Multilevel Dodecagonal Space Vector Structures and Modulation Schemes with Hybrid Topologies for Variable Speed AC Drives

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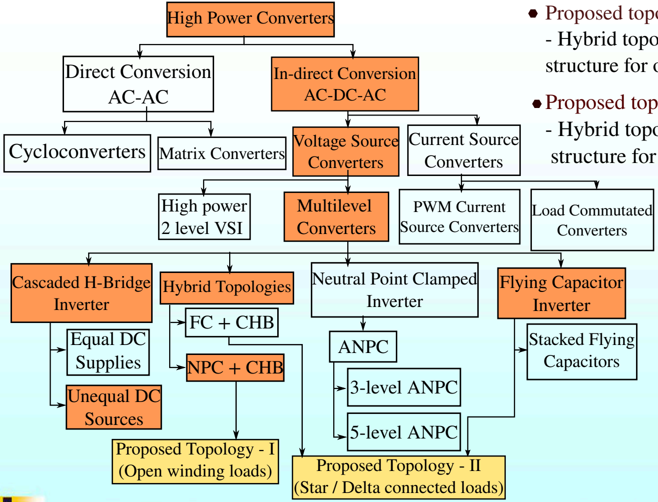
Applications and Challenges

- The most preferred choice of power converters for electric power conversion in the industry.
  - Transportation, traction
  - Industrial drives
  - Energy management
  - Power transmission and distribution
- Although multilevel inverters are already proven technology, it presents challenges for research, design and development.
  - Performance (fidelity of phase voltages, harmonic content)
  - Efficiency
  - Modulation Schemes
  - Reliability
  - Power Density
  - Packaging

Classification of Multilevel Converters

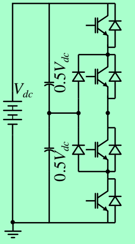
Proposed Topologies



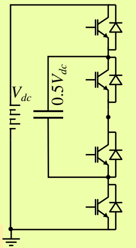
- Proposed topology-I
  - Hybrid topology with NPC+CHB structure for open-end wound IM
- Proposed topology-II
  - Hybrid topology with FC+CHB structure for standard IM

Classification of Multilevel Converters

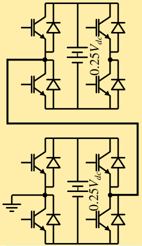
Traditional Multilevel Topologies



- Neutral Point Clamped Inverter
- Very simple structure
- Industry standard as of now
- A large number of diodes
- Capacitor mid-point balancing issues



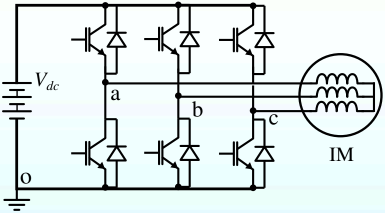
- Flying Capacitor Inverter
- Used in the industry for low power drives
- No clamping diodes requirement
- Large number of capacitors
- Full load current flows through capacitors
  - capacitor charge can be controlled using switching redundancies

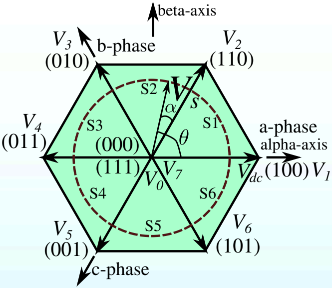


- Cascaded H-Bridge Converter
- Low voltage devices
- Requirement of many isolated DC power supplies
- Commercial systems available upto 17-level topology

Two level Inverter

Topology and SV Structure

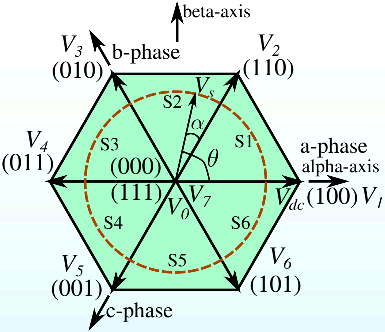




- Two possible pole voltage values at any instant
- Generates a hexagonal Voltage Space Vector Structure
- Any point within the hexagon can be generated by switching - in average sense
- Any reference vector, is generated in average sense using Volt-Second balance

Two level Inverter

Space Vector Modulation



$$\vec{V_s} = V_{ao} + V_{bo}\, e^{j120^\circ} + V_{co}\, e^{j240^\circ}$$

$$\vec{V_s} = |V_s|\angle\theta = V_\alpha + jV_\beta$$

$$T_1 = \frac{|V_s| T_s \sin(60^\circ - \alpha)}{V_{dc} \sin 60^\circ}$$

$$T_2 = \frac{|V_s| T_s \sin\alpha}{V_{dc} \sin 60^\circ}$$

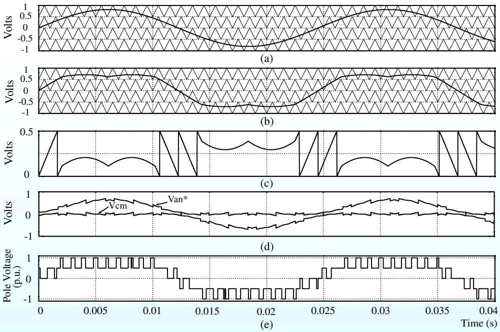
$$T_0 = T_s - (T_1 + T_2)$$

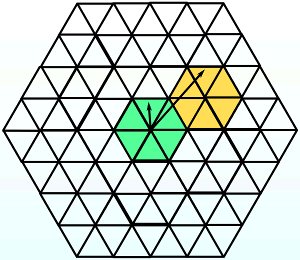
- All three pole voltages are considered together
- Active vectors supply power, Zero Vectors do not
- T_0 is split to two equal halves to obtain better harmonic performance

$T_0/2,\ T_1,\ T_2,\ T_0/2$

Modulation for Multilevel Inverters

Level Shifted Carriers

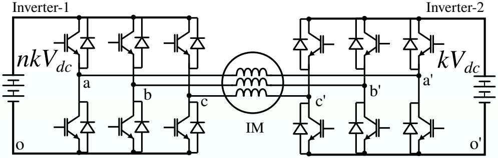




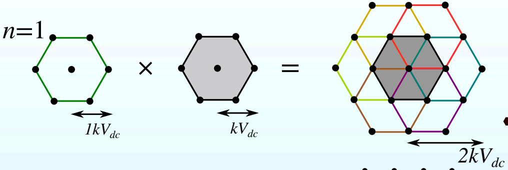
- Level Shifted Carrier algorithm
- (N-1) carriers for a N-level converter
- Geometrically, it is shifting of the hexagon where the reference is, to the smallest centre hexagon

Open-end winding IM

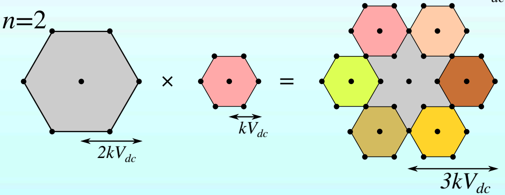
Superposition of SV structures



- $\overrightarrow{V_R} = V_{aa'} + V_{bb'}e^{j120^\circ} + V_{cc'}\, e^{j240^\circ}$
- Effectively it is superposition of two SV Structures
- Un-equal DC links
  n=1 is three level structure
  n=2 is four level structure

