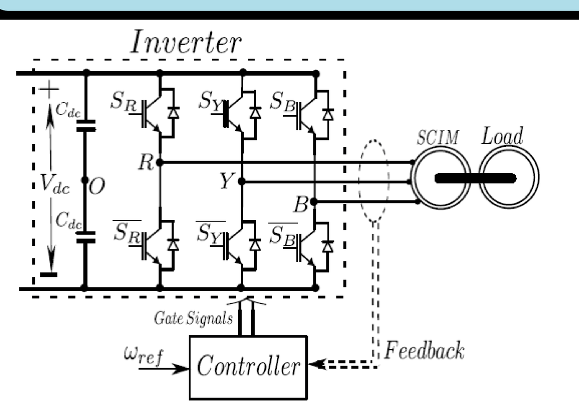
Low Switching Frequency Pulse Width Modulation for Induction Motor Drives

Avanish Tripathi, Prof. G Narayanan

Department of Electrical Engineering Indian Institute of Science, Bangalore - 560012 INDIA

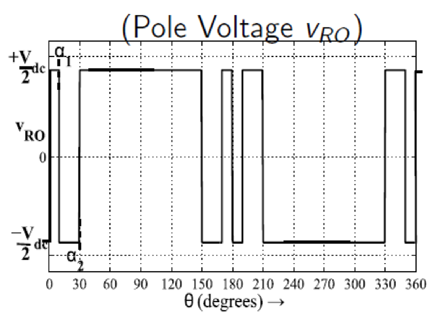
avanish@ee.iisc.ernet.in, gnar@ee.iisc.ernet.in

Introduction

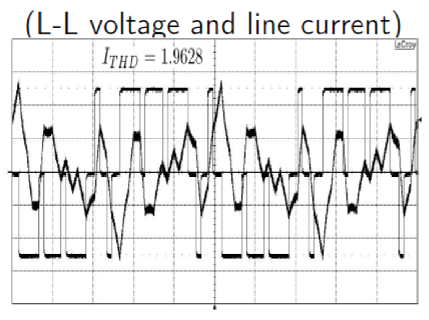


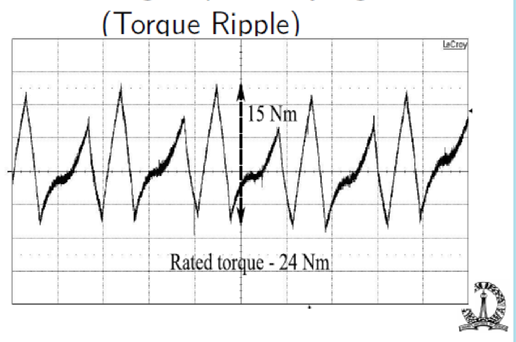
- Variable-amplitude variable-frequency voltage is generated to control the induction motor
- Switching frequency is generally much higher than maximum modulation frequency
- Switching frequency is low in high-power IM drives due to high switching energy losses
- In high-speed IM drives the maximum modulation frequency is quite high
- This work addresses the problems associated with such cases where the ratio of switching frequency to fundamental frequency (pulse number, P) is low

Problems with Low Pulse Number Applications



- Line-line voltage contains low-order voltage harmonics (*i.e.*, 5^{th}, 7^{th}, 11^{th}, 13^{th} ....)
- These voltage harmonics produce current and fluxes of same order
- High harmonic distortion in line current
- Pulsating torque is very high

