A Novel Application of Pseudorandom based Technique for Acoustic Noise and Vibration Reduction of PMSM Drive

Presented by
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Speaker Biodata

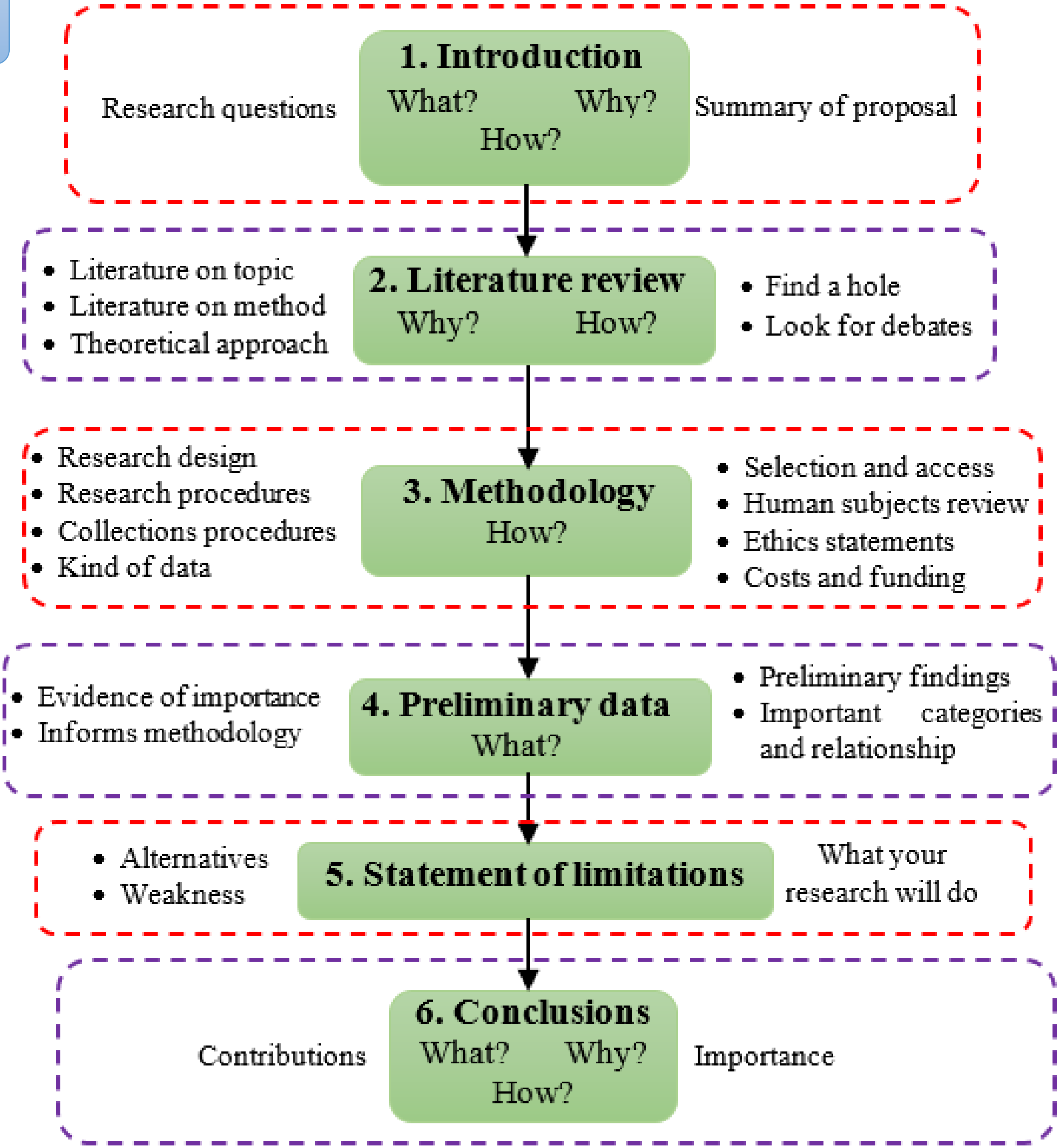
Dr. Rajesh M. Pindoriya (GM’14 - M’20) received the B. Tech degree in Electrical and Electronics Engineering from Rajasthan Technical University Kota, Rajasthan, India in 2012 and M. E. in Power Electronics and Electrical Drives from Gujarat Technological University, Ahmedabad, Gujarat, India in 2014. He received Ph.D. degree in Power Electronics and Electrical Drives from the Indian Institute of Technology Mandi, India, in 2020. He is currently working as a Project Engineer at IIT Mandi, India.

His research interests include design controllers for the Permanent Magnet Synchronous Motor (PMSM) and Brushless Direct Current (BLDC) motor drives. Also, working on analysis and reduction of acoustic noise and vibration of PMSM and BLDC Motor drives. Dr. Pindoriya is a member of the Institution of Electronics and Telecommunication Engineers (IETE) (AM’17, M’21) and member of the Institution of Engineering (IE) (AM’17, M’21).

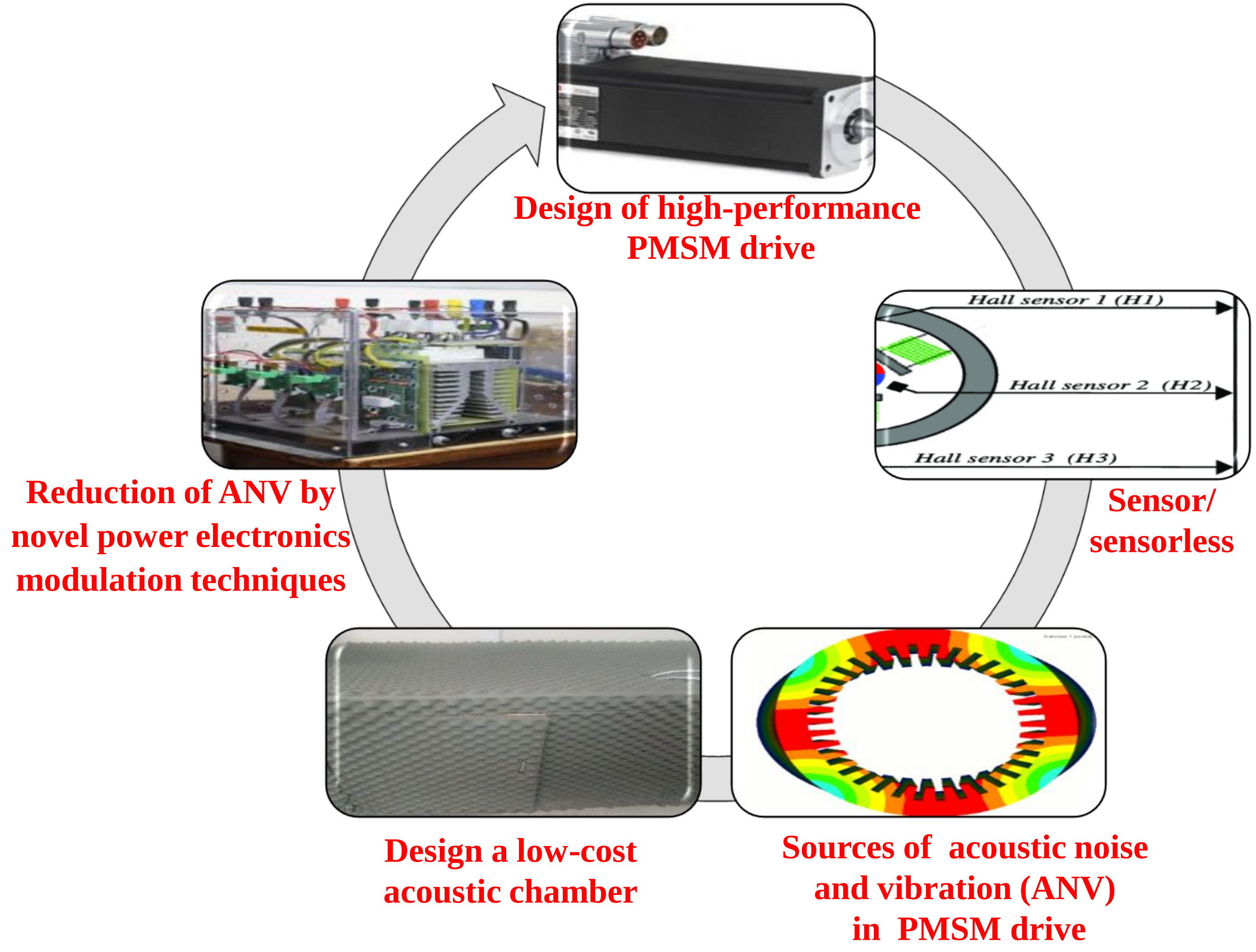
Outline

- Research Proposal Flow Chart
- Introduction: Electrical Drives
- Research Problem Statements
- Acoustic Noise and Vibration (ANV) in PMSM drive
- Novel Random Pulse Width Modulation (RPWM) techniques for ANV reduction
- Results and Discussions

Research Proposal Flow Chart



Research Problem Statements



- ❖Control of brushless PMSM drive
- ❖Investigation and reduction of Acoustic Noise and Vibration (ANV) of PMSM drive
- ❖Sensorless operation of PMSM drive

Applications of Electric Drives

Definition of electric drive

- “Systems employed for motion control are called **drives**”
- “Drives employing electric motors are known as **electrical drives**”

