or buck the DC input voltage depending upon the interval of the shoot- through zero states during a switching cycle [8-11].

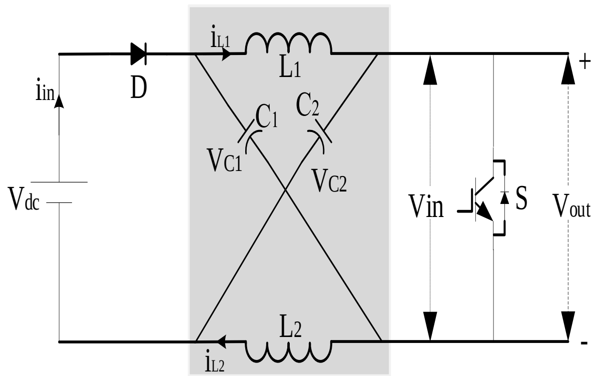


Fig.1. Schematic representation of a Z-source network

During the shoot-through mode, switch 'S' is ON and diode 'D' is OFF, in non-shoot through mode, switch 'S' is OFF and the diode 'D' is ON vice versa. The circuit of the shoot-through mode is depicted in Fig. 2, from the circuit shown in Table 1.

$$V_L=VC \quad (1)$$

$$V_{in}=0 \quad (2)$$

The circuit of a non-shoot through mode is depicted in figure .3, from the circuit the output of the LC network can be [7],

$$V_L=V_{dc}-V_C \quad (3)$$

$$V_{in}=V_C-V_L \quad (4)$$

$$Vin=2V_C-V_{dc}$$

(5)

Let, the average voltage of the inductor is zero, so the relationship between output voltage and capacitor is seen in [7],

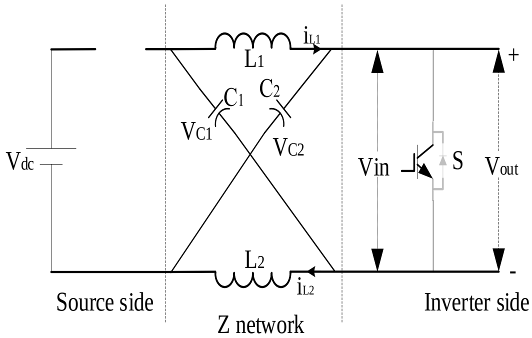
$$\frac{V_c}{V_{in}} = \frac{T_{ns}}{T_{ns} - T_{sh}} \qquad (6)$$

Where T_{sh} is the total period of shoot-through mode, and T_{ns} is the total period of non-shoot through mode. By substituting equation (6) in (5), then,

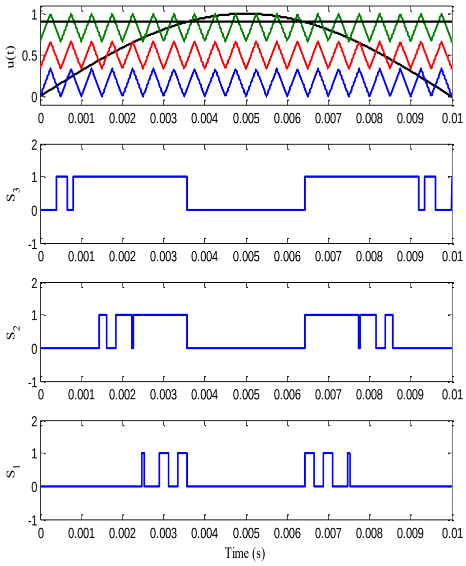
$$V_{in} = \left(\frac{1}{1-2(\frac{T_{sh}}{T})}\right)V_{dc} \qquad (7)$$

$$B = \left(\frac{1}{1-2(\frac{T_{sh}}{T})}\right) \qquad (8)$$

where T is the switching period, and B is the boost factor.