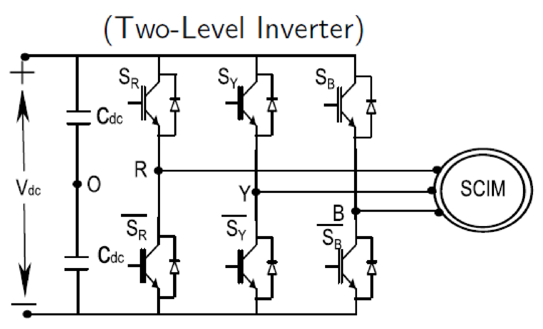


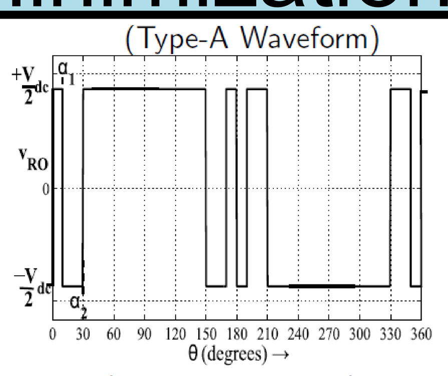


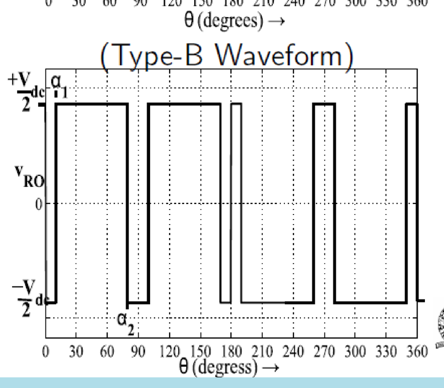
Objectives

- Minimization of line current THD
- Determination of optimal switching sequences in space vector
- Minimization of pulsating torque in frequency domain and synchronous reference frame
- Extend the proposed scheme to neutral point clamped three-level inverter
- Predict the current and torque ripple based on PWM voltage
- Closed-loop control of IM drive operated with low switching frequency varying between 250Hz and 500Hz

Current THD Minimization

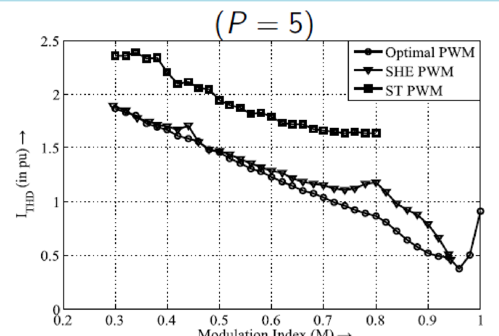


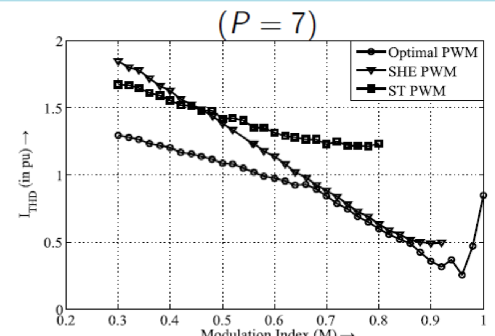


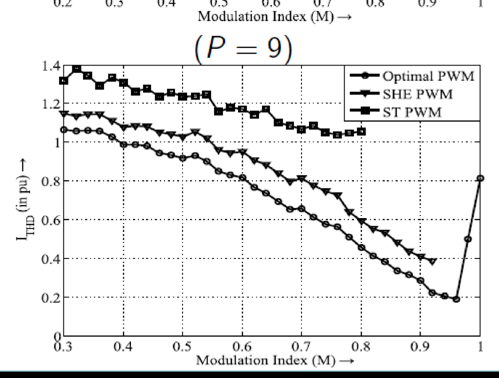


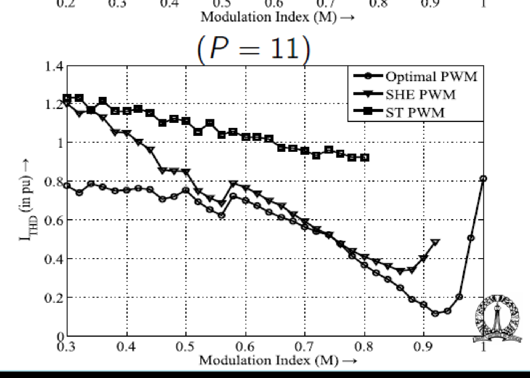
- Two types of pole voltages are possible (type-A and type-B)
- Switching transitions at 0° are opposite to each other
- Optimal PWM is solved for pulse numbers (P) 5, 7, 9 and 11

