Switched Capacitive Filter for Harmonic Suppression in Variable Speed Induction Motor Drives

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Outline

- Motivation
- Eliminating 5^{th} and 7^{th} order harmonics
- Problems to be addressed
- Capacitive filtering - Ensuring an inverter to contribute zero active power
- Proposed Solution
- Experimental Results
- Related work done
- Summary
- Publications

Motivation

Effect of 5th and 7th order harmonics on Induction Motors

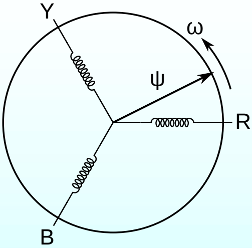
- Fundamental

  $V_{R1}=V_1\sin\omega t$

  $V_{Y1}=V_1\sin(\omega t+120^O)$

  $V_{B1}=V_1\sin(\omega t-120^O)$

Air Gap Flux



Motivation

Effect of 5th and 7th order harmonics on Induction Motors

- Fundamental

  $V_{R1}=V_1\sin\omega t$

  $V_{Y1}=V_1\sin(\omega t+120^O)$

  $V_{B1}=V_1\sin(\omega t-120^O)$

- 5^{th} Harmonic

  $V_{R5}=V_5\sin 5\omega t$

  $V_{Y5}=V_5\sin\{5(\omega t+120^O)\}$
  $=V_5\sin(5\omega t-120^O)$

  $V_{B5}=V_5\sin\{5(\omega t-120^O)\}$
  $=V_5\sin(5\omega t+120^O)$

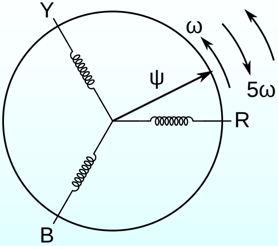
- 7^{th} Harmonic

  $V_{R7}=V_7\sin 7\omega t$

  $V_{Y7}=V_7\sin\{7(\omega t+120^O)\}$
  $=V_7\sin(7\omega t+120^O)$

  $V_{B7}=V_7\sin\{7(\omega t-120^O)\}$
  $=V_7\sin(7\omega t-120^O)$

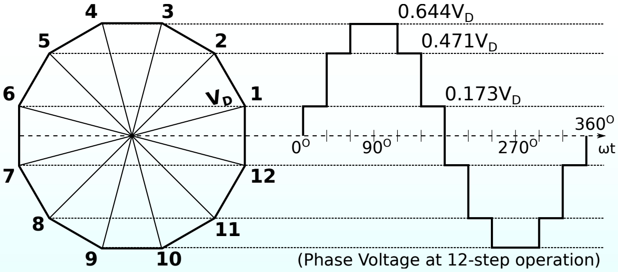
Air Gap Flux



6^{th} Harmonic flux ripple over the fundamental, resulting in torque ripple

Eliminating 5th and 7th order harmonics

12-sided Voltage Space Vectors(VSV)



(Phase Voltage at 12-step operation)

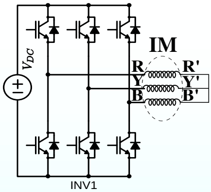
$$V_{phase,n} = \frac{4}{\pi}\int_0^{\frac{\pi}{2}} V_{phase}\sin(n\omega t)d\omega t$$

$$V_{phase,n} = \frac{4V_d}{n\pi}\left[0.173 + 0.298\cos(\frac{n\pi}{6}) + 0.173\cos(\frac{n\pi}{3})\right]$$

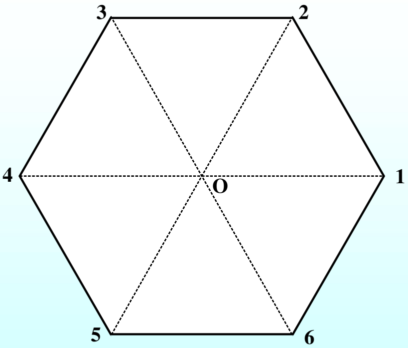
$$\mathbf{V_{phase,1} = 0.659V_d;\ V_{phase,5} = V_{phase,7} = V_{phase,17} = V_{phase,19} = 0}$$