Why its required

- To control the speed and torque of the electric motors

Applications of electric drives

Air condition

Celling fan

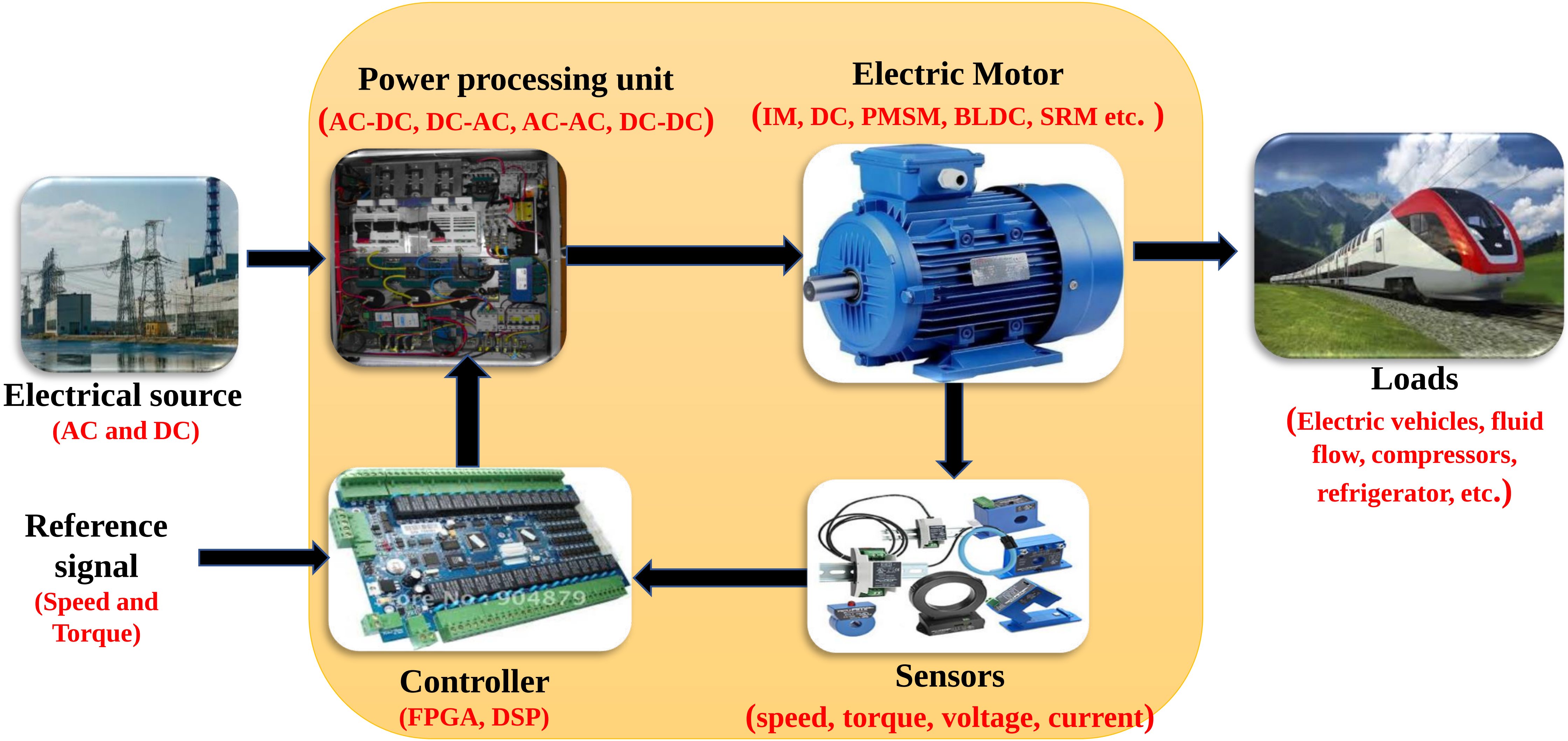
Refrigerator

Lift

Vacuumed cleaner

Ship

Components of Electric Drives



Applications of PM based Drives [1]

AC, DC and Universal Motors

Transition to

As consumers demand more energy efficient products, more PMSM & BLDC motors are being used

PM Machines

[1] R. Krishnan, Permanent Magnet Synchronous and Brushless DC Motor Drives, *CRC Press*, 2010.

Advantages and Disadvantages of PM Drives [1-2]

Advantages

1. **High Efficiency** - Not in Induction Motor
2. **Better Controllability**
3. **Sensorless Operation**
4. **High torque to weight ratio**
5. **High energy Density -** Hence compact
6. **Low acoustic Noise -** Compared to DC brushed and brush-less Motors
7. **No excitation losses**

Disadvantages

1. Electronics Inverter required
2. Possible faults happen

[1] R. Krishnan, Permanent Magnet Synchronous and Brushless DC Motor Drives, *CRC Press*, 2010.
[2] F . Niu, B. Wang, A. S. Babel, E. G. Strangas, "Comparative Evaluation of Direct Torque Control Strategies for Permanent Magnet Synchronous Machines", *IEEE Transactions on Power Electronics*, pp.1-17, 2013.

Introduction: Speed Control of Sensored based PMSM Drive [3]

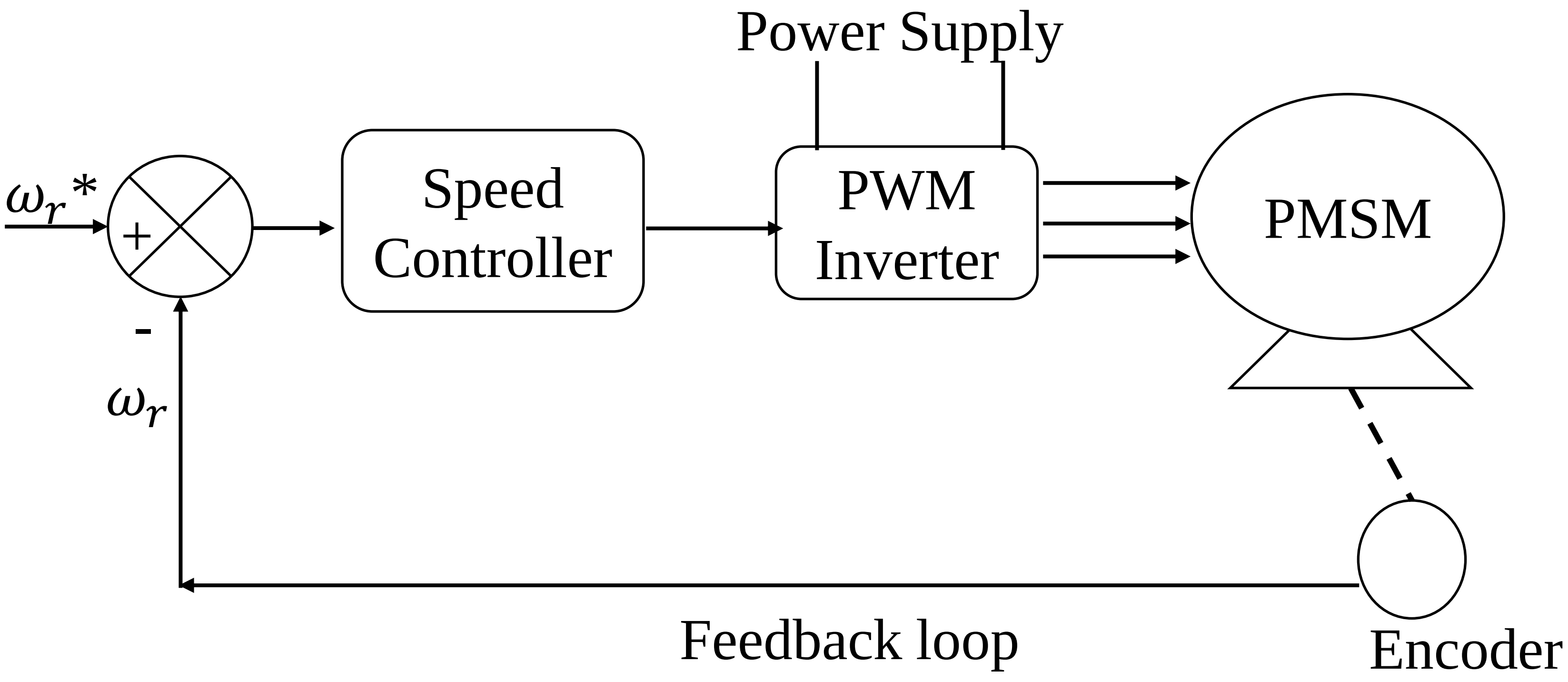


Fig. 1. Speed control of Sensored based PMSM drive

To present the sensors several disadvantages

1. **Reduced reliability**
2. **Increased cost**
3. **Weight**
4. **Size**
5. **Increased complexity of the drive system**

[3]. A. Sathyan, N. Milivojevic, Y. J. Lee, M. Krishnamurthy, and A. Emadi, "An FPGA Based Novel Digital PWM Control Scheme for BLDC Motor Drives," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3040–3049, Aug. 2009.

Sources of Acoustic Noise and Vibration in PMSM Drive

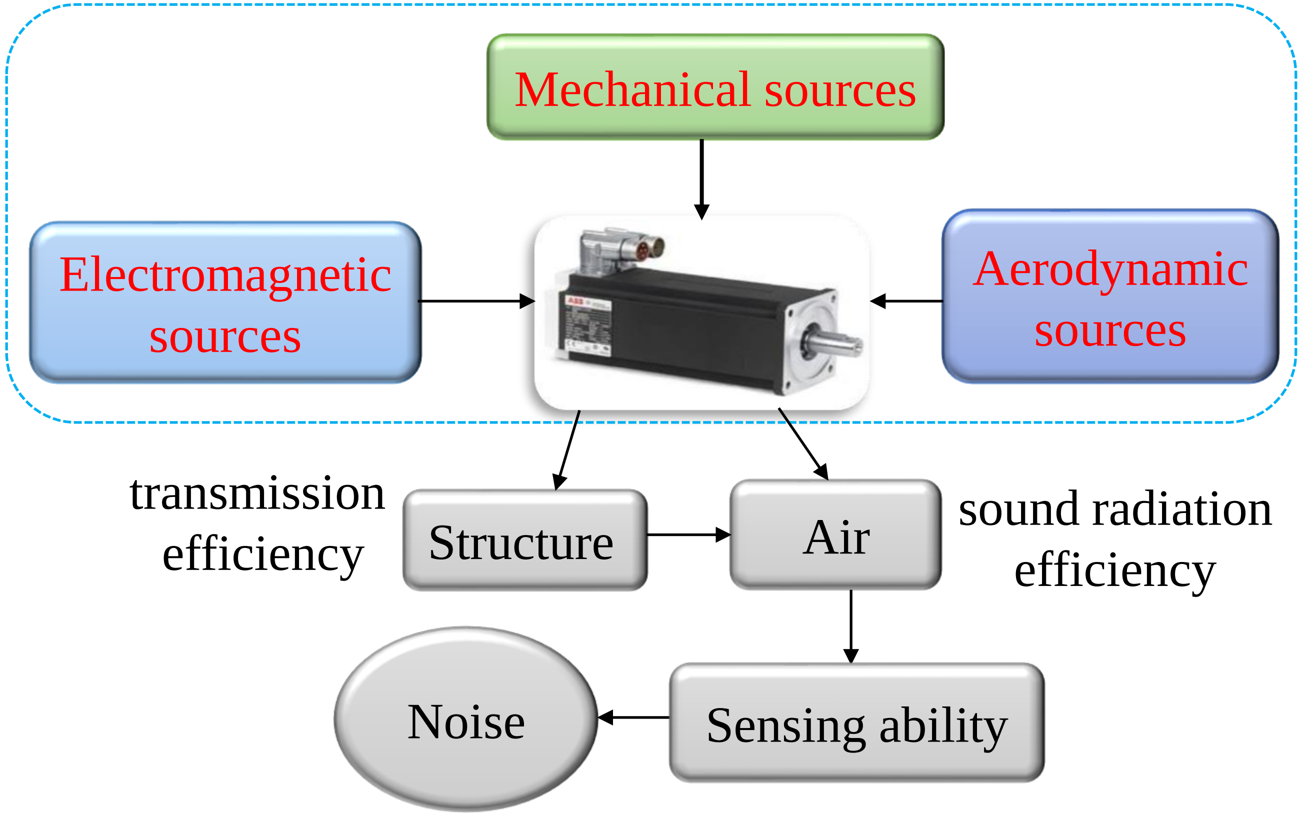
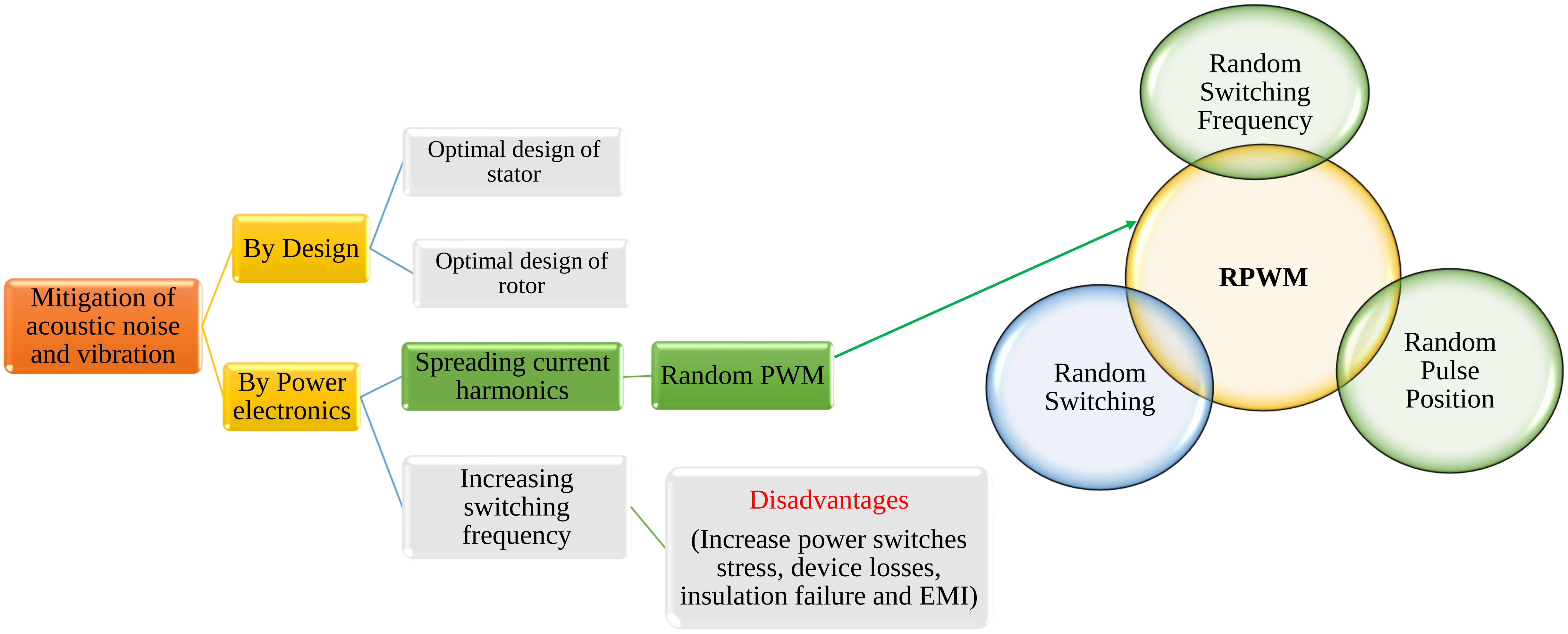