Performance Evaluation in Terms of Current THD









Space Vector Analysis

Table: Sequence of vectors applied in sector I for $P = 5$, $N = 2$

Modulation index (M)	Vector sequence in Optimal Type A	Vector sequence in Optimal Type B	Optimal vector sequence
$0 < M \leq 0.8$	101 – 272	012 – 127	101-272
$0.8 < M \leq 0.88$	101 – 272	012 – 127	012 – 127
$0.88 < M \leq 0.94$	121 – 212	012 – 127	012 – 127
$0.94 < M < 1.0$	121 – 212	012 – 127	121 – 212

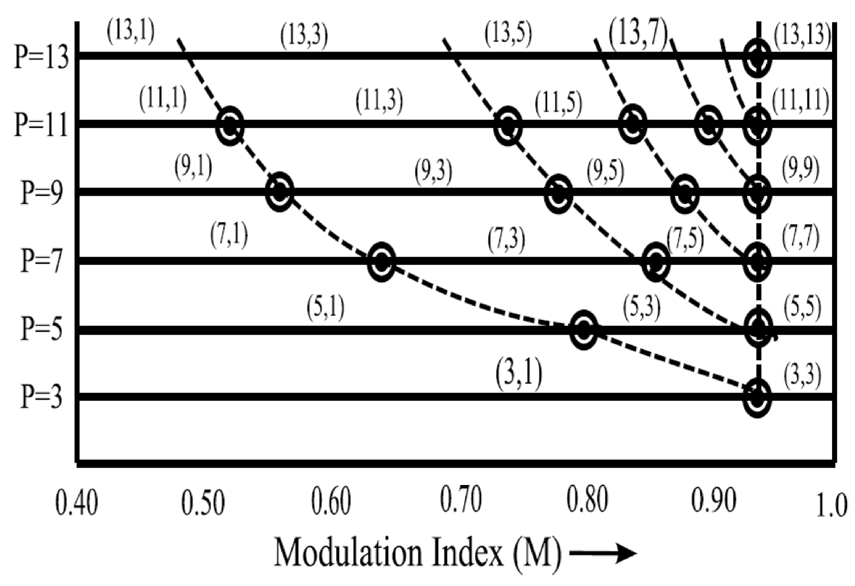
Table: Switching transitions in sector I for $P = 5$, $N = 2$

Modulation index (M)	Optimal vector sequence	No. of transitions N_{aa}	No. of transitions N_{az}	Optimal sequence code
$0 < M \leq 0.8$	101-272	1	4	(5,1)
$0.8 < M \leq 0.94$	012 – 127	3	2	(5,3)
$0.94 < M < 1.0$	121 – 212	5	0	(5,5)

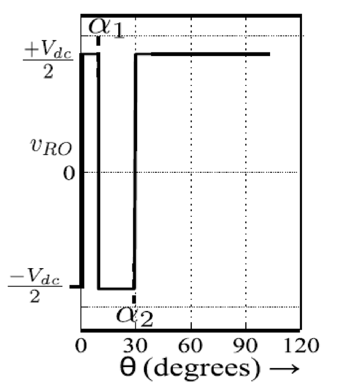
- Only nearest active vectors are applied and initial state in sector I is either 0 or 1
- Zero states 7 and 0 are not applied in 1st and 2nd halves of sector I, respectively
- Number of active vector transitions (N_{aa}) gradually increases with M
- Optimal sequence code ⇒ (P, N_{aa})