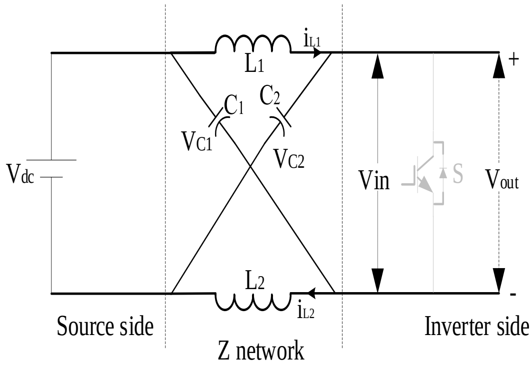


(a) Equivalent Circuit

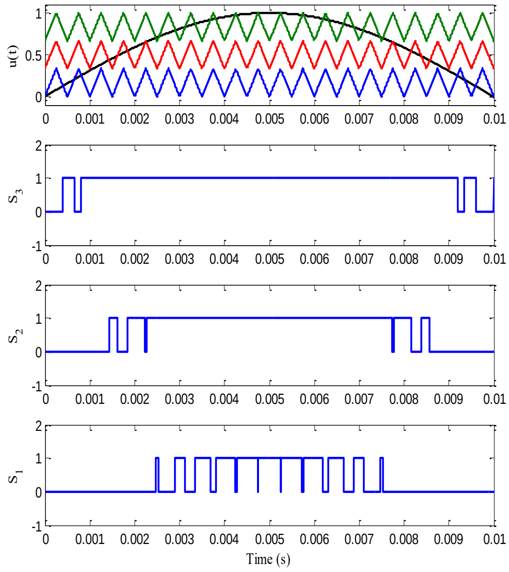


(b) Pulse generation

Fig. 2. Shoot through mode operation



(a) Equivalent Circuit



(b) Pulse generation

Fig. 3. Non-Shoot through mode operation

Table.1. Switching states of Z-source network

Mode of operation	State
Shoot-through mode	'S' ON, 'D' OFF
Non-shoot-through mode	'S' OFF, 'D' ON

All the mentioned descriptions and examinations of the Z-source system are focused around the presumption that the inductance of inductor in the impedance system is sufficiently incredible to keep up the inductor current at very nearly consistent. While, when the inductance is little, and inductor current ripple is high or broken these suppositions are not fulfilled.

III. Z-Source Cascaded H-Bridge Multilevel Inverter

MLI separates the primary DC source into several input supplies that are connected to generate the AC power with an output waveform similar to the staircase approximation of sine signal. The staircase approximation of sine waveform is prevalently known as the stepped approximation. In general, the number of levels in MLI helps to choose the power rating of the converter. The desirable connections in MLI are either shunt or series or both are carried out to accomplish higher current and voltage. One of the greatest advantages of using an MLI is the transformer can be eliminated, and this helps to enhance efficiency and cost-effectiveness, [12-18].

This section proposed a Z-source three phase seven-level CHB inverter with multicarrier PWM control. The performance investigation of the presented Z-source CHB inverter with shoot through and non-shoot through modes has been carried out in this paper. In the proposed seven-level Z-source cascaded MLI, voltage regulation as well as buck-boost operations are achieved by novel implementation of the PI controller to control over the shoot through the mode of the inverter with multicarrier PWM.

IV. Modulation Topologies

Various modulation strategies are employed in the multicarrier based switching scheme, they have a good control freedom degree, Alternate Phase Opposition Disposition (APOD), Phase Opposition Disposition (POD), Phase Disposition (PD), carrier overlapping (CO) are variable frequency (VF) strategies are used in this proposed inverter. The modulating voltage is a trapezoidal reference signal. Figs. 5-8 show the waveforms of hybrid pulse generation for seven-level CHB Inverter. The carrier counts (n) for seven-level inverter is 6 (i.e. m-1), in this three carriers are above the zero reference, and three carriers are below the reference respectively.

$$Amplitude\ \ modulation\ \ index\ (m_a) = \frac{2A_m}{(m-1)A_c} \qquad (9)$$

where, A_c - Amplitude of carrier, A_m - Amplitude of modulating waveform and m - Number of levels.

Equation (9) used to find the amplitude modulation index for PD, POD, APOD and VF PWM techniques.

$$Frequency\ \ modulation\ \ index\ (m_f) = \frac{f_c}{f_m} \qquad (10)$$

where, f_c - Frequency of carrier and f_m - Frequency of modulating the waveform

Equation (10) used to find the frequency modulation index for PD, POD, APOD, VF and CO PWM techniques. In this paper modulation frequency index is 40 and is varied from 0.7 to 1.