Fig. 2. Noise generation and propagation in electrical machines

- Acoustic noise is an **undesirable audible sound**
- Vibrations may be perceived **directly where they are transmitted to the body**

Acoustic Noise and Vibration: Mitigation Techniques



Introduction: Acoustic Chamber [5-6]

Why Acoustic chamber???

- Nowadays consumers demand more **smooth and silent devices**, whether it is a computer, power electronics gadget and etc.

- Therefore **testing of all devices one free-field enclosure** is required.

- It provides a **free-field environment**, which is nearly close to free from background noise and humming noise.

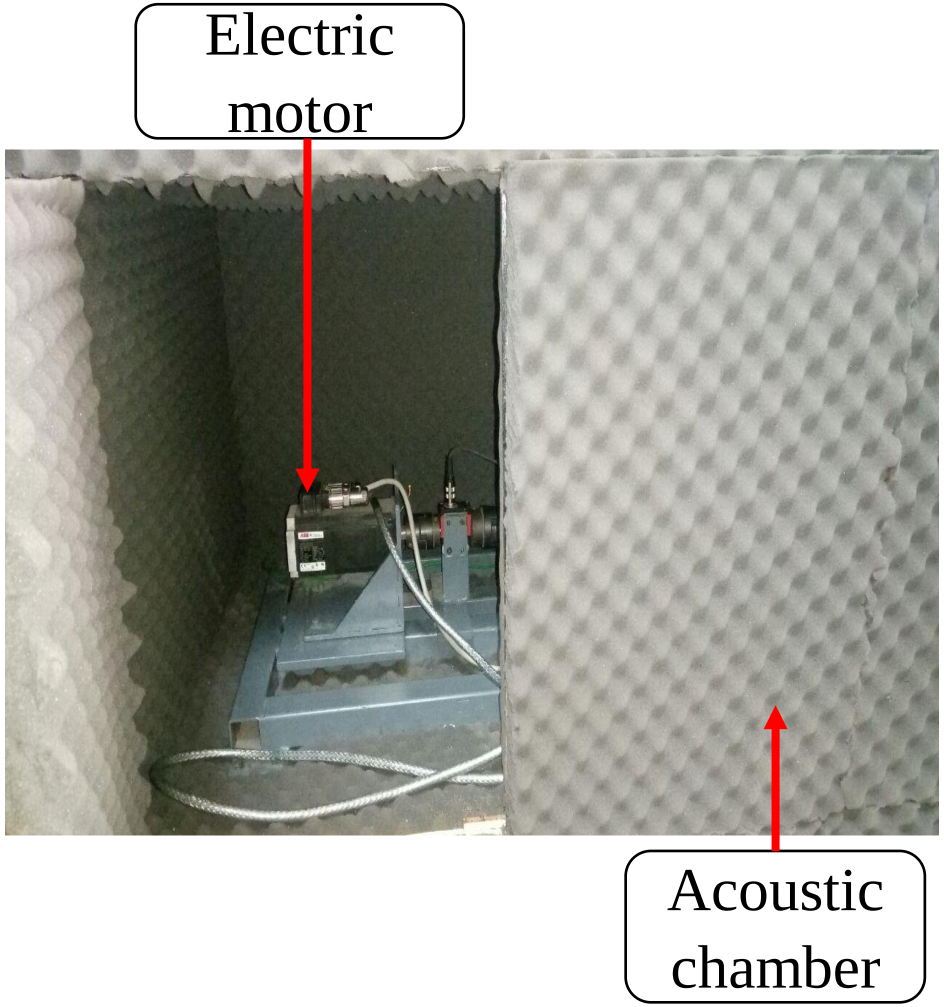
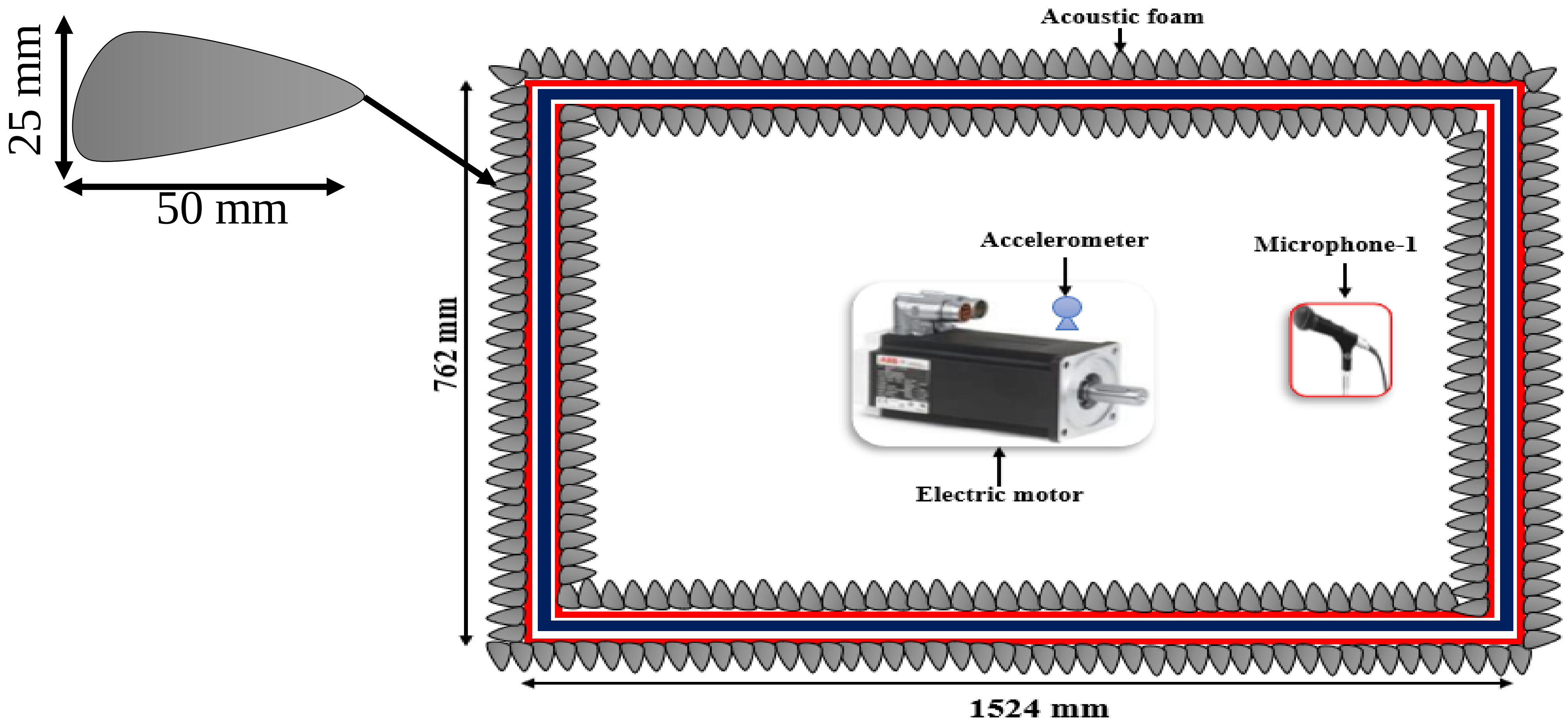


Fig. 3. Pictorial view of acoustic chamber

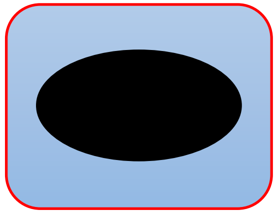
[5] Determination of Sound Power Levels of Noise Sources: Precision Methods for Anechoic and Semi Anechoic Rooms, *ISO 3745:1977*, *ISO Standards Handbook*, Switzerland, 1990.

[6] R. Rusz, "Design of a Fully Anechoic Chamber", *Master's Degree Project Thesis*, 2015.