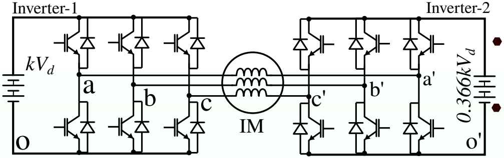


- $V_{ao} - V_{a'o'}$ is the effective phase voltage
- Difference of pole voltages is the effective phase voltage of the system

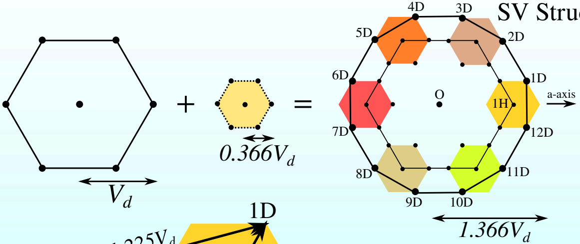


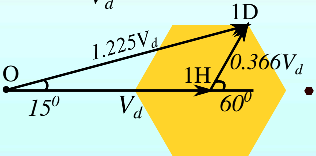
Dodecagonal SV structure

Superposition of SV structures



- Inverter-1 with DC-link V_d
  Inverter-2 with DC-link $0.366V_d$
- Effective SV structure is superposition of two SV Structures- V_d and $0.366V_d$

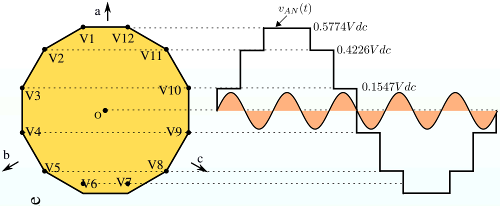




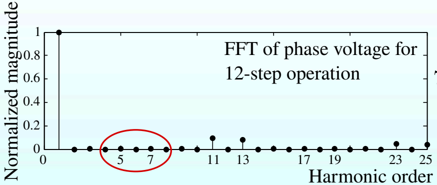
- Vector addition of V_{ao} and $V_{c'o'}$ generates the point 1D

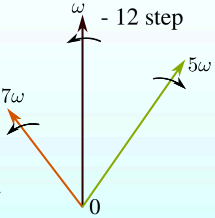
Advantages of Dodecagonal SV structure

5th and 7th harmonic elimination



- Complete elimination of fifth harmonics and seventh harmonics for full modulation range
  - linear modulation,
  - over-modulation and
  - 12 step

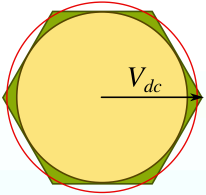




- The fundamental and fifth harmonic rotate in opposite directions
- After 30° rotation of the fundamental, the fifth harmonic from from previous switching and current switching are in phase opposition
- Similarly, 7th harmonic is also eliminated

Advantages of Dodecagonal SV structure

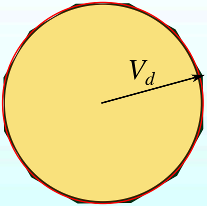
Extension of Linear Modulation Range



Hexagonal Switching	Fundamental
6 step operation	$0.637V_{dc}$
End of Linear modulation range	$0.577V_{dc}$

Ratio = 90.6%

Corresponding frequency = 45.3Hz



Dodecagonal Switching	Fundamental
12 step operation	$0.659V_d$
End of Linear modulation range	$0.644V_d$

Ratio = 97.3%

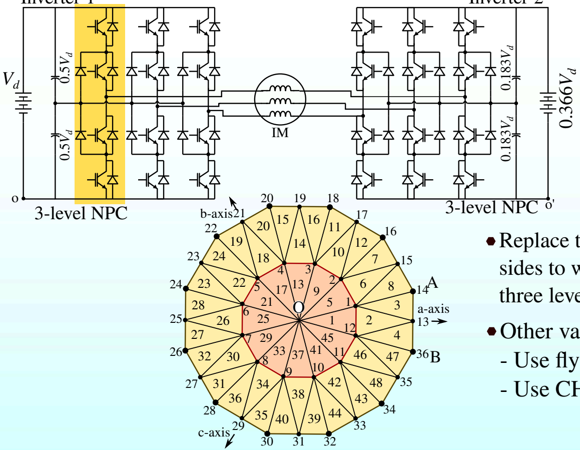
Corresponding frequency = 48.85Hz

- The peak of fundamental component should be the rated voltage at 50Hz (6-step or 12-step operation)

$$\text{So, } 0.659V_d = 0.637V_{dc}$$

Multilevel Dodecagonal SV structure

3 level dodecagonal SV structure

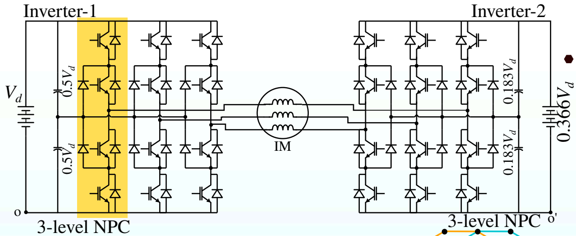


- Replace two level inverters on both sides to with 3 level NPC to obtain three level dodecagonal SV structure
- Other variations
  - Use flying capacitor topology
  - Use CHB topology on both sides

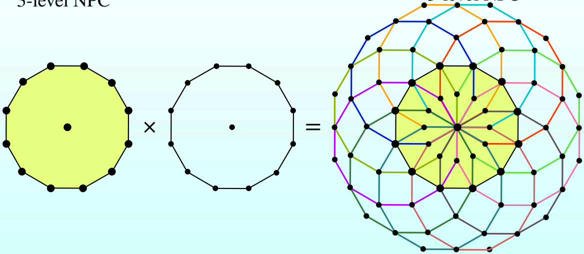
Das A, Sivakumar K, Ramchand R, Patel, C. & Gopakumar K, "A Pulsewidth Modulated Control of Induction Motor Drive Using Multilevel 12-Sided Polygonal Voltage Space Vectors
IEEE Trans. Ind. Electron., 2009, 56, 2441-2449.