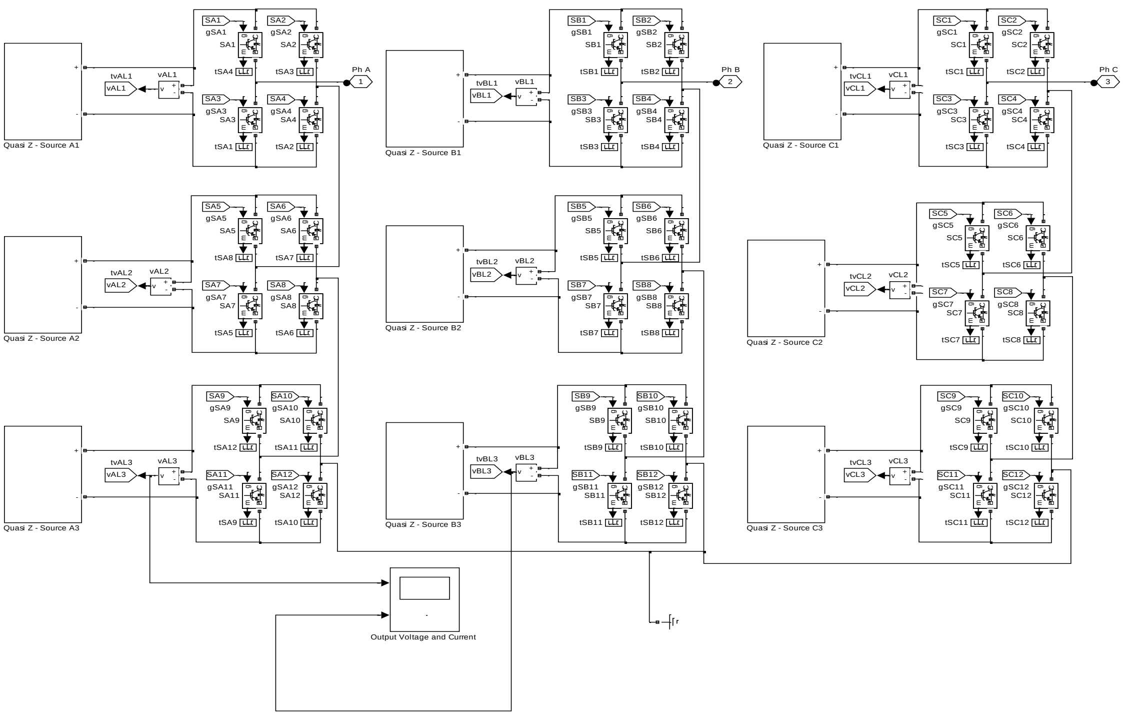


Fig. 4. Seven-level cascaded H-bridge inverter

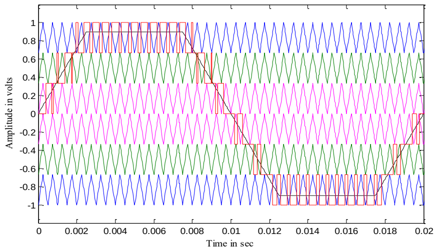


Fig. 5. PD PWM strategy with trapezoidal reference

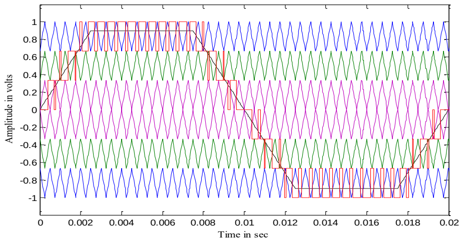


Fig. 6. POD PWM strategy with trapezoidal reference

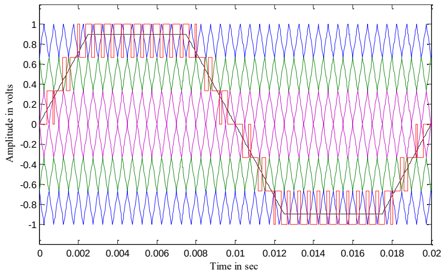


Fig. 7. APOD PWM strategy with trapezoidal reference

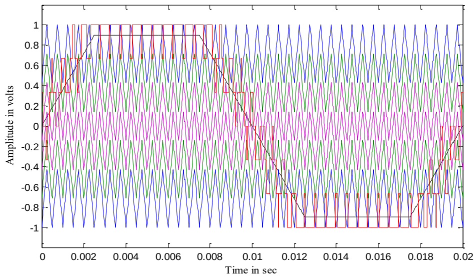


Fig. 8. CO PWM strategy with trapezoidal reference

Fig. 5 shows the six carriers are arranged in phase, with each other (PD PWM) with trapezoidal reference. Fig. 6 shows the six carriers are arranged above the reference are in phase and the below the reference carriers are 180 degrees out of phase with the above carriers (POD PWM) with trapezoidal reference. Fig. 7 shows the six carriers are arranged in out of phase with its neighbor by 180 degrees (APOD PWM) with trapezoidal reference. Fig. 8 shows the CO PWM technique, for an m-level inverter carrier overlapping PWM using m-1 carrier signals with the same frequency fc and same peak to peak amplitude Ac, are disposed of such that the band occupies to overlap each other. Ac/2 is the vertical overlap distance between each carrier signals [15]. The amplitude of Am and frequency of fm is centered in the mid of carrier signals. The reference signal is compared continuously with carrier signals, when the reference amplitude is more than a carrier magnitude, then the semiconductor switches correspond to that carrier are turned "ON", otherwise, the semiconductor switches are tuned "OFF" [16].