Optimal Switching Sequence Map

- Optimal sequence codes and the M ranges are plotted on a P Vs M map
- The curves can be extended to any pulse number



Torque Ripple Minimization



- Amplitude of n^{th} harmonic voltage component is given as:

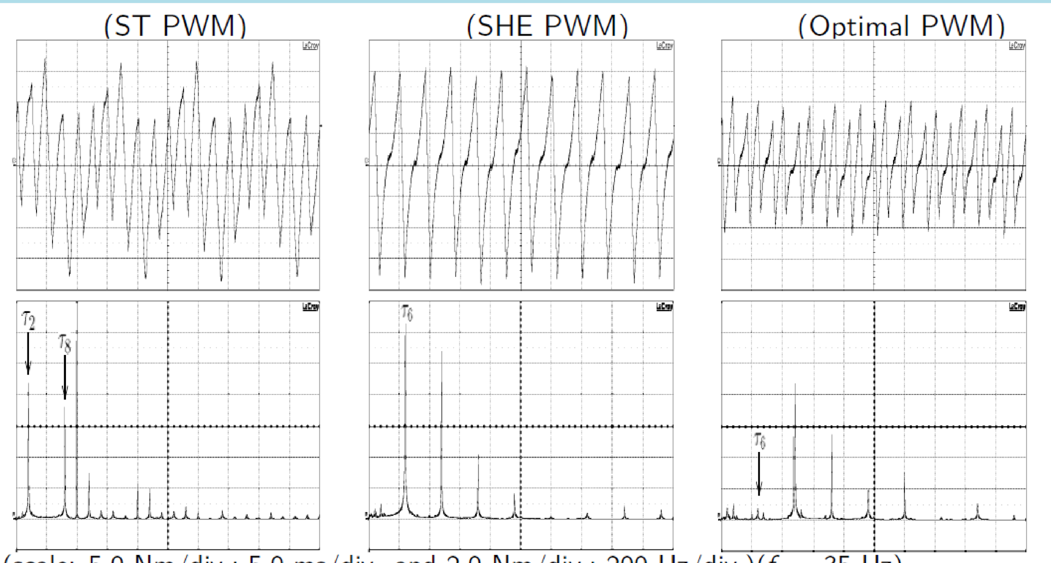
$$V_n = \frac{2V_{dc}}{n\pi}(1 - 2\cos(n\alpha_1) + 2\cos(n\alpha_2))$$

- Selective harmonic elimination (SHE) PWM eliminates (N-1) voltage harmonics for N switching angles per quarter, *e.g.*

$$V_5 = (1 - 2\cos(5\alpha_1) + 2\cos(5\alpha_2)) = 0$$

- In optimal, α_1 and α_2 are selected such that $\| \frac{V_5}{5} + \frac{V_7}{7} \|$ is minimized subject to $(\frac{V_5}{5} = \frac{V_7}{7})$ for minimization of τ_6
- The fundamental voltage component is kept at desired level in both the cases
- The theory of torque harmonic minimization is extended to other pulse numbers also
- First (N-1) torque harmonics are minimized for N switching angles per quarter