Multilevel Dodecagonal SV structure

NPC based - 6 concentric Dodecagons



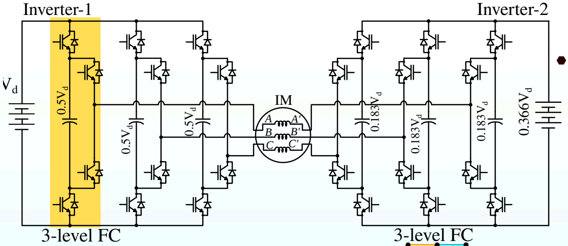
- Superposition of two dodecagons yeilds SV structure with Six Concentric Dodecagons



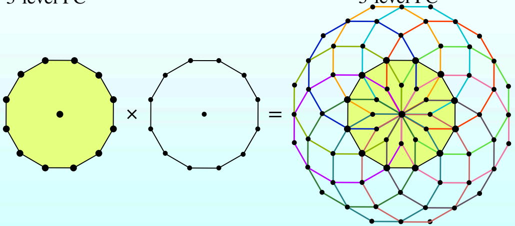
Das, A. & Gopakumar, K. "A Voltage Space Vector Diagram Formed by Six Concentric Dodecagons for Induction Motor Drives" IEEE Trans. Power Electron., 2010, 25, 1480-1487

Multilevel Dodecagonal SV structure

FC based - 6 concentric Dodecagons



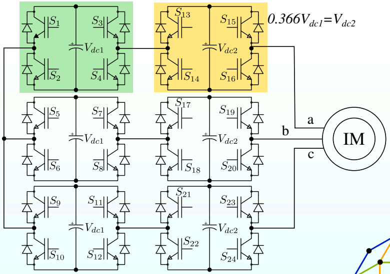
- Superposition of two dodecagons yeilds SV structure with Six Concentric Dodecagons



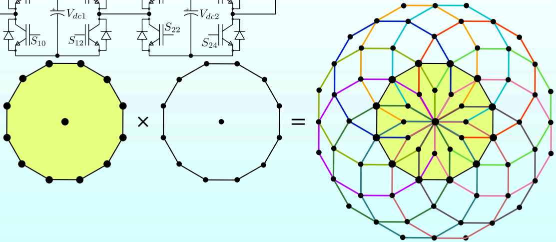
Mathew J, Rajeevan P, Mathew K, Azeez N & Gopakumar K. "A Multilevel Inverter Scheme With Dodecagonal Voltage Space Vectors Based on Flying Capacitor Topology for Induction Motor Drives" IEEE Trans. Power Electron., 2013, 28, 516-525.

Multilevel Dodecagonal SV structure

For standard IM - CHB based topology



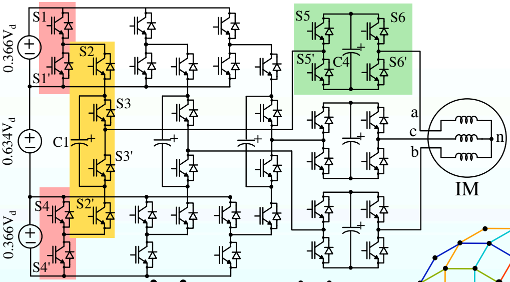
- Six Concentric Dodecagons from single side
- Requires six isolated DC power supplies



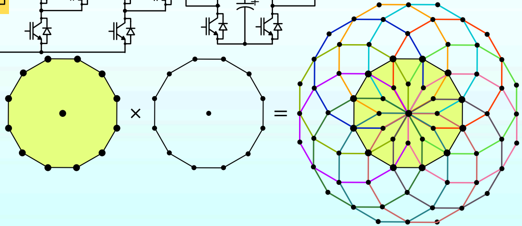
Mathew, K. Das, A. Patel, C. Ramchand R. & Gopakumar K. "An asymmetric cascaded H-Bridge inverters for generating 12-sided polygonal space vector diagrams for Motor drives." EPE journal, 2011, 21, 21-28.

Multilevel Dodecagonal SV structure

For standard IM - Hybrid topology



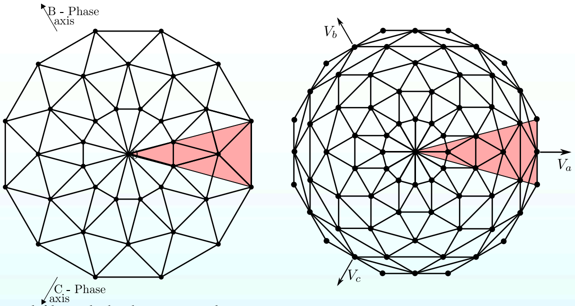
- Six Concentric Dodecagons from single side
- Requires three isolated DC power supplies



Mathew J, Mathew K, Azeez, N, Rajeevan, P. & Gopakumar K. "A Hybrid Multilevel Inverter System Based on Dodecagonal Space Vectors for Medium Voltage IM Drives" IEEE Trans. Power Electron., 2013, 28, 3723-3732

Multilevel Dodecagonal Voltage Space Vectors with Symmetric Triangles for Medium Voltage Induction Motor Drive

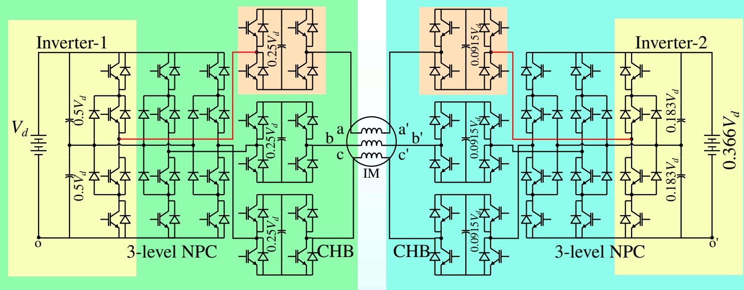
Typical Multilevel Dodecagonal Structures



- Typical multilevel dodecagonal space vector structures
- Each 30^o sector is divided into non-identical triangles
- A Symmetric SV Structure with Congruent Triangles is proposed

Mathew K, Das A, Patel C, Ramchand R, & Gopakumar K, "An asymmetric cascaded H-Bridge inverters for generating 12-sided polygonal space vector diagrams for Motor drives," EPE journal, 2011, 21, 21-28.

Power Circuit Topology



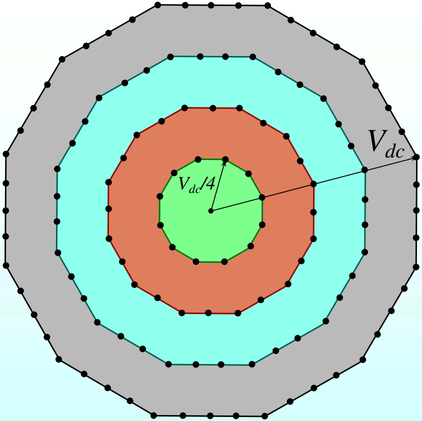
- Proposed Inverter Topology
- Two inverters on each side of Open-end winding Induction Machine

DC Links : V_d and $0.366V_d$

- 3 level NPC Structure cascaded with floating capacitor H-Bridge
- Floating capacitor H-Bridge- Can be balanced every Switching instant!