$$Amplitude\ modulation\ index\,(m_a) = \frac{A_m}{\left(\frac{m}{4}\right)A_c} \qquad (11)$$

V. SIMULATION RESULTS

The hybrid carrier-based PWM switching pulses are applied to a seven-level CHB inverter. The simulations have been carried out in MATLAB/ Simulink. The modulation index ranging from 0.7 to 1.0 and the corresponding total harmonic distortion (THD) values are measured using FFT analysis, V_{rms}, CF and FFT for the same modulation indices are depicted in Tables 2 to 5 of seven-level inverter.

Figs. 9, 11, 13 and 15 show the line-to-neutral voltages and Figs. 10, 12, 14 and 16 shows the THD of the line-to-neutral voltages that controlled by PD, POD, APOD, and CO modulation respectively. From the THD analysis of the proposed hybrid, carrier-based PWM switching strategies are eliminated the lower-order harmonics completely.

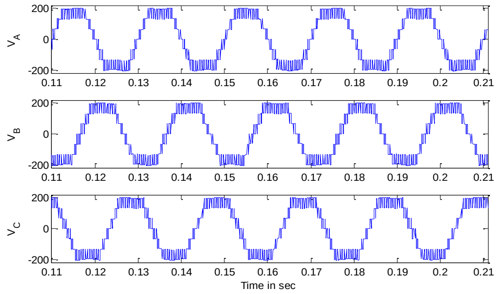


Fig. 9. The output voltage produced by PD PWM strategy

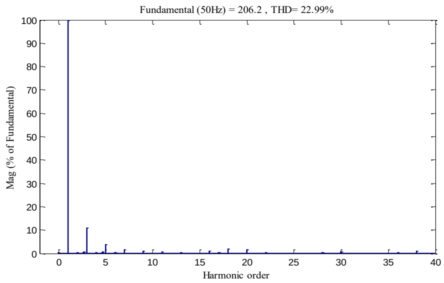


Fig. 10. FFT of the output voltage of PD PWM strategy

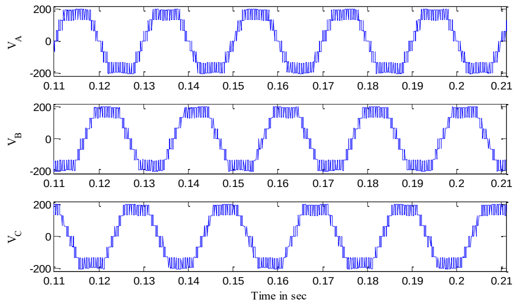


Fig. 11. The output voltage produced by POD PWM strategy

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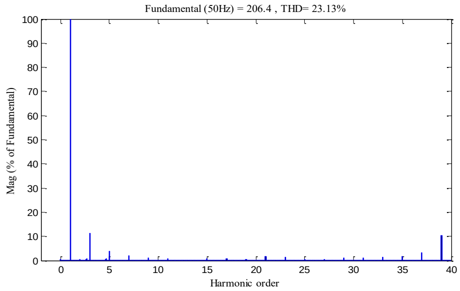