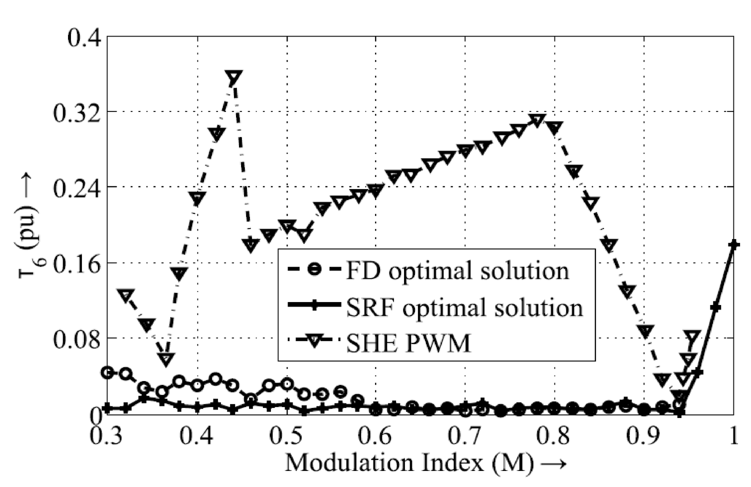
Comparison of Pulsating Torque For P=5



(scale: 5.0 Nm/div.; 5.0 ms/div. and 2.0 Nm/div.; 200 Hz/div.)(f_1 = 35 Hz)

- The pk-pk τ and τ_6 are reduced for optimal PWM as compared to sine-triangle (ST) PWM and selective harmonic elimination (SHE) PWM

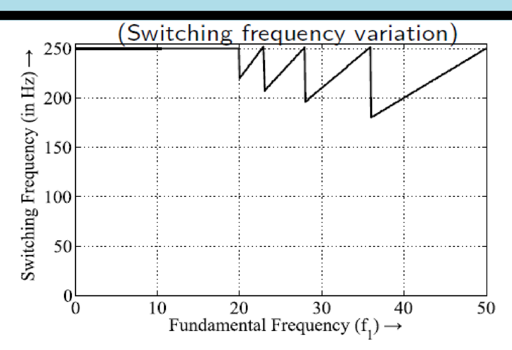
Experimental Comparison of Harmonic Torque for P=5

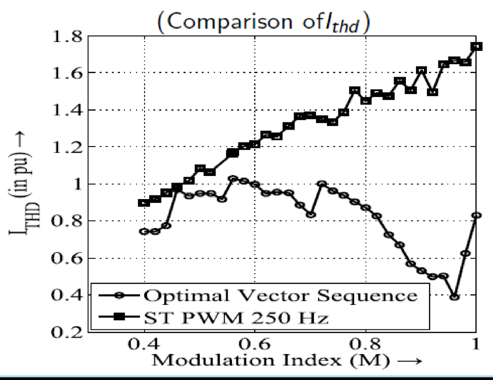


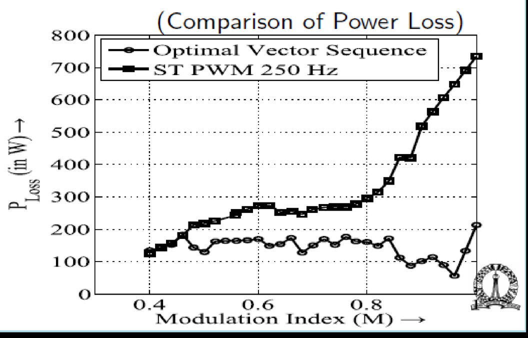
- Two optimal PWM methods are proposed - Frequency domain and synchronous reference frame base
- Both are seen to reduce τ_6 as compared to SHE PWM, over wide range of speed

Hybrid Optimal PWM

- Switching sequence is obtained for various pulse numbers
- A hybrid optimal PWM with max switching freq (f_{sw}) of 250 Hz is proposed
- $f_1 < 20$ Hz - asyn ST PWM; $f_1 \geq 20$ Hz - optimal PWM