Proposed Dodecagonal SV structure

with symmetric triangles

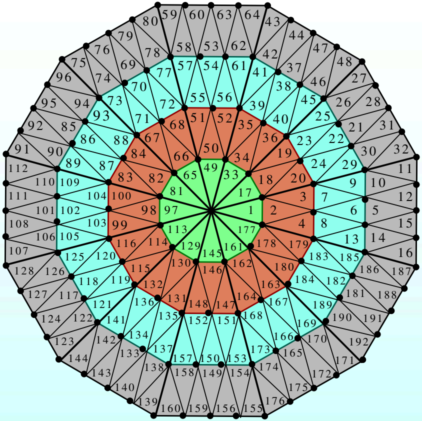


- Four Layers of Dodecagons
- Radius of Dodecagons are in ratio $0.25V_{dc} : 0.5V_{dc} : 0.75V_{dc} : V_{dc}$
- 121 Space Vector Locations

Sudharshan Kaarthik R, Gopakumar K, Mathew J, & Undeland T. "Medium-Voltage Drive for Induction Machine With Multilevel Dodecagonal Voltage Space Vectors With Symmetric Triangles," IEEE Trans. Ind. Electron., 2015, 62, 79-87

Proposed Dodecagonal SV structure

with symmetric triangles

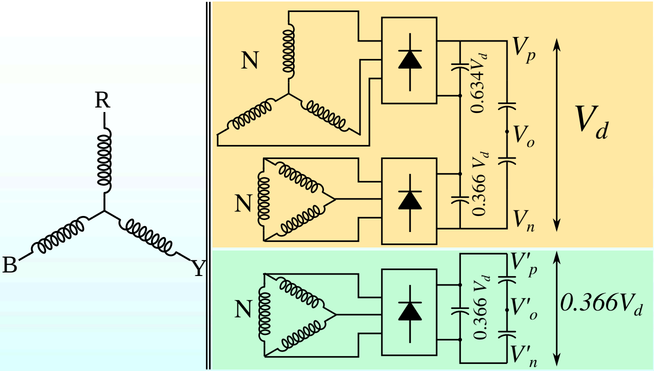


- Four Layers of Dodecagons
- Radius of Dodecagons are in ratio $0.25V_{dc} : 0.5V_{dc} : 0.75V_{dc} : V_{dc}$
- 121 Space Vector Locations
- 192 Identical Triangles

  Lesser dv/dt because of smaller triangles

Sudharshan Kaarthik R, Gopakumar K, Mathew J, & Undeland T. "Medium-Voltage Drive for Induction Machine With Multilevel Dodecagonal Voltage Space Vectors With Symmetric Triangles," IEEE Trans. Ind. Electron., 2015, 62, 79-87

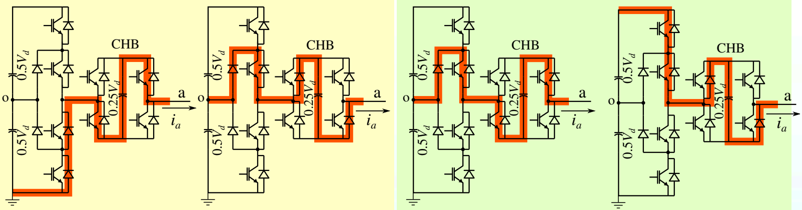
Assymetrical DC link Voltage generation



- V_d and $0.366V_d$ obtained by Star-Delta connections
- All 3 Secondaries have same No. of Turns
- No requirement of custom transformer design

Power Circuit Topology

Capacitor voltage balancing with pole voltage redundancies



$0 + 0.25\ V_d$ Discharging

$(0.5 - 0.25)\ V_d$ Charging

$(0.5 + 0.25)\ V_d$ Discharging

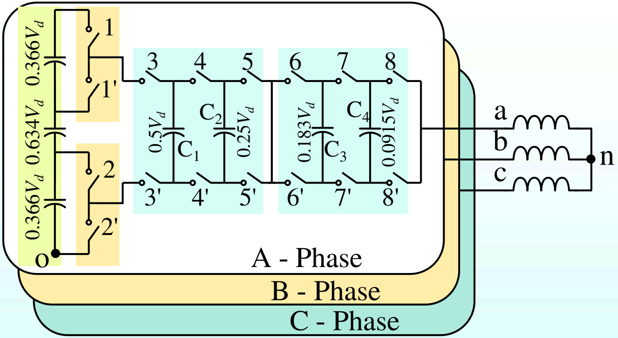
$V_d - 0.25\ V_d$ Discharging

- Pole Voltage: $0.25V_d$
- Pole Voltage: $0.75V_d$

- Switching combinations - Shown for positive current direction
  CHB is reversed for negative current direction
- Capacitor voltage correction for every switching instant
- Balancing possible irrespective of current direction
  and load power factor

Power Circuit Topology

Topology for feeding power from single side for star or delta connected IM



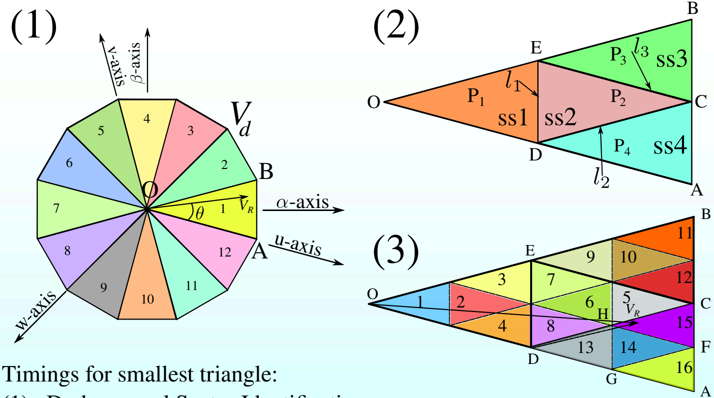
- The inverter consists of cascade of two three level flying capacitor inverters stacked between two half bridges
- Lesser wiring complexity!

PWM Timing Calculations

Location of reference voltage vector

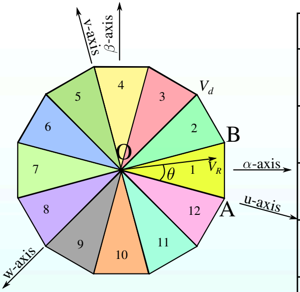
- Divide the space vector structure into triangles.
- In this case all triangles are congruent, the structure itself is symmetric.
- Use of only sampled reference values - No angle information required.
- 121 Space vector locations (SVL), 192 triangles.
  - $\mathbf{V_R} T_s = \mathbf{V_1} T_1 + \mathbf{V_2} T_2 + \mathbf{V_0} T_0$
  - $T_s = T_1 + T_2 + T_0$

Steps involved in Triangle identification



- Timings for smallest triangle:
  (1) Dodecagonal Sector Identification
  (2) Each sector is divided into 4 sub-sectors(ss): Sub-sector identification
  (3) Each sub-sector is divided into 4 sub-sub-sectors(sss): sss identification