Eliminating 5th and 7th order harmonics

Generating 12-sided VSV

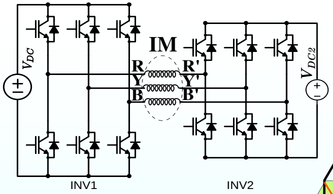


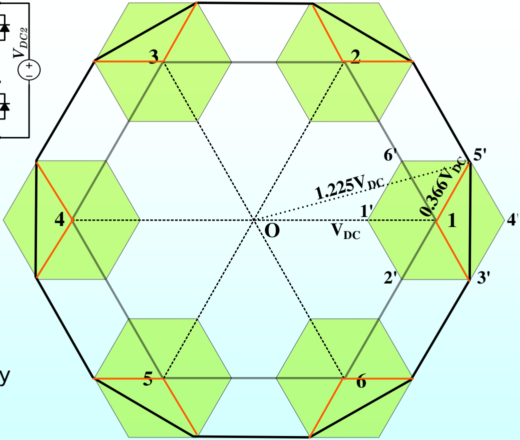
- Two-level inverter feeding star connected 3-phase IM
- Hexagonal space vector structure
- Higher switching frequency required for harmonic suppression
- Bulky passive line filters required for harmonic suppresion



Eliminating 5th and 7th order harmonics

Generating 12-sided VSV





- Second inverter feeding from other end of IM winding terminals
- 12-sided space vector structure
- Multiple DC power supply (V_{DC}, $0.366V_{DC}$)

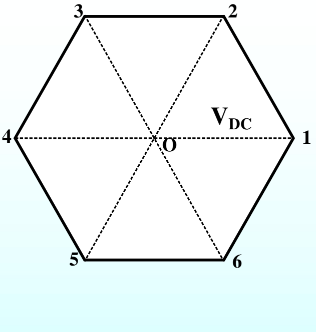
K. K. Mohapatra, K. Gopakumar, V. T. Somasekhar, and L. Umanand, “A harmonic elimination and suppression scheme for an open-end winding induction motor drive,” IEEE Trans. Ind. Electron., vol. 50, no. 6, pp. 1187–1198, Dec. 2003.

Problems to be addressed

- Eliminating 5^{th} and 7^{th} order harmonics for the full speed range of the induction motor
- Avoiding multiple DC supplies
- Avoiding bulky passive line filters
- Avoiding any offline computation and requirement for look-up tables (required in Selective Harmonic Elimination)
- Shifting high frequency switching to low voltage stress devices
- Increasing the linear modulation range of the inverter

Capacitive Filtering

Ensuring Zero Active Power by Inverter-2



Peak fundamental voltage for six-step operation= **$0.637V_{DC}$**

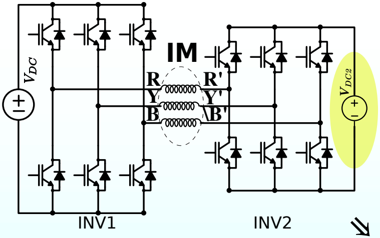
Peak fundamental voltage for twelve-step operation= **$0.659V_d$**

Equal fundamental voltage⇒Equal active power generation

$V_d=0.966V_{DC}$

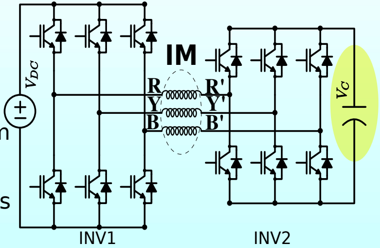
Proposed Solution

Power Circuit



- Multiple power supply
- Active power contribution from the secondary inverter

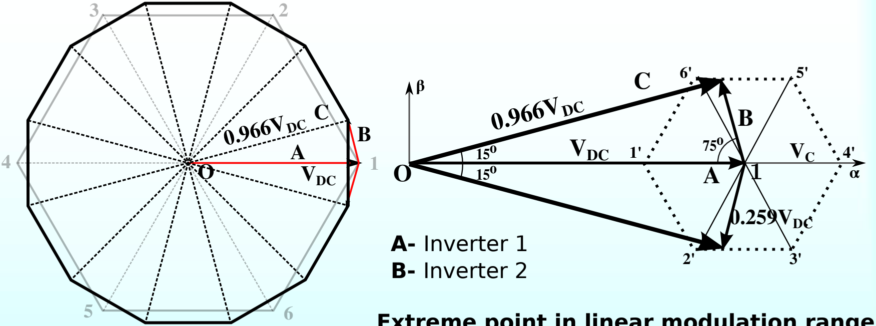
⇘



- DC supply of secondary inverter substituted by capacitor
- No active power contribution from secondary inverter
- Capacitor fed inverter operates as filter

Proposed Solution

Vector Construction



A- Inverter 1
B- Inverter 2

16' kT_1 + **15'** $(1\text{-}k)T_1$ = **B** T_1

$\Rightarrow V_C\angle{-60^o}\ kT_1 + V_C\angle 60^o\ (1\text{-}k)T_1$
$= 0.259V_{DC}\angle{-75^o}\ T_1 \quad (1)$