Schematic Layout of Low-Cost Acoustic Chamber



Microphone-2



Amplifier as a noise source

Sound barrier sheet (thickness of 3 mm)

Wooden ply (thickness of 12 mm)

An Experimental Setup for Characterization of Acoustic Chamber

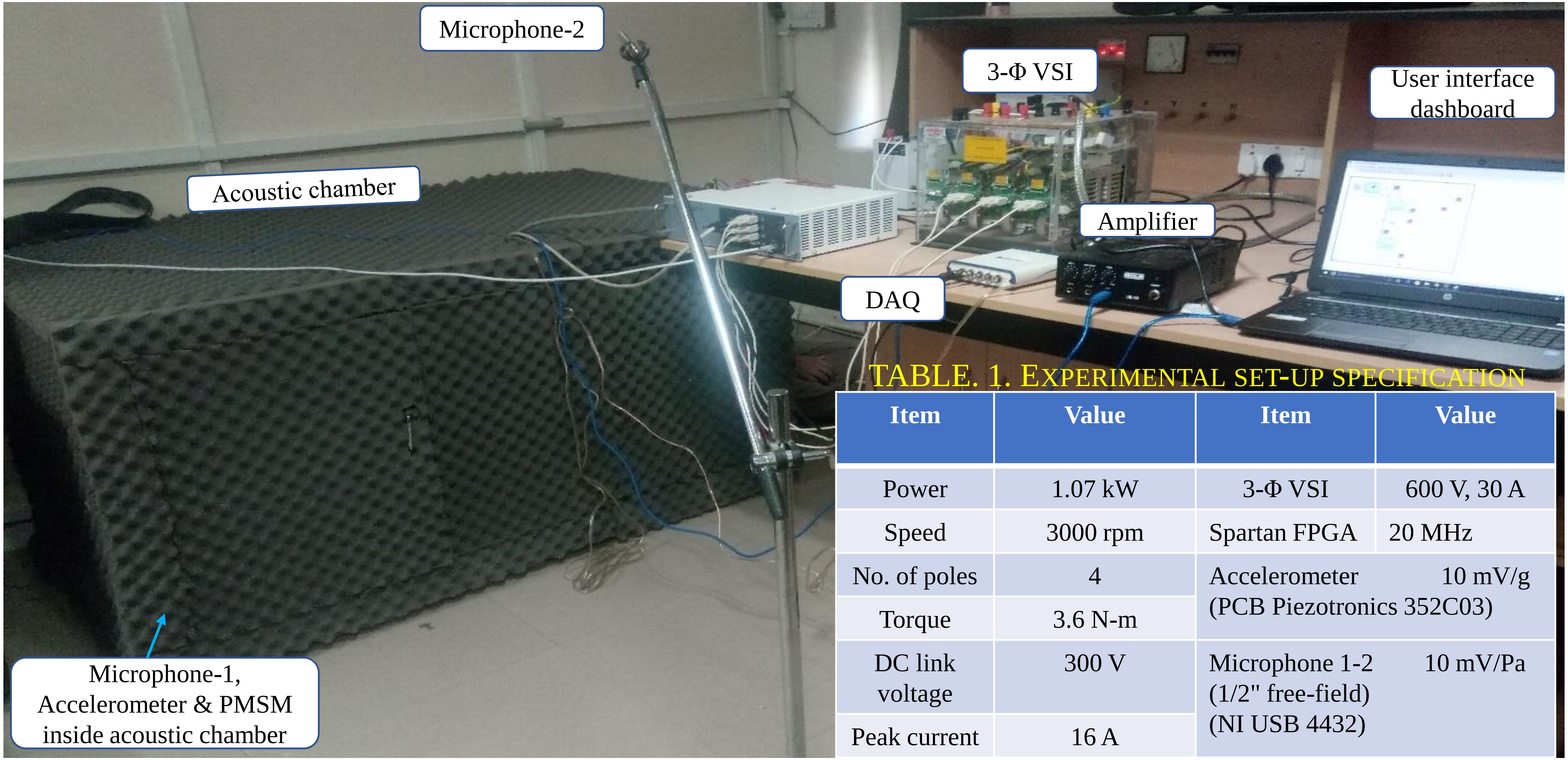


TABLE. 1. EXPERIMENTAL SET-UP SPECIFICATION

Item	Value	Item	Value
Power	1.07 kW	3-Φ VSI	600 V, 30 A
Speed	3000 rpm	Spartan FPGA	20 MHz
No. of poles	4	Accelerometer (PCB Piezotronics 352C03)	10 mV/g
Torque	3.6 N-m		
DC link voltage	300 V	Microphone 1-2 (1/2" free-field) (NI USB 4432)	10 mV/Pa
Peak current	16 A		

Specification of Acoustic Chamber (AC)

Sr. No.	Items	Requirements
1	Standards	EN ISO 3745 IEC 60268-1
2	Cut-off frequency [Hz]	40
3	Internal height of AC [mm]	1000
4	Internal net volume of AC [mm^3]	11430
5	Internal height above sound passing floor [mm]	300
6	Outer width of AC [mm]	1500
7	Outer length of AC [mm]	2000
8	Outer height of AC [mm]	1100
9	Gate of AC [mm]	700*500