Sector identification



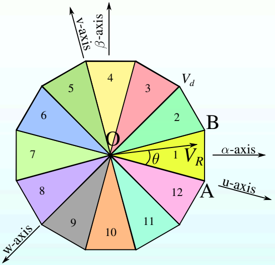
Condition		Sector
$V_u > V_v > V_w$	$V_v < 0$	1
	$V_v > 0$	2
$V_v > V_u > V_w$	$V_u < 0$	3
	$V_u > 0$	4
$V_v > V_w > V_u$	$V_w < 0$	5
	$V_w > 0$	6
$V_w > V_v > V_u$	$V_v < 0$	7
	$V_v > 0$	8
$V_w > V_u > V_v$	$V_u < 0$	9
	$V_u > 0$	10
$V_u > V_w > V_v$	$V_w < 0$	11
	$V_w > 0$	12

- Transform V_α and V_β to V_u, V_v, V_w

$$V_u = 0.644\,V_\alpha - 0.173V_\beta$$
$$V_v = -0.173V_\alpha + 0.644V_\beta$$
$$V_w = -0.471\,V_\alpha - 0.471V_\beta$$

- Use table to identify sector
- S= 1, 2, 3 ... 11, 12

Dodecagonal Sector timings



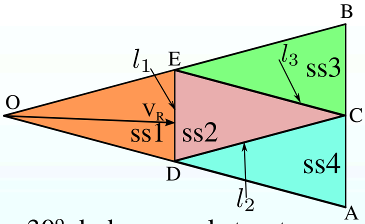
- Once 30º sector S is identified, PWM timings can be calculated from v_{alpha}, v_{beta}
- T_1, T_2 and T_0 are timings for OA, OB & O Triangle OAB (S=1)
- $T_1 = \frac{2T_s}{V_d}[v_\alpha \sin(S \cdot 30^\circ - 15^\circ) - v_\beta \cos(S \cdot 30^\circ - 15^\circ)]$

  $T_2 = \frac{2T_s}{V_d}[-v_\alpha \sin((S-1) \cdot 30^\circ - 15^\circ) + v_\beta \cos((S-1) \cdot 30^\circ - 15^\circ)]$

  $T_0 = T_s - T_1 - T_2$
- $S = 1, 2, 3 ... 12$

Subsector Structure

Division within each 30^o sector



30^o dodecagonal structure divided into 4 sub-sectors

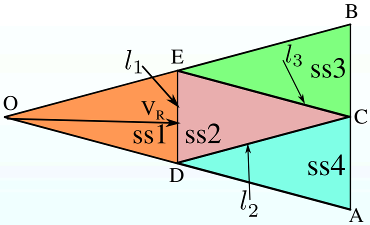
- Lines l_1, l_2 and l_3 divide the sector into four sub-sectors
- These lines are defined as given below:
  Tip of V_R is on $\boldsymbol{l_1}$ (ED) if $T_0 = T_s/2$
  Tip of V_R is on $\boldsymbol{l_2}$ (DC) if $T_1 = T_s/2$
  Tip of V_R is on $\boldsymbol{l_3}$ (EC) if $T_2 = T_s/2$
  T_0, T_1, T_2 are timings for OA, OB and O

sub-sector identification

- If $T_0 > T_s/2$, ss=1
  If $T_1 > T_s/2$, ss=3
  If $T_2 > T_s/2$, ss=4
  else, ss=2

Subsector Structure

Sub-sector timings



30° dodecagonal structure AOB divided into 4 sub-sectors

- Subsector (ss) is known
- Subsector timings are known T'_1, T'_2 and T'_0

- sub-sector identification

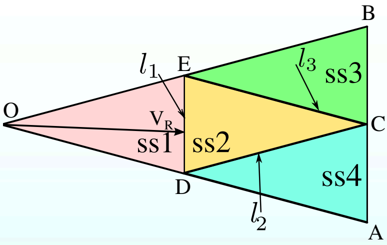
  If $T_0 > T_s/2$, ss=1
  If $T_1 > T_s/2$, ss=3
  If $T_2 > T_s/2$, ss=4
  else, ss=2

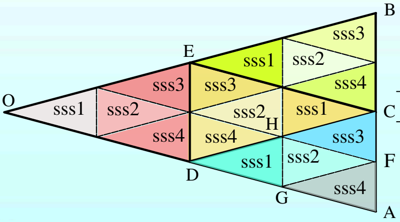
- sub-sector timings (T'_0, T'_1, T'_2)

ss = 1 (DOE)	**ss = 2 (ECD)**
$T'_1 = 2T_1$	$T'_1 = T_s - 2T_2$
$T'_2 = 2T_2$	$T'_2 = T_s - 2T_1$
$T'_0 = 2T_0 - T_s$	$T'_0 = T_s - 2T_0$
ss = 3 (ADC)	**ss = 4 (CEB)**
$T'_1 = 2T_1$	$T'_1 = 2T_1 - T_s$
$T'_2 = 2T_2 - T_s$	$T'_2 = 2T_2$
$T'_0 = 2T_0$	$T'_0 = 2T_0$

Subsector Structure

Sub-sub-sector timings





- sub-sub-sector identification

  If $T'_0 > T_s/2$, sss=1

  If $T'_1 > T_s/2$, sss=3

  If $T'_2 > T_s/2$, sss=4

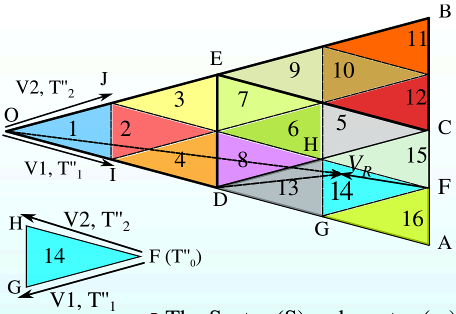
  else, sss=2

- sub-sub-sector timings (T''_0, T''_1, T''_2)

sss = 1 (DOE)	**sss = 2 (ECD)**
$T''_1 = 2T'_1$	$T''_1 = T_s - 2T'_2$
$T''_2 = 2T'_2$	$T''_2 = T_s - 2T'_1$
$T''_0 = 2T_0 - T_s$	$T''_0 = T_s - 2T'_0$
sss = 3 (ADC)	**sss = 4 (CEB)**
$T''_1 = 2T'_1$	$T''_1 = 2T'_1 - T_s$
$T''_2 = 2T'_2 - T_s$	$T''_2 = 2T'_2$
$T''_0 = 2T'_0$	$T''_0 = 2T'_0$

Sub-subsector Structure

Division within each sub-sector



- Sub-sub sector structure is the same as sub-sector structure
  Eg. Triangle 1 is similar to DOE (ss)
  DOE (ss) is similar to AOB (S)
- Smallest triangles are numbered 1 to 16 in Sector S=1
- Timing calculation is same as that of sub-sector

- The Sector (S), sub-sector (ss) and sub-sub-sector (sss) are known
- The PWM timings for smallest triangle (sss) is known
- Triangle number can be calculated as follows

Triangle = (S-1)x16 + (ss-1)x4 + sss

- Example: Let S = 1 (AOB), ss = 4 (ADC) and sss = 2 (HFG)