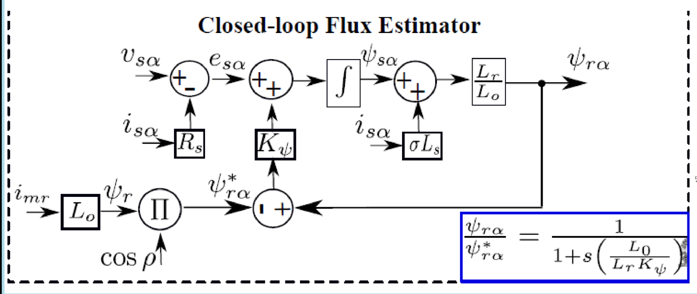


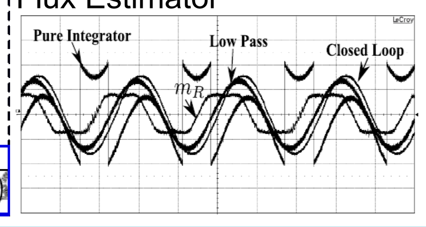


Vector Control of IM

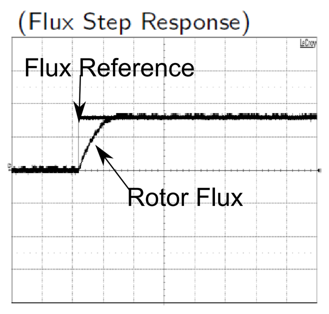
Challenges with Low switching Frequency PWM

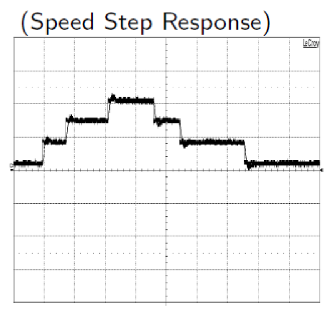
- Decoupled control of flux and torque is required for fast dynamics
- Too high current ripple ⇒ may destabilize the controller
- The inverter delay becomes significant
- The rotor flux estimation is required for sensorless control
- Flux estimation becomes inaccurate (phase and amplitude) due to low sampling frequency
- Closed loop flux estimator design is proposed and it is compared with open loop flux estimator

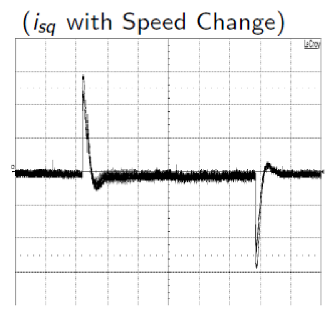


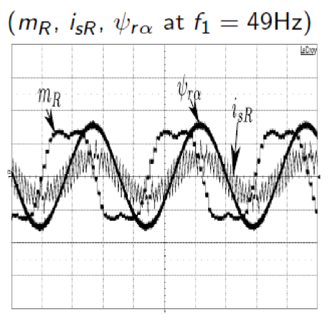


Controller Performance Evaluation









- Speed response is found to be very good at low switching frequency
- Torque (i_{sq}) reference changes with every step-change in speed and Torque (i_{sq}) is found to be tracking
- The reference and the actual quantity are found to be almost overlapping
- Steady state waveforms of line current, rotor-flux and modulating signal are shown at $f_1 = 49$Hz

Experimental Setup

- 3-ϕ Induction Motor
  - 3.7kW, 415V
  - 1460rpm

Parameter	Value
R_s	1.28 Ω
R_r	1.28 Ω
L_s	0.267 H
L_r	0.267 H
L_m	0.259 H

- 3-ϕ Inverter
  - IGBT based
  - V_{dc} = 520V

FPGA based controller board is used for open-loop V/f control

Important Publications

- A. Tripathi and G. Narayanan, "Evaluation and minimization of low-order harmonic torque in low-switching-frequency inverter fed induction motor drives," *IEEE Trans. Ind. Appl.*, Mar 2015, Early access.
- A. Tripathi and G. Narayanan, "Evaluation and minimization of low-order harmonic torque in low-switching-frequency inverter fed induction motor drives," *IEEE PEDES*, Dec 2014, pp. 1-6.
- A. Tripathi and G. Narayanan, "Investigations on optimal pulse-width modulation to minimize total harmonic distortion in the line current," *IEEE IICPE*, Dec 2014, pp. 1-6.
- A. Tripathi and G. Narayanan, "High-Performance Off-line Pulse Width Modulation Without Quarter Wave Symmetry For Voltage-Source Inverter," *IEEE ICAECC*, Oct 2014, pp. 1-6.