Vector Control Technique for PMSM Drive

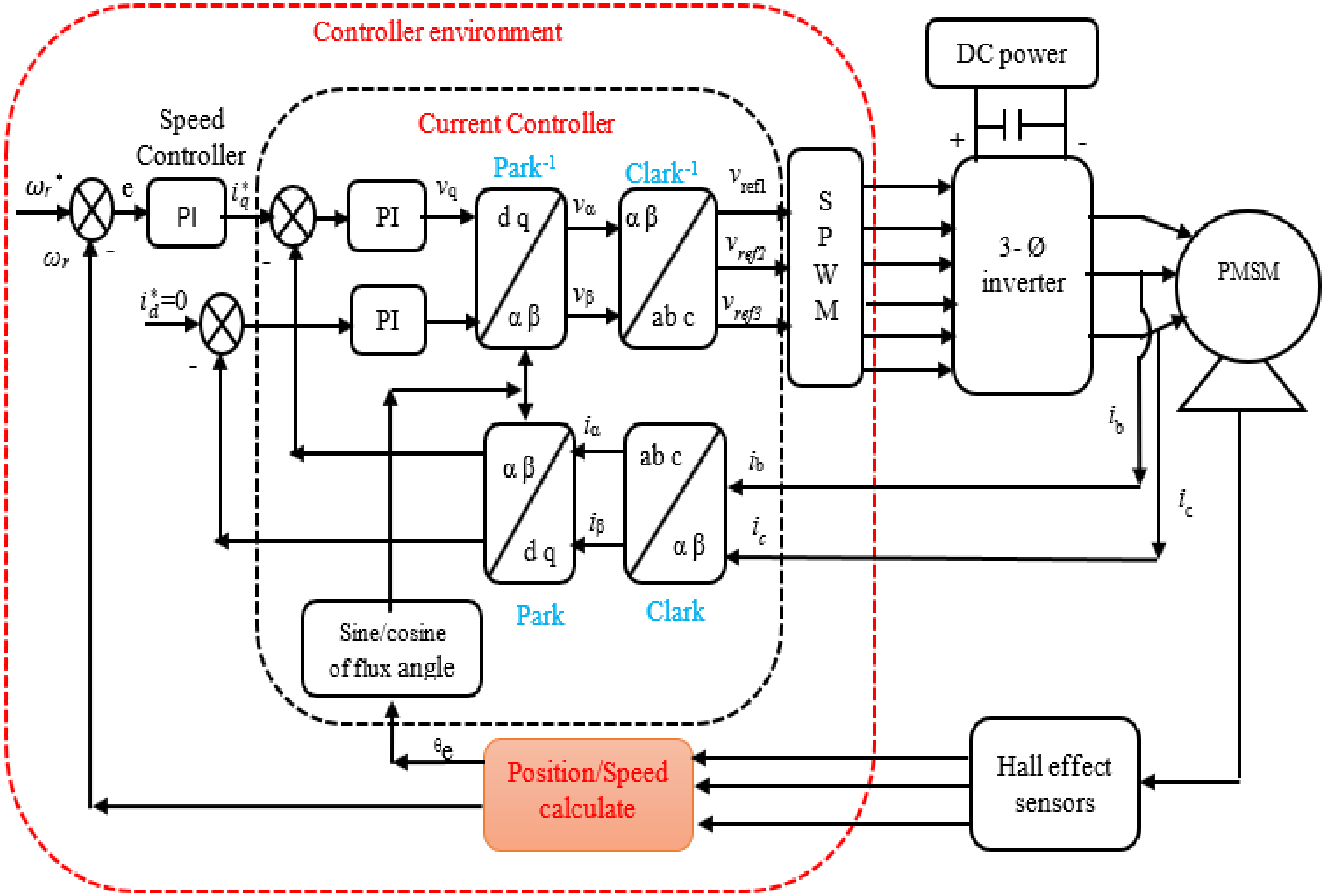


Fig. 4. Vector control design and control system for a PMSM drive

Pseudorandom Triangular Pulse Width Modulation (PTPWM) Technique

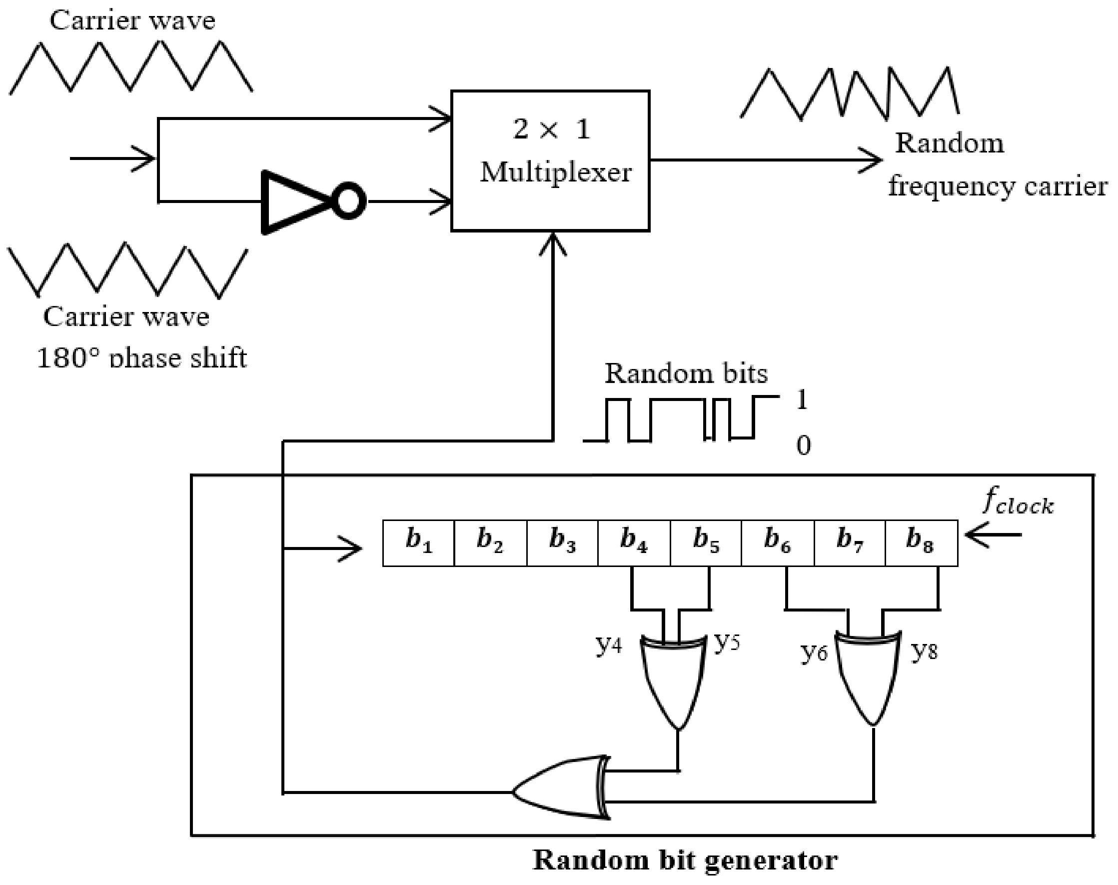


Fig. 5. Block diagram of PTPWM technique

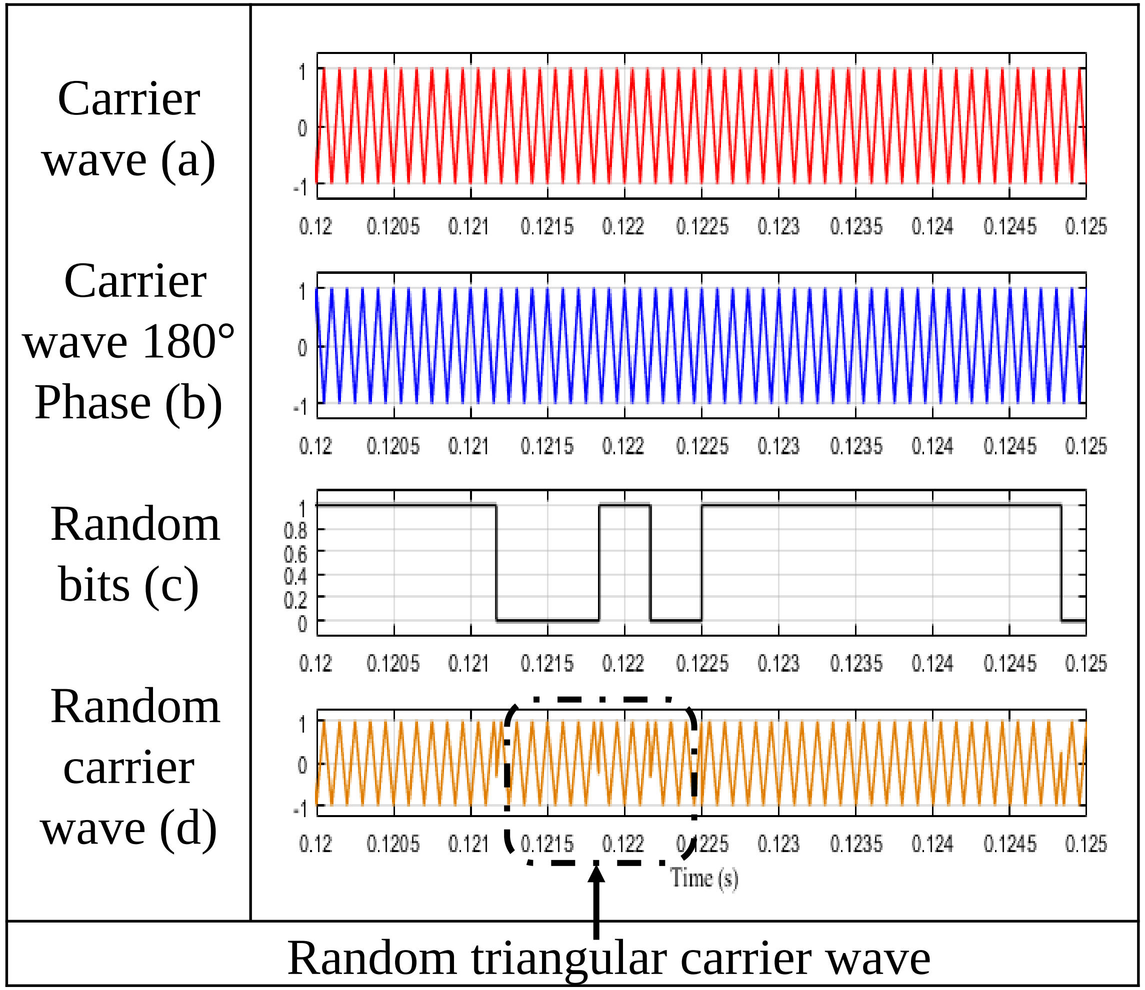


Fig. 6. Intermediate waveforms for PTPWM technique

RPWM: Benchmark Performance

(a)

(b)

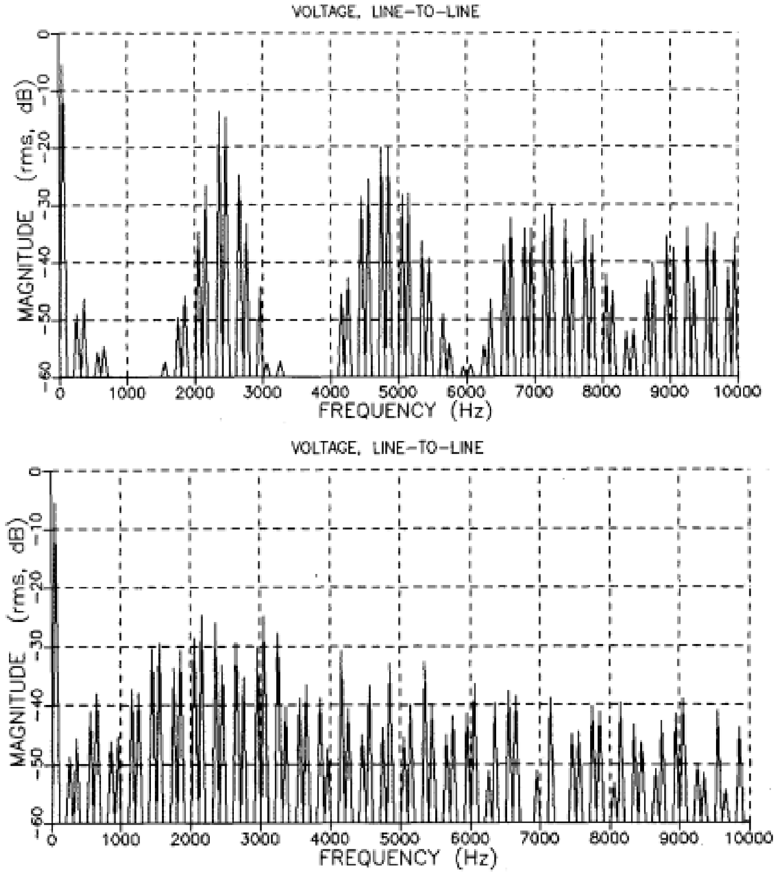


Fig. 7. Example voltage spectra (f_{out} = 50 Hz, m = 1) of a three-phase inverter with the space vector PWM: (a) constant N_s, (N_s = 8), (b) random Ns, (N_s, = 5 ... 11)

(a)

(b)

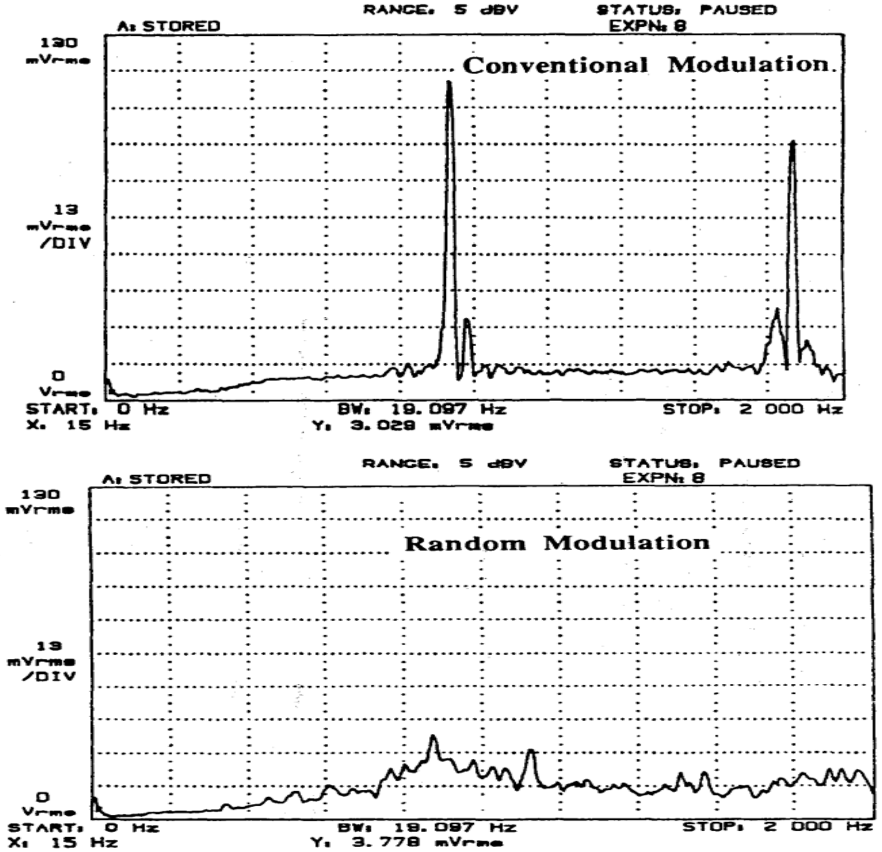


Fig. 8. Example spectra of acoustic noise emitted from an inverter-fed induction motor: (a) deterministic PWM, (b) RPWM

[1] A. M. Trzynadlowski, F. Blaabjerg, J. K. Pedersen, R. L. Kirlin and S. Legowski, "Random pulse width modulation techniques for converter-fed drive systems-a review," in *IEEE Transactions on Industry Applications*, vol. 30, no. 5, pp. 1166-1175, Sept.-Oct. 1994.

Generation of Torque Ripple

- The phase current in the N^{th} phase:

$$i_N = \hat{I}\left[sin\left(\omega t + (N-1)\frac{2\pi}{N}\right) + K_{I3} sin\,3\left(\omega t + \ (N-1)\frac{2\pi}{N}\right) + \cdots\right] \quad (1)$$

- The MMF due to the N^{th} phase:

$$\mathrm{F_N} = \frac{1}{2}\mathrm{i_N m}\frac{4}{\pi}\left[K_{\mathrm{w1}}\sin\left(\alpha + (n-1)\frac{2\pi}{N}\right) + \frac{1}{3}K_{\mathrm{w3}}\sin\,3\left(\alpha + \ (n-1)\frac{2\pi}{N}\right) + \cdots\right] \quad (2)$$

- Torque expression for three-phase PMSM:

$$T = 1.5\hat{I}\hat{B}mDLPK_{w1} \times \begin{bmatrix} 1 + \frac{K_3K_{w3}K_{I3}}{K_{w1}} + \frac{K_5K_{w5}K_{I5}}{K_{w1}} + \cdots + \\ \left(K_{I7} - K_{I5} + \frac{K_3K_{w3}K_{I9}}{K_{w1}} - \frac{K_3K_{w3}K_{I3}}{K_{w1}} + \frac{K_5K_{w5}}{K_{w1}} + \frac{K_7K_{w7}}{K_{w1}} + \frac{K_9K_{w9}K_{I3}}{K_{w1}} + \cdots\right)\cos 6\omega t + \\ \left(K_{I13} - K_{I11} + \frac{K_3K_{w3}K_{I9}}{K_{w1}} - \frac{K_5K_{w5}K_{I7}}{K_{w1}} - \frac{K_7K_{w7}K_{I5}}{K_{w1}} - \frac{K_9K_{w9}K_{I3}}{K_{w1}} + \cdots\right) cos\ 12\omega t \end{bmatrix} \quad (3)$$

- The average component and harmonics of order multiple of six :

$$T = T_0 + \sum_{n=1}^{\infty} T_{6n}\cos(n6\omega t + \text{Ø}_{6n}) \quad (4)$$

$\hat{I}$	Peak stator phase current
ω	Angular frequency of supply
i	Instantaneous current
K_{Ip}	Peak value relative to fundamental of p^{th} harmonic in current waveform.
F_{N}	MMF in the N phase
m	Turns in series per pole per phase
K_{w1}	First harmonic winding factor
α	Electrical angle around stator core
n	n^{th} order current harmonic
T_0	Average torque

[2] H. R. Bolton and R. A. Ashen, "Influence of motor design and feed-current waveform on torque ripple in brushless DC drives," in *IEEE Proceedings B - Electric Power Applications*, vol. 131, no. 3, pp. 82-90, May 1984.