Fig. 12. FFT of the output voltage of POD PWM strategy

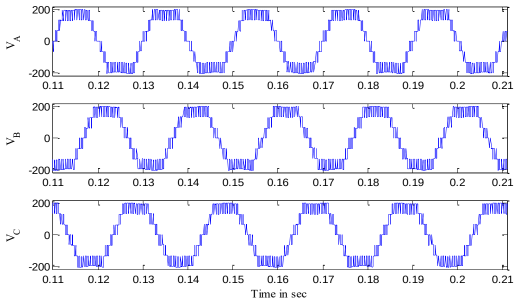

Fig. 13. The output voltage produced by APOD PWM strategy

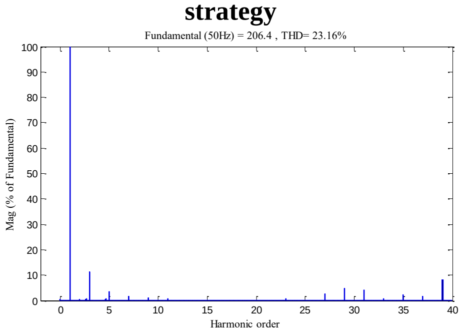

Fig. 14. FFT of the output voltage of APOD PWM strategy

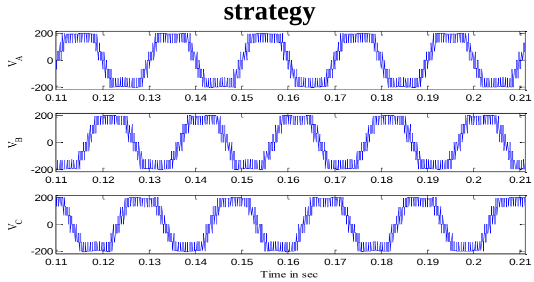

Fig. 15. The output voltage produced by CO PWM strategy

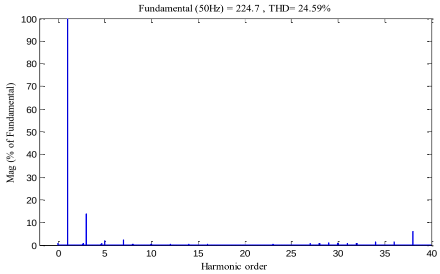

Fig. 16. FFT of the output voltage of CO PWM strategy

Table 2. % THD for seven-level CHB inverter

m_a	% THD			
	PD	POD	APOD	CO
1	18.08	16.33	16.20	23.98
0.95	19.08	19.32	19.36	25.31
0.9	22.99	23.13	23.16	24.59
0.85	25.85	26.10	25.83	28.50
0.8	24.94	24.45	24.79	28.20
0.75	26.38	26.42	26.54	30.98

Table 3. VRMS (fundamental) for seven-level CHB inverter

m_a	V_{RMS} (FUNDAMENTAL)			
	PD	POD	APOD	CO
1	159.3	161.4	161	162
0.95	155.3	155.4	155.4	159.8
0.9	145.8	146	146	158.9
0.85	136	136.1	136.2	148.2
0.8	128.3	128	128.3	146.6
0.75	122.3	122.8	122.2	135.7
0.7	108.2	108.9	108.5	129.8

Table 4. Crest factor for seven-level CHB inverter

m_a	CREST FACTOR			
	PD	POD	APOD	CO
1	1.414	1.414	1.414	1.415
0.95	1.414	1.414	1.414	1.414
0.9	1.414	1.414	1.414	1.414
0.85	1.413	1.414	1.414	1.413
0.8	1.414	1.413	1.414	1.415
0.75	1.414	1.414	1.414	1.415
0.7	1.415	1.413	1.413	1.414

Table 5. Form factor for seven-level CHB inverter

m_a	FORM FACTOR			
	PD	POD	APOD	CO
1	1.109	1.110	1.110	1.109
0.95	1.110	1.110	1.110	1.110
0.9	1.110	1.110	1.110	1.110
0.85	1.110	1.110	1.110	1.109
0.8	1.109	1.110	1.109	1.109
0.75	1.109	1.110	1.109	1.109
0.7	1.109	1.110	1.110	1.109

Table 6. THD vs Modulation Index

CHB	Modulation Index (m_a=1)			
	PD	POD	APOD	COPWM
7 level	18.08	16.33	**16.20**	**23.98**

VI. CONCLUSION

This paper presents the design of a seven-level Z-source CHB inverter that can perform Boost DC-AC energy conversion. The proposed inverter employs Z-source to boost input DC voltage that can be controlled with Z-networks shoot through and non-shoot through states. Maximum boost gain with the lower modulation index and the modulation index increases the maximum boost gain of the Z-source inverter decreases. In addition, suggested inverter utilizes one DC voltage source and one Z-network. As a result, the control of DC link voltage is very simple. Hybrid multicarrier PWM strategy with trapezoidal reference based Z-source seven-level CHB inverter has been evaluated. The performance indices such as CF, %THD, V_{rms}, and FF have been estimated for PD, POD, APOD and CO PWM strategies.

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It is found that the highest % THD happens in CO modulation, and the lowest one occurs in APOD method. The simulation outcomes depict that using the APOD method decreases the voltage THD considerably. Also, POD method increases the voltage more than the APOD method. Both methods can provide higher V_{rms} and fewer numbers of dominant harmonic than the other techniques.

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