Triangle = (1-1) x16 + (4-1) x 4 + 2 = 0 + 12 + 2 = 14

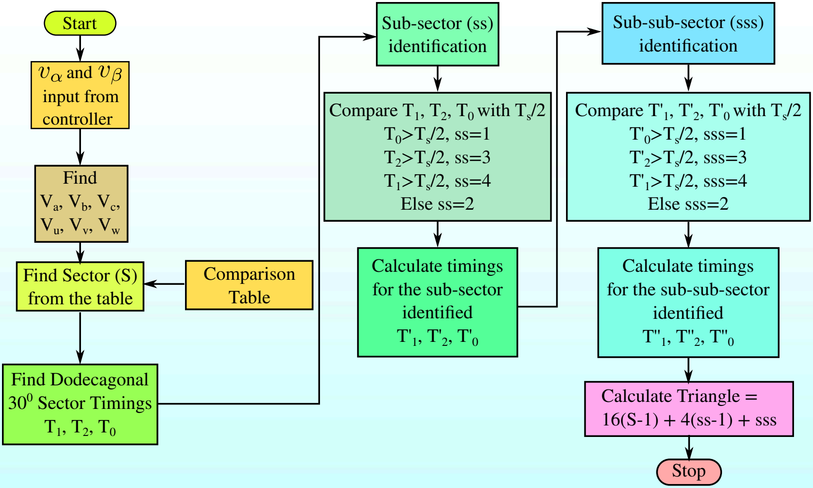
Timing Calculation

Summary

1. Identify sector S from v_α and v_β (S = 1 to 12).
2. Each dodecagonal sector $\implies$ four sub-sectors.
3. Find the sub-sector (SS = 1 to 4) by comparing T_1 and T_2 with $T_s/2$.
4. Find the sub-sub-sector (SSS = 1 to 4) by comparing T_1' and T_2' with $T_s/2$.
5. Calculate the triangle number from sector, sub-sector and sub-sub-sector values and PWM timings using geometry.

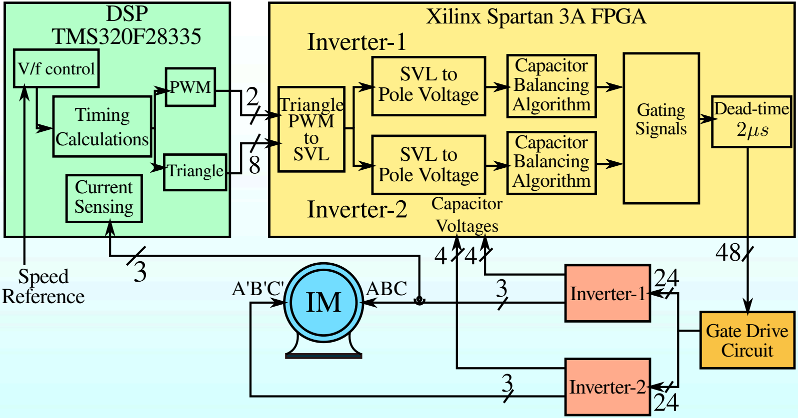
Timing Calculation

Flow Chart



Hardware Setup

System Block Diagram



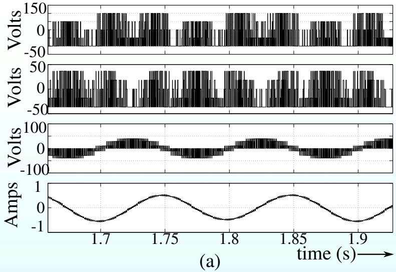
Results

Experimental Conditions

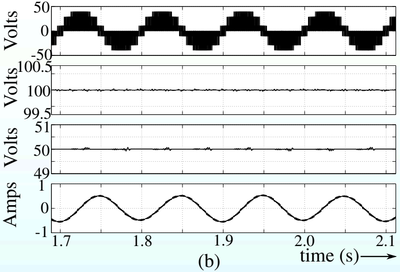
- Motor Specs : 3.7KW, 415V, 50Hz, 4-pole IM
- Power Semiconductor Devices used : 75A, 1200V IGBT half-bridge modules (SKM75GB12T4)
- Control : DSP (TMS320F28335), FPGA (SPARTAN XC3S200)
- Sensors used : LV 25-P
- PWM method : Synchronous PWM - 12 samples per cycle
- Simulation : Matlab-Simulink

Results

Simulation results for 10 Hz operation



(a)



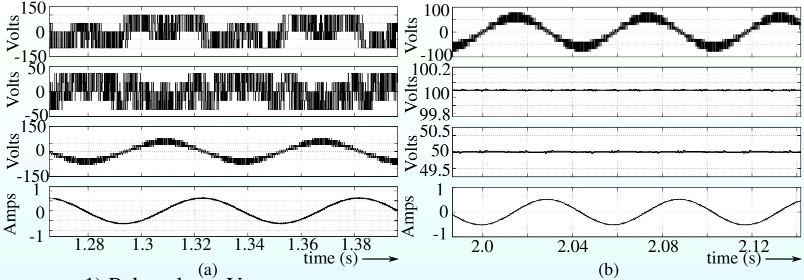
(b)

1) Pole voltage V_{ao}
2) Pole voltage $V_{a'o'}$
3) Phase voltage of Phase-A
4) Phase current of Phase-A

1) Phase voltage of Phase-A
2) NPC Capacitor voltage of Inverter-1
3) CHB Capacitor voltage of Inverter-1
4) Phase current of Phase-A

Results

Simulation results for 17 Hz operation

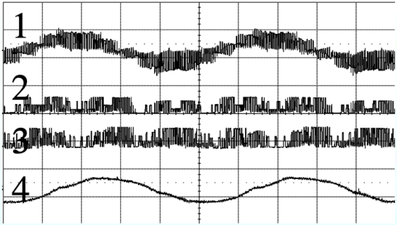


1) Pole voltage V_{ao}
2) Pole voltage $V_{a'o'}$
3) Phase voltage of Phase-A
4) Phase current of Phase-A

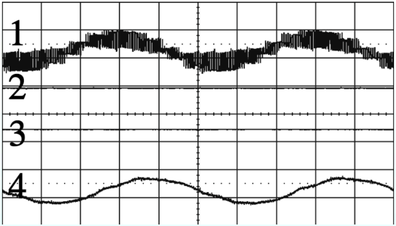
1) Phase voltage of Phase-A
2) NPC Capacitor voltage of Inverter-1
3) CHB Capacitor voltage of Inverter-1
4) Phase current of Phase-A

Results

Experimental results for 10 Hz operation



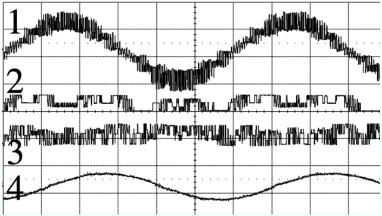
Voltage and current wave-forms of Phase-A
y-axis: 1)Phase voltage, 200 V/div
2)Pole voltage V_{ao} , 350 V/div
3)Pole voltage $V_{a'o'}$, 150 V/div
4)Phase current, 2 A/div.
x-axis: 20ms/div.