Resolving Eq. 1 in α-β axes:

$\mathbf{V_C=0.289V_{DC}}$
k=0.732

Extreme point in linear modulation range

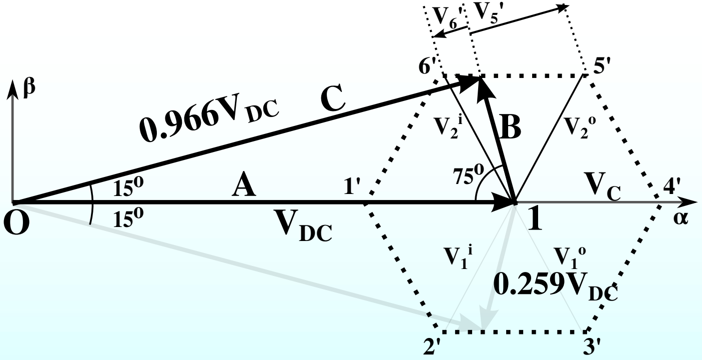
$V_{phase,pk}=(2/3)(0.966V_{DC}\cos 15^o)=\mathbf{0.622V_{DC}}$

Extreme linear modulation supply frequency= **48.8Hz**

Increase in linear modulation range (%)= **7.8%**

Proposed Solution

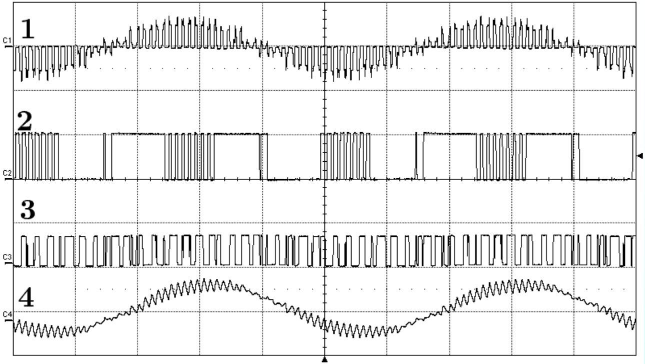
Capacitor Voltage Control



- **V_6'** and **V_5'** having opposing effect on the capacitor for a particular load current direction
- Capacitor voltage controlled by controlling duty ratio *k*

Experimental Results

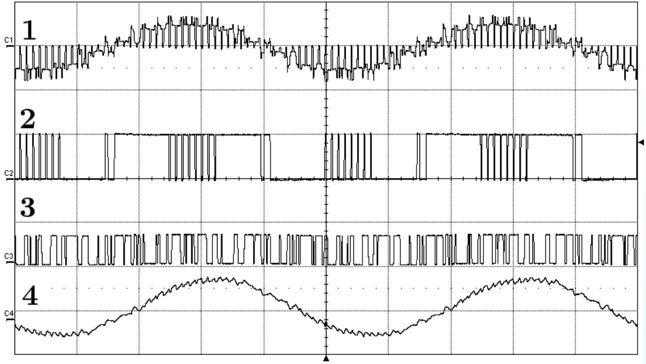
20Hz



1. Phase Voltage-(200V/div), **2.** Inv-1 Pole Voltage-(200V/div)
3. Inv-2 Pole Voltage-(100V/div), **4.** Phase current-1A/div.
X-axis: 10ms/div

Experimental Results

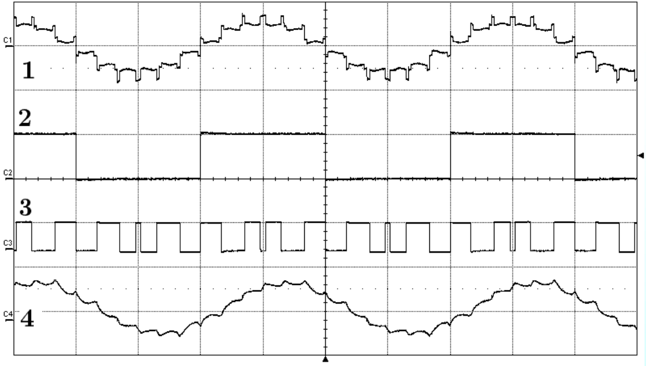
40Hz



1. Phase Voltage-(200V/div), **2.** Inv-1 Pole Voltage-(200V/div)
3. Inv-2 Pole Voltage-(100V/div), **4.** Phase current-1A/div.
X-axis: 5ms/div