An Experimental Setup of PMSM Drive

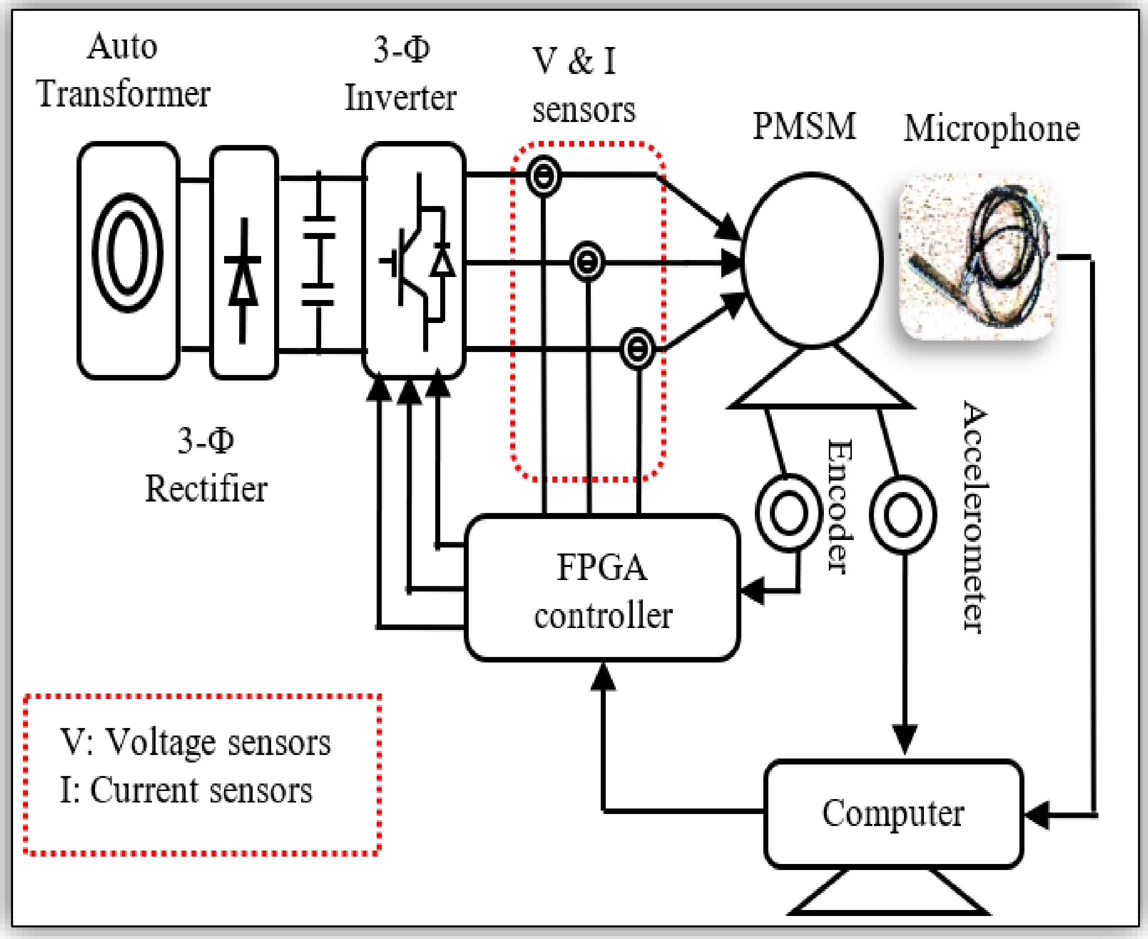


Fig. 9. Schematic diagram of experimental set-up

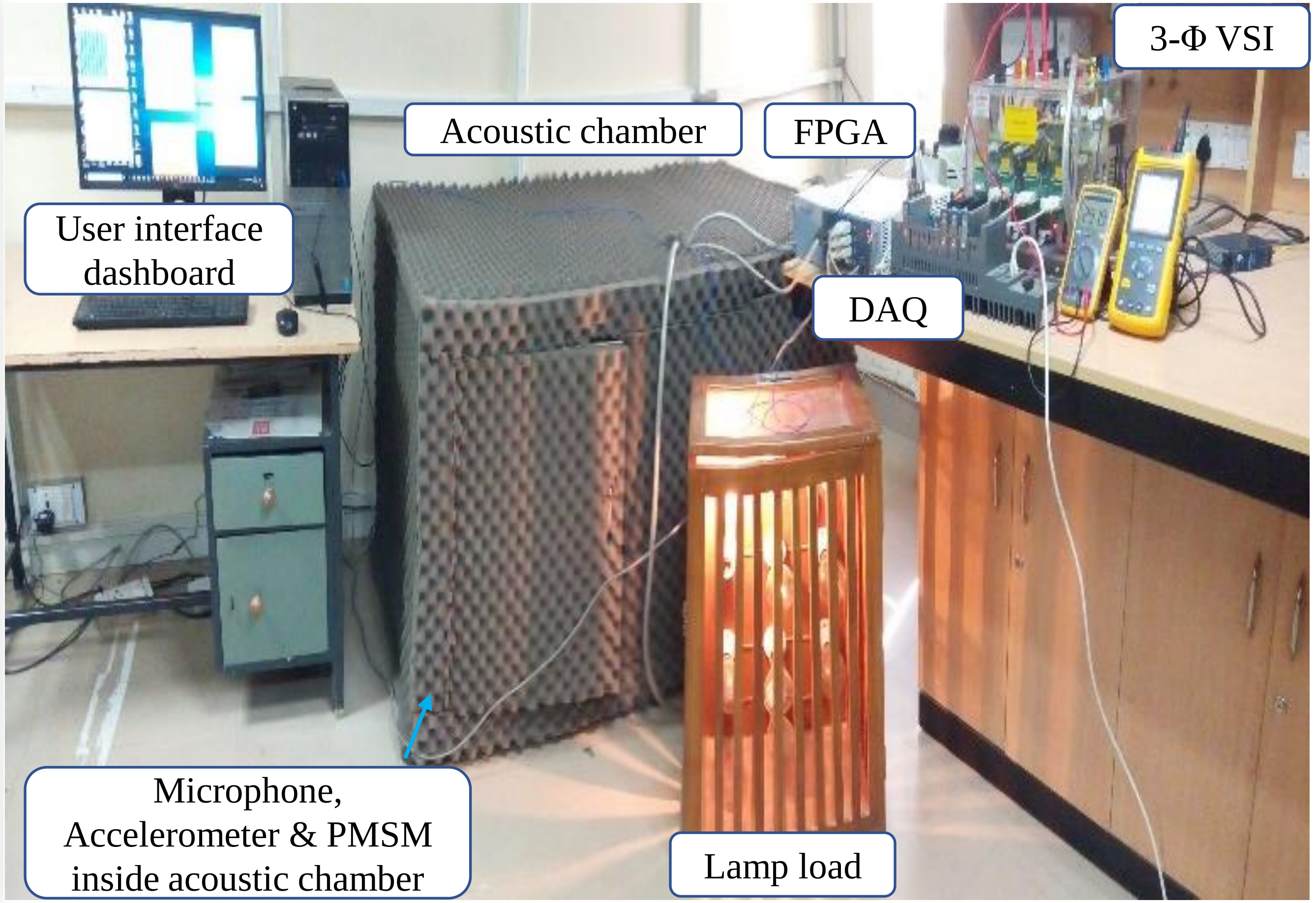
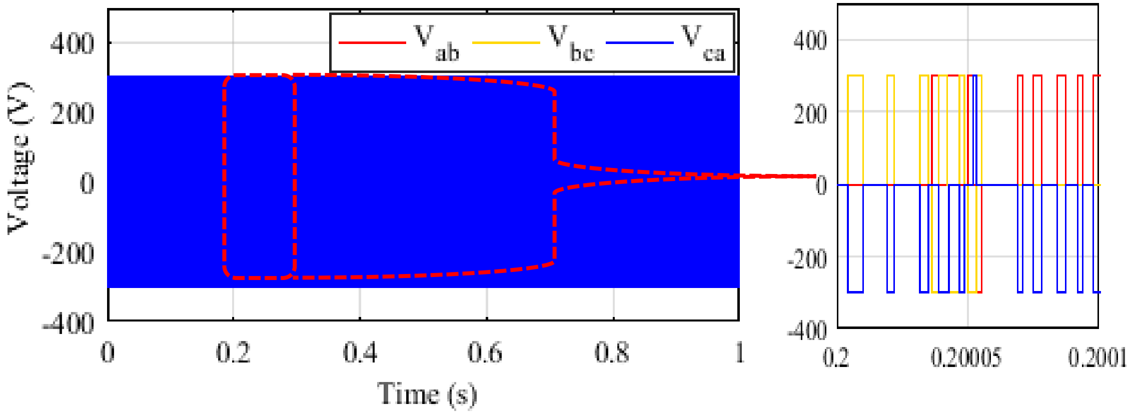
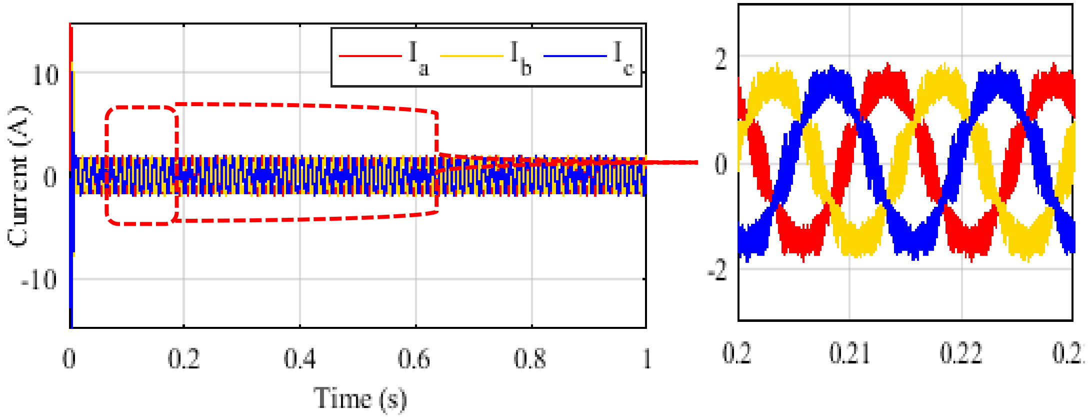


Fig. 10. An experimental set-up for an analysis of acoustic noise and vibration of PMSM drive

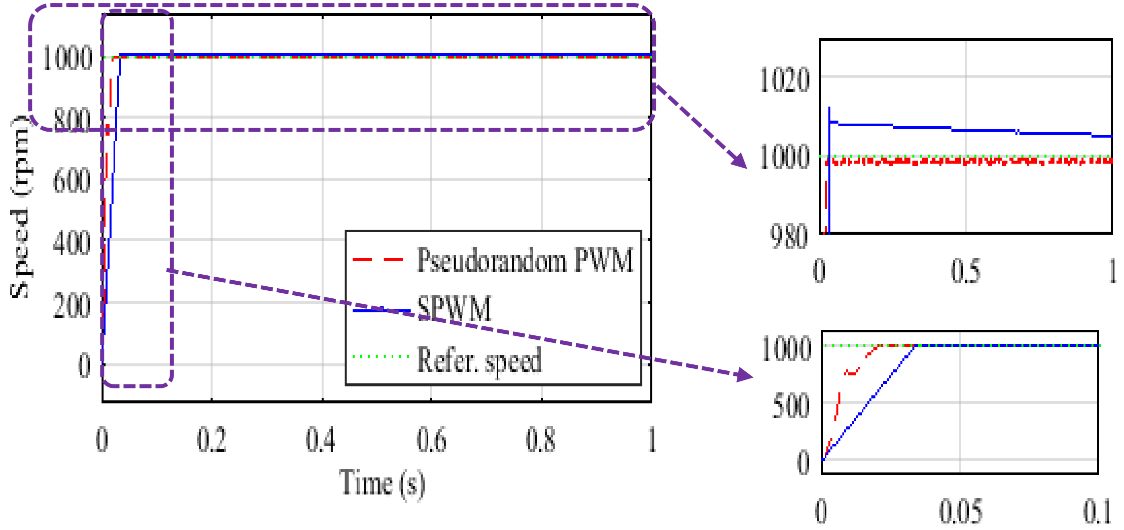
Simulation Results: Three-Phase PMSM Drive