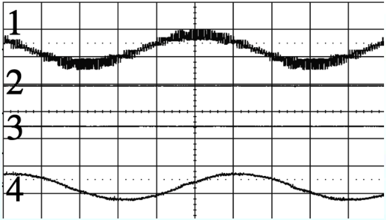
Capacitor ripple voltages of Phase-A capacitors
y-axis: 1)Phase voltage, 200 V/div
2)Ripple voltage of NPC cap. of Inverter-1, 10 V/div
3)Ripple voltage of CHB cap. of Inverter-1, 10 V/div
4)Phase current, 2 A/div.
x-axis:20ms/div,

Results

Experimental results for 17 Hz operation



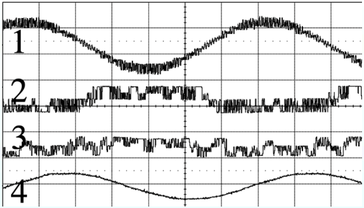
Voltage and current wave-forms of Phase-A
y-axis: 1)Phase voltage, 100 V/div
2)Pole voltage V_{ao} , 350 V/div
3)Pole voltage $V_{a'o'}$, 150 V/div
4)Phase current, 2 A/div.
x-axis: 10ms/div.

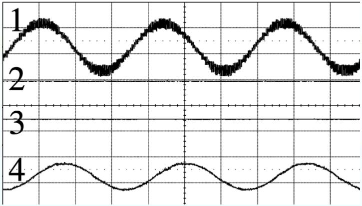


Capacitor ripple voltages of Phase-A capacitors
y-axis: 1)Phase voltage, 200 V/div
2)Ripple voltage of NPC cap. of Inverter-1, 10 V/div
3)Ripple voltage of CHB cap. of Inverter-1, 10 V/div
4)Phase current, 2 A/div.
x-axis:20ms/div,

Results

Experimental results for 30 Hz operation



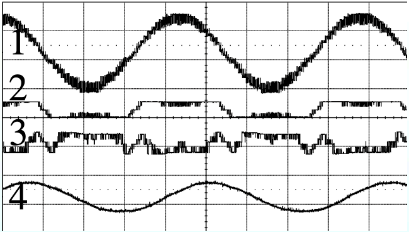


Voltage and current wave-forms of Phase-A
y-axis: 1)Phase voltage, 200 V/div
2)Pole voltage V_{ao} , 350 V/div
3)Pole voltage $V_{a'o'}$, 150 V/div
4)Phase current, 2 A/div.
x-axis: 10ms/div.

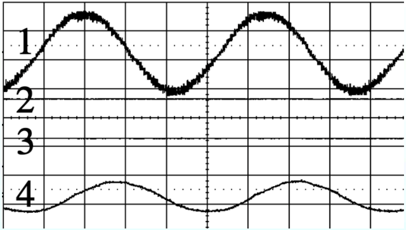
Capacitor ripple voltages of Phase-A capacitors
y-axis: 1)Phase voltage, 200 V/div
2)Ripple voltage of NPC cap. of Inverter-1, 10 V/div
3)Ripple voltage of CHB cap. of Inverter-1, 10 V/div
4)Phase current, 2 A/div.
x-axis:20ms/div,

Results

Experimental results for 45 Hz operation



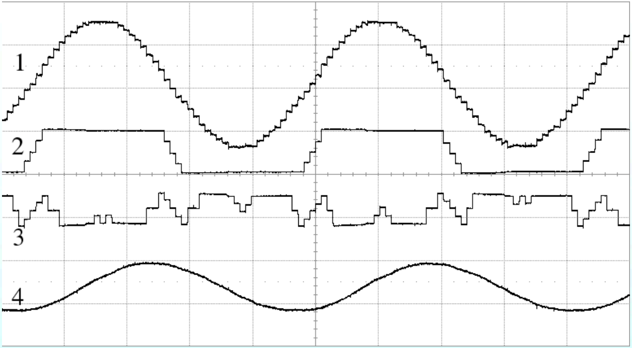
Voltage and current wave-forms of Phase-A
y-axis: 1)Phase voltage, 200 V/div
2)Pole voltage V_{ao} , 350 V/div
3)Pole voltage $V_{a'o'}$, 150 V/div
4)Phase current, 2 A/div.
x-axis: 5ms/div.



Capacitor ripple voltages of Phase-A capacitors
y-axis: 1)Phase voltage, 200 V/div
2)Ripple voltage of NPC cap. of Inverter-1, 10 V/div
3)Ripple voltage of CHB cap. of Inverter-1, 10 V/div
4)Phase current, 2 A/div.
x-axis:5ms/div,

Results

Experimental results for 48 Step operation



Phase Voltage 200V/div.

Pole Voltage of V_{dc} inverter 350V/div.

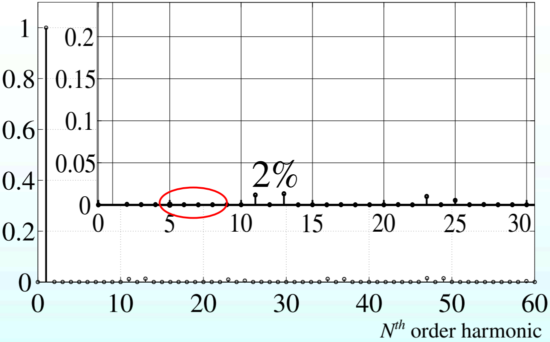
Pole Voltage of $0.366V_{dc}$ inverter 50V/div.

Phase Current 1A/div.

- Space Vector Locations on the outer most dodecagon
- Generated a 48 stepped waveform
- No PWM - stepped operation

Results

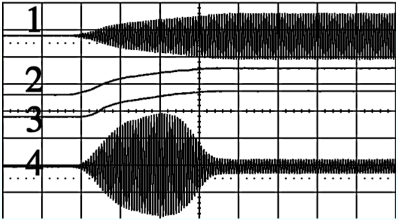
48 Step operation - FFT of Phase Voltage



- Fast Fourier Transform (FFT) for 48 stepped operation
- Complete elimination of 5^{th} and 7^{th} harmonics
- 11^{th} and 13^{th} harmonics are less than 2%

Results

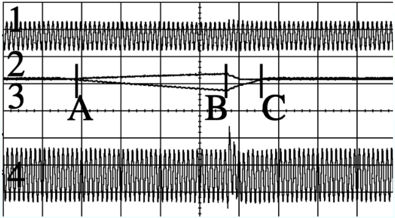
Transient operation



Voltage and current waveforms of Phase-A during starting up of the motor, (40 Hz)

1. Phase Voltage, 200 V/div.
2. Voltage across the CHB capacitor (Inverter-1), 100V/div.
3. Voltage across the CHB capacitor (Inverter-2), 50 V/div.
4. Phase current, 2 A/div.

x-axis: 0.5 s/div



Disabling the charge control scheme of CHB capacitors of phase-A at time ‘A’ and re-establishing the charge control at ‘B’, 40 Hz operation. x-axis: 0.5 s/div