Experimental Results

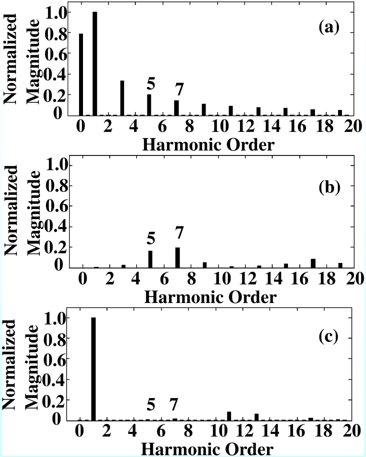
50Hz



1. Phase Voltage-(200V/div), **2.** Inv-1 Pole Voltage-(200V/div)
3. Inv-2 Pole Voltage-(100V/div), **4.** Phase current-1A/div.
X-axis: 5ms/div

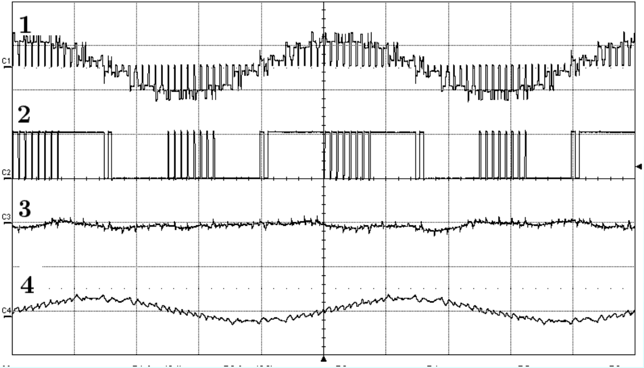
Experimental Results

50Hz



Experimental Results

Capacitor Ripple at 40Hz

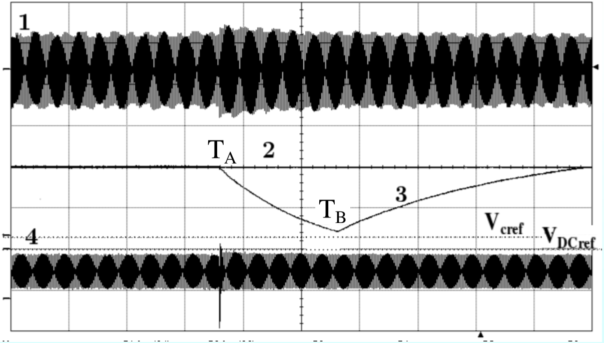


1. Phase Voltage-(200V/div)**, 2.** Inv-1 Pole Voltage-(200V/div)
3. Capacitor Ripple voltage-(5V/div)**, 4.** Phase current-2A/div.
X-axis: 5ms/div

Experimental Results

Capacitor Control at 40Hz

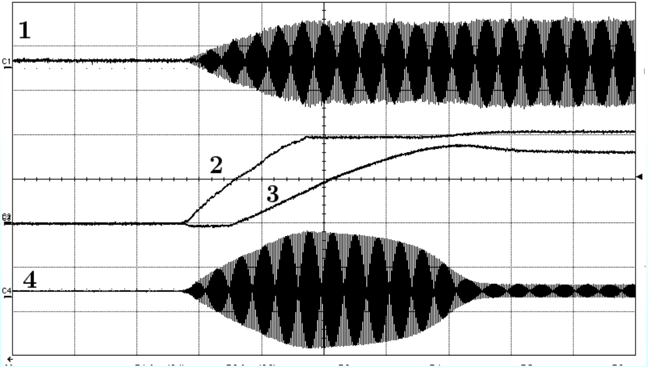
T_A voltage controller reset; T_B controller switched ON



1. Phase Voltage-(50V/div), **2.** DC-BusVoltage-(50V/div)
3. Capacitor voltage-(20V/div), **4.** Phase current-0.5A/div.
X-axis: 1s/div

Experimental Results

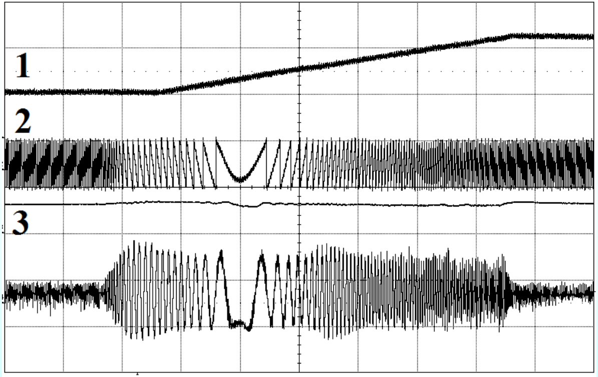
Starting Transients at 40Hz



1. Phase Voltage-(50V/div)**, 2.** DC-BusVoltage-(50V/div)
3. Capacitor voltage-(20V/div)**, 4.** Phase current-2A/div.
X-axis: 1s/div