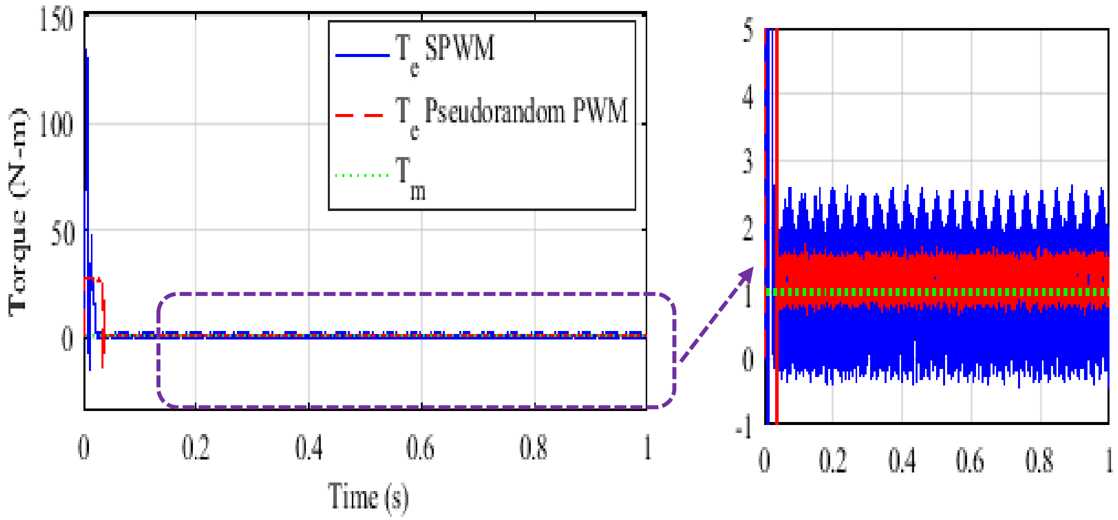
(a): Stator voltage response



(b): Stator current response

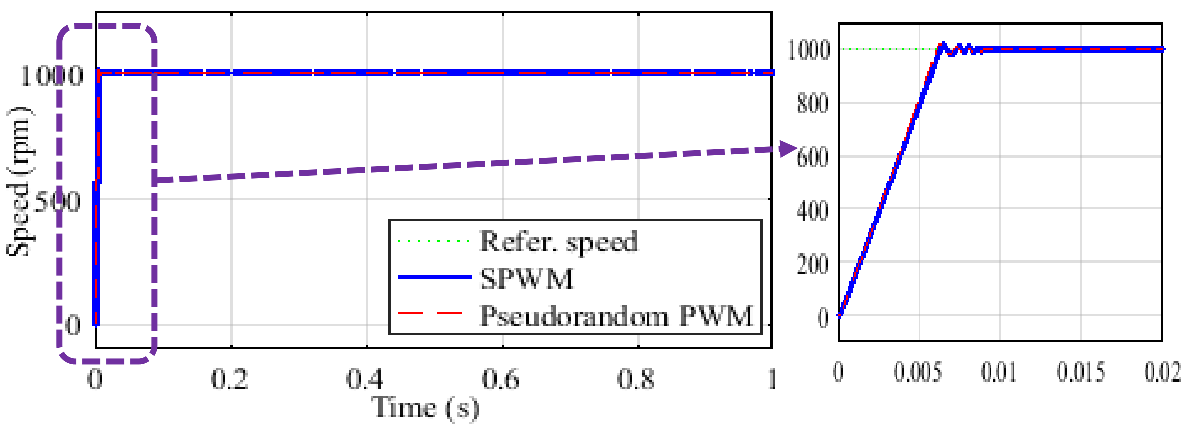


(c): Steady-state speed response

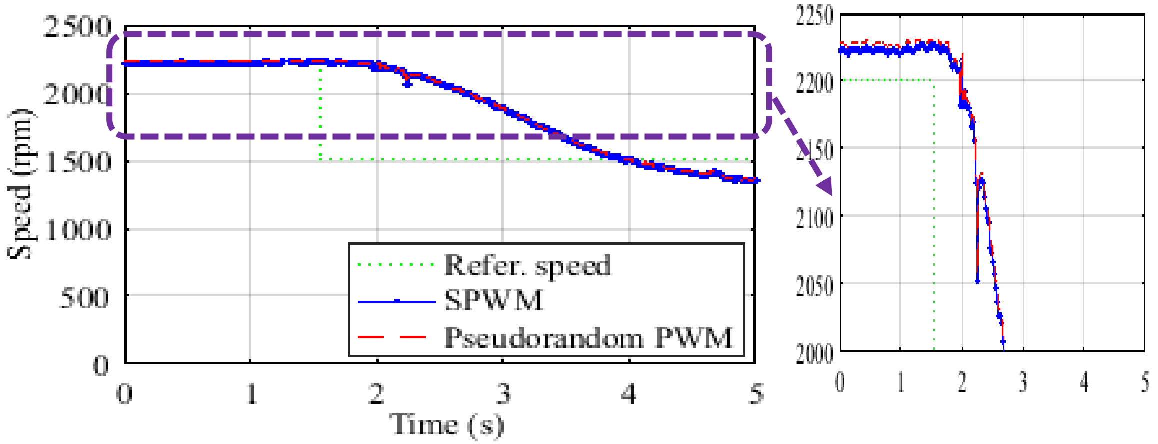


(d): Steady-state torque response

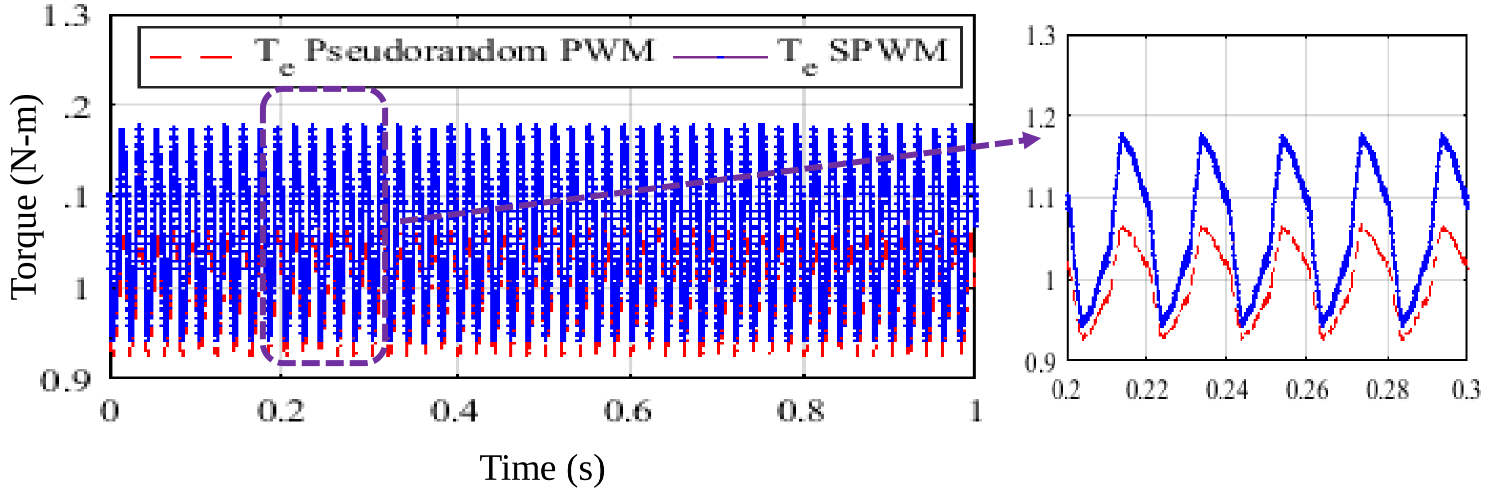
Experimental Results: Three-Phase PMSM Drive



(a): Steady-state speed response

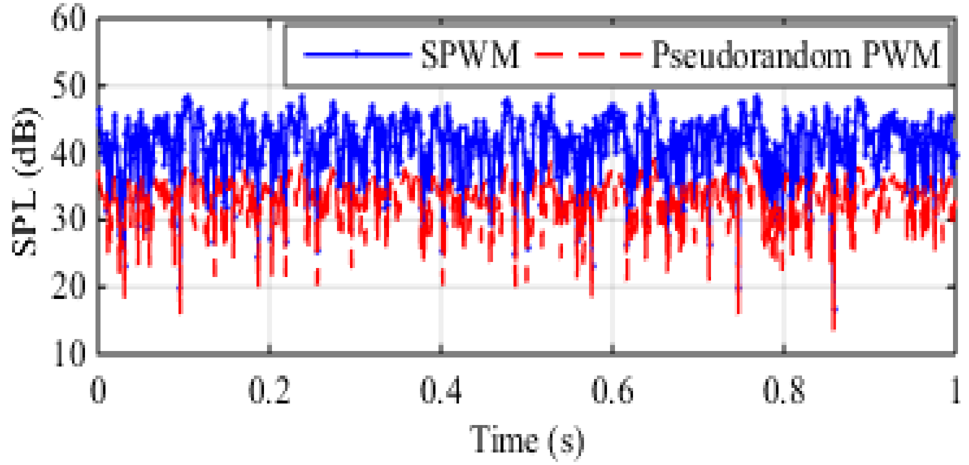


(b): Dynamic speed response

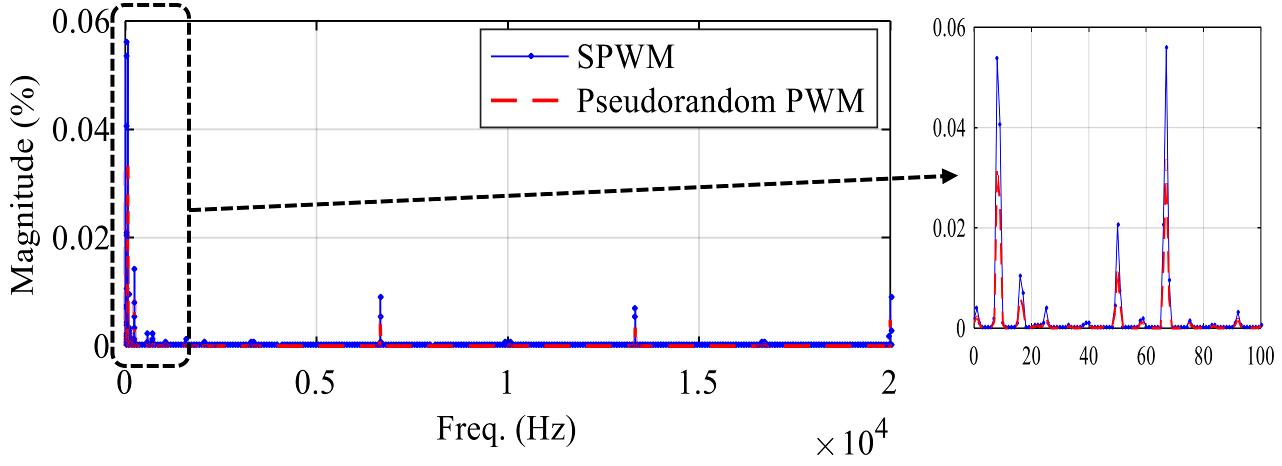


(c): Steady-state torque response

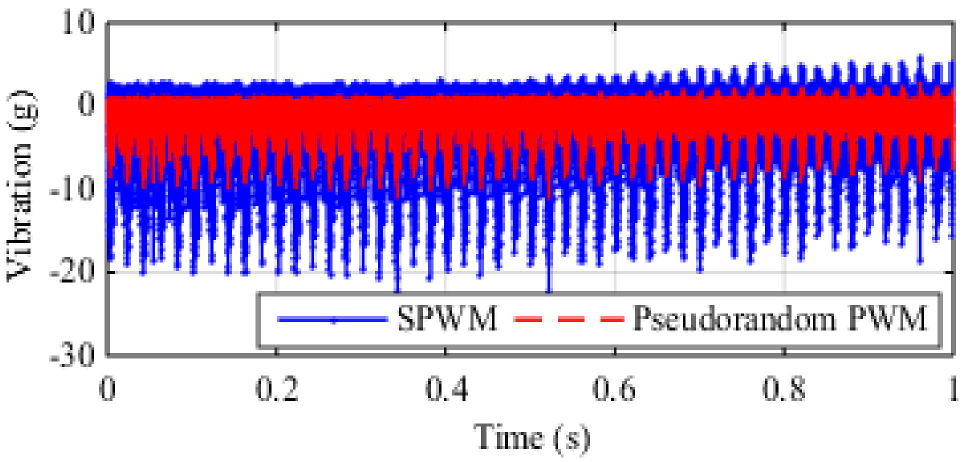
Experimental Results: Three-Phase PMSM Drive



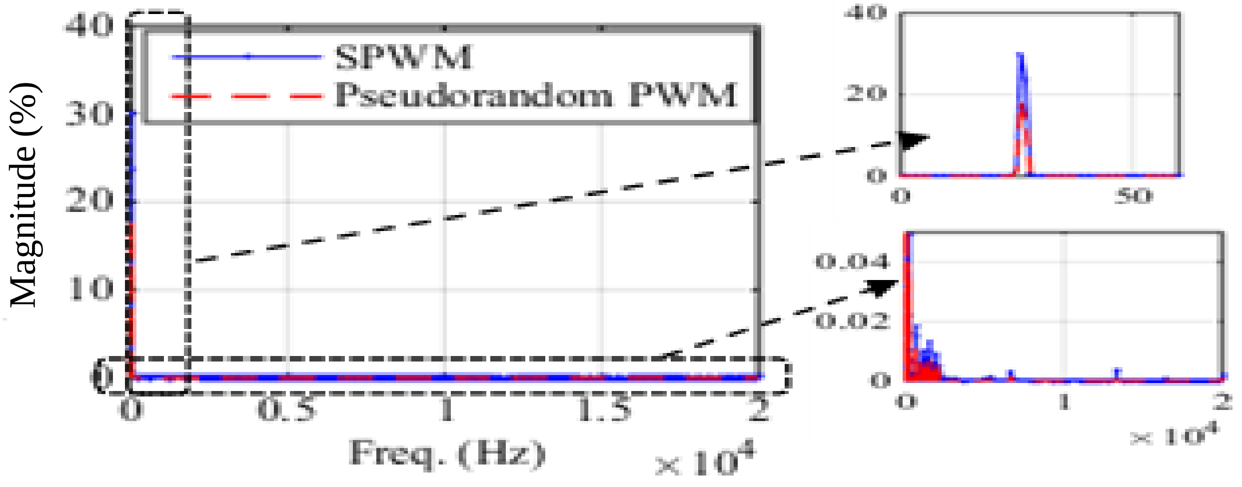
(a): Time domain spectrum of sound



(b): Frequency domain spectrum of sound



(c): Time domain spectrum of vibration



(d): Frequency domain spectrum of vibration

Comparison of SPWM and PTPWM Technique

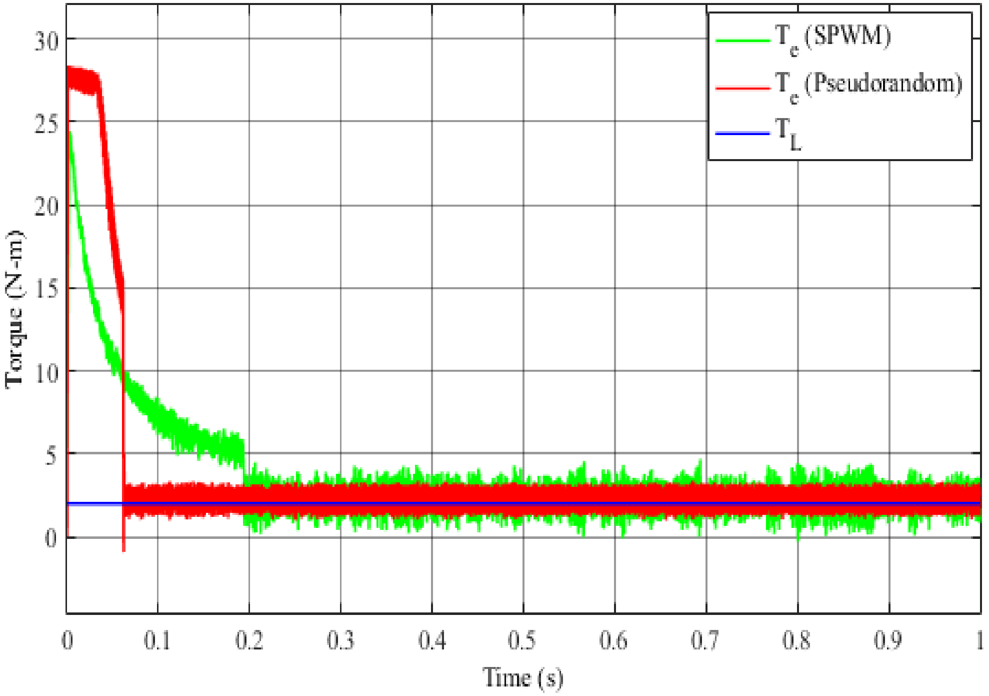


Fig. 11. Comparison of torque ripple of PMSM drive

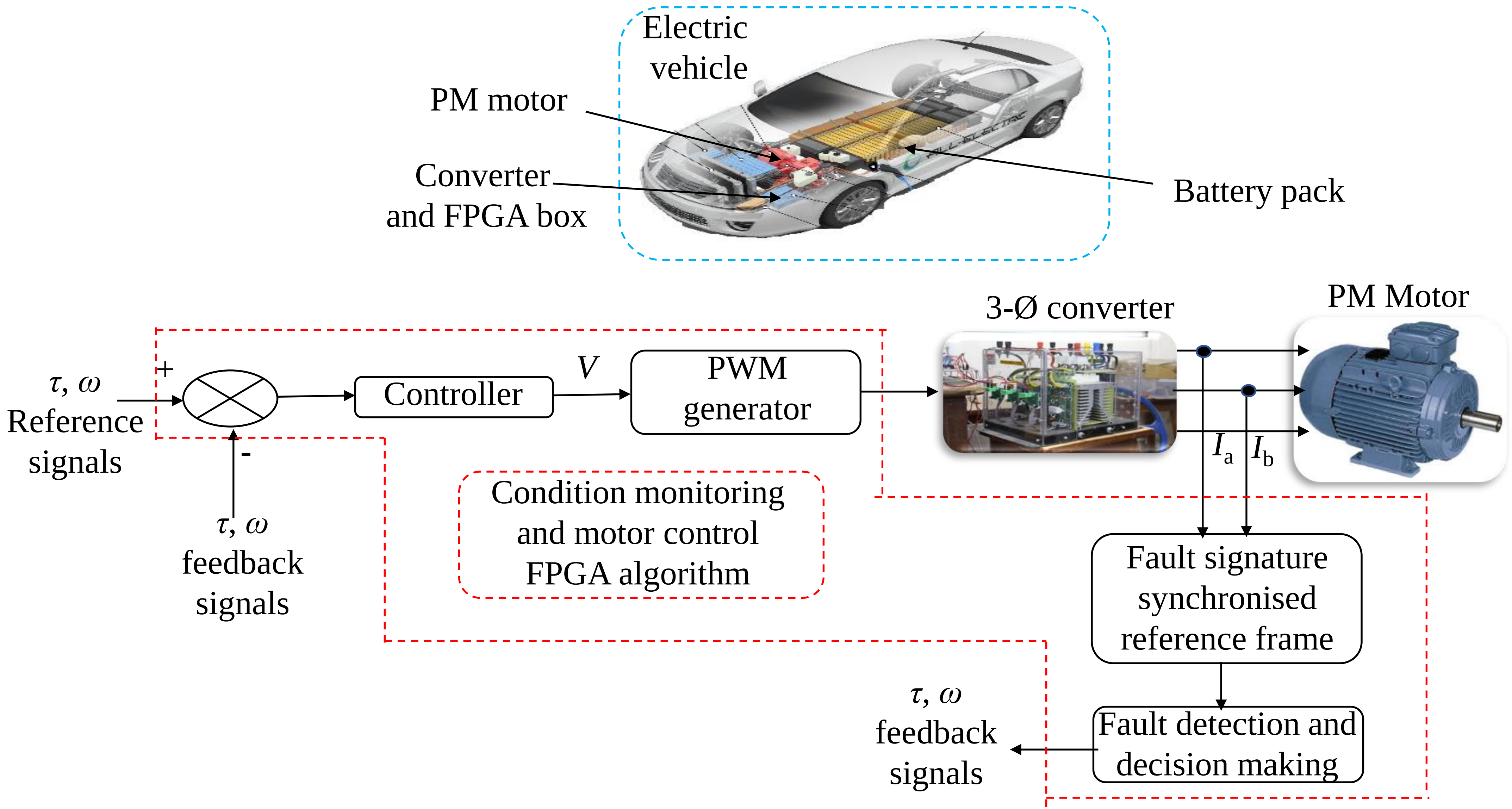
TABLE. 2. COMPARISON OF ACOUSTIC NOISE OF PMSM DRIVE

S. No	T_m (N-m)	Sound Power Level (dB)		% of reduction of acoustic noise
		SPWM technique	PTPWM technique	
1	1	48	37	22.92
2	1.5	52	42.23	18.79
3	2	59.5	48.45	18.57

TABLE. 3. COMPARISON OF VIBRATION OF PMSM DRIVE

S. No	T_m (N-m)	Vibration (g)		% of reduction of vibration
		SPWM technique	PTPWM technique	
1	1	1.8	0.9	40.12
2	1.5	2.8	1.2	53.4
3	2	3.2	1.7	46.2

Drive Embedded Fault Diagnosis Scheme Integrated to EV Applications



Summary

- An experimental investigation of Acoustic Noise and Vibration (ANV) of PMSM drive
- Designed low-cost acoustic chamber with cut-off frequency of 40 Hz
- Reduced 20% and 40% of acoustic noise and vibration of PMSM drive by random PWM techniques, respectively

Thank you for your attention

Queries

The future really is in our hands!