Experimental Results

Vector Control Speed Reversal (-48Hz - 48Hz)



1: Machine speed(2500rpm/div), 2: Rotor position(6.28rad/div)
3: Filter capacitor voltage(100V/div), 4: Phase Current(2A/div)
Timescale: 1s/div

Experimental Results

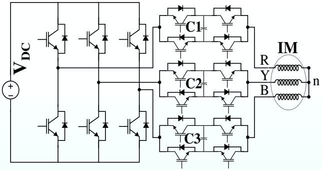
Switching Frequency Comparison between Inverters

Frequency(Hz)	Switching Frequency(Hz)	
	Inverter-1	**Inverter-2**
10	180	360
20	360	720
30	540	1080
40	720	1440

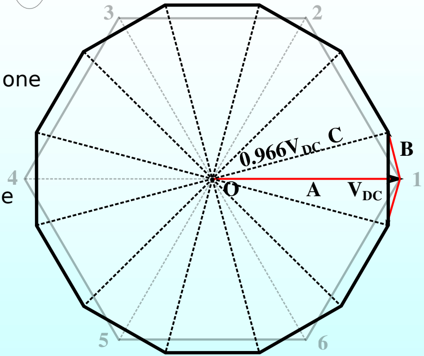
- Higher switching frequency required in conventional 2-level inverter to **suppress** $6n \pm 1$ order harmonics
- Voltage stress across switches of secondary inverter is almost one third of that of primary inverter.

Related Work Done

Capacitive Filtering for Star Connected Induction Motor

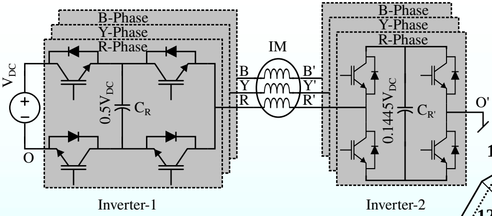


- Capacitors brought to one end of the motor
- **A** vector applied from 2-level inverter
- **B** vector applied by the cascaded H-bridges
- Phase voltage never exceeds (2/3)V_{DC}
- **V_C=0.1445V_{DC}**

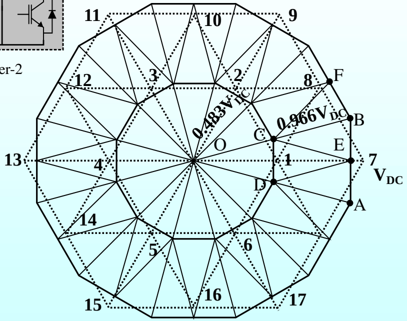


Related Work Done

Capacitive Filtering Applied to form 3-level 12-sided VSV



- Capacitive filter applied to conventional 3-level Flying Capacitor
- Multilevel 12-sided voltage space vector structure realized using single DC supply
- Phase voltage never exeeds (2/3)V_{DC}
- **V_C=0.1445V_{DC}**



Summary

- Dodecagonal voltage space vector realized using single DC supply
- Complete elimination of the 5^{th} and 7^{th} order harmonics for the full speed range of the drive, including six-step operation of the primary inverter
- Increase in linear modulation range (45.3Hz to 48.8Hz)
- Higher switching frequency shifted to low voltage switches resulting in lesser switching loss
- No pre-charging circuitry required for the capacitor. Capacitor voltage inherently controlled by the PWM
- Proposed capacitive filtering scheme has been tested with rotor field oriented vector control with tight capacitor voltage control

Publications

- S. Pramanick, N. Abdul Azeez, S. Kaarthik, K. Gopakumar, and C. Cecati,“Low order harmonic suppression for open-end winding IM with dodecagonal space vector using a single dc-link supply”, *IEEE Trans. Ind. Electron.*, vol. 62, issue 99, pp. 5340-5347, 2015.
- S. Pramanick, S. Kaarthik, N. Abdul Azeez, K. Gopakumar, S. Williamson and K. Rajashekara,“A Harmonic Suppression Scheme for Full Speed Range of a Two Level Inverter Fed Induction Motor Drive using Switched Capacitive Filter”, *IEEE Trans. Power Electron.*, 2016
- S. Pramanick, M. Boby, N. Abdul Azeez, K. Gopakumar and S. Williamson,“A 3-Level Dodecagonal Space Vector based Harmonic Suppression Scheme for Open-End Winding IM Drives with Single DC Supply,” *IEEE Trans. Ind. Electron.*, vol. PP, no. 99, pp. 11, 2016.

THANK YOU