1. Phase Voltage, 200V/div.
2. CHB capacitor (Inverter-1), 50 V/div.
3. CHB capacitor (Inverter-2), 20 V/div
4. Phase current, 2 A/div;

Summary

- Space vector structure with Symmetric triangles
- Power Circuit Topology
  - Standard NPC and H-Bridge modules are used
  - Inherent capacitor balancing for CHB
  - No pre-charging circuitry required for start-up
  - In case of CHB device failure, CHB can be bypassed and system can handle full power
- Generic timing calculation method for SV structure
  - No iterative search required for triangle identification (Direct Hit)
  - Needs only v_α and v_β
  - No look-up table, off-line computation, angle estimation required
  - Can be used with closed loop systems

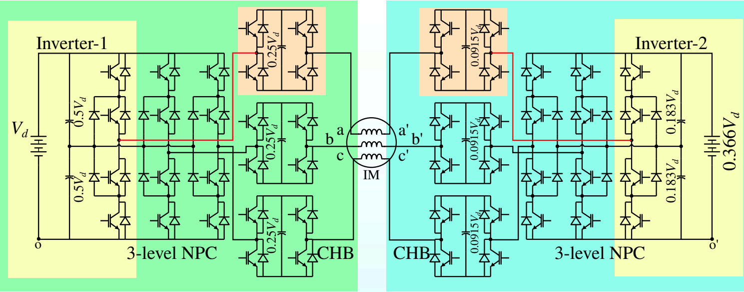
Summary

- Phase Voltage Harmonics - Elimination and suppression
- Completely eliminates $6n \pm 1$ (n = odd) harmonics in phase voltages and currents
- Extension in linear modulation range due to dodecagonal switching
- Lesser dv/dt due to smaller identical triangles
  - in phase voltages
  - across power switches
- Lesser EMI/EMC issues
- Hence, the proposed system is well suited for medium voltage and high power motor drive applications

Nineteen level Dodecagonal Space Vector Structure with Scalable 24-stepped Phase Voltage for full operating range for Medium Voltage Induction Motor Drive

Power Circuit Topology

Proposed Inverter Topology



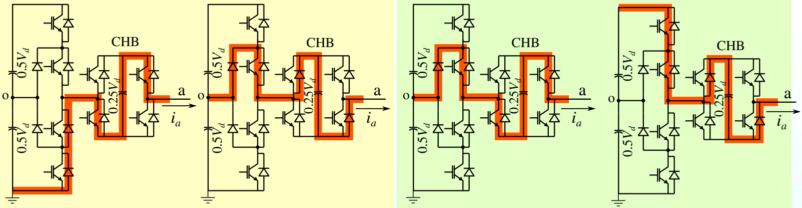
- Proposed Inverter Topology
- Two inverters on each side of Open-end winding Induction Machine

DC Links : V_d and $0.366V_d$

- 3 level NPC Structure cascaded with floating capacitor H-Bridge
- Floating capacitor H-Bridge- Can be balanced every Switching instant!

Power Circuit Topology

Capacitor voltage balancing with pole voltage redundancies

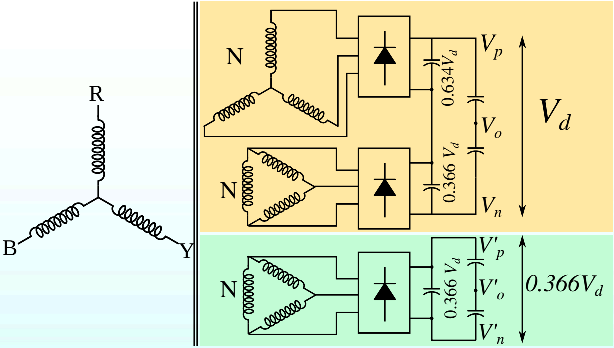


$0 + 0.25\ V_d$ Discharging	$(0.5 - 0.25)\ V_d$ Charging	$(0.5 + 0.25)\ V_d$ Discharging	$V_d - 0.25\ V_d$ Discharging

- Pole Voltage: $0.25V_d$
- Pole Voltage: $0.75V_d$

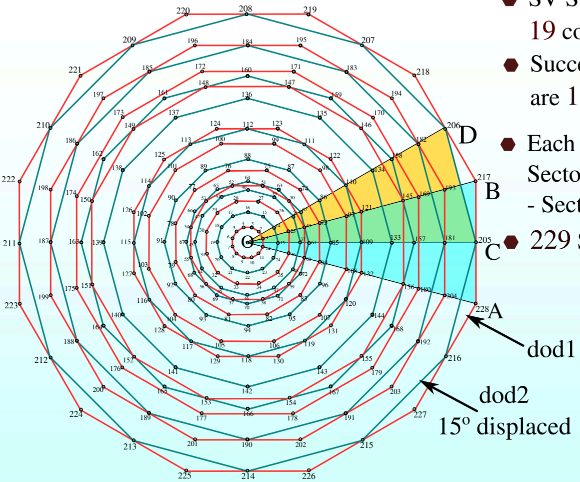
- Switching combinations - Shown for positive current direction
  CHB is reversed for negative current direction
- Capacitor voltage correction for every switching instant
- Balancing possible irrespective of current direction and load power factor

Assymetrical DC link Voltage generation

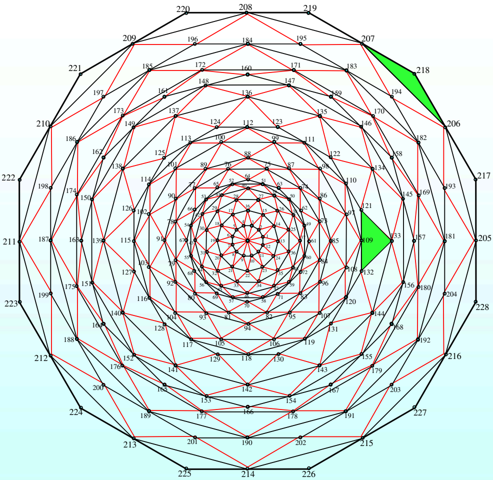


- V_d and $0.366V_d$ obtained by Star-Delta connections
- All 3 Secondaries have same No. of Turns
- No requirement of custom transformer design

SV Structure with 19 Concentric Dodecagons



- SV Structure has 19 concentric Dodecagons
- Successive dodecagons are 15^0 displaced
- Each dodecagon generates Sectors (OAB), (OCD) - Sectors are 15^o displaced
- 229 Space Vector Locations



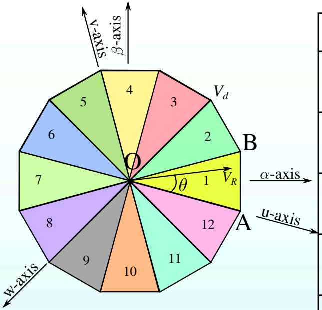
- SV Structure has 19 concentric Dodecagons
- Successive dodecagons are 15^0 displaced
- 229 Space Vector Locations
- SV region is divided into 384 triangles

PWM Timing Calculations

- Divide the space vector structure into triangles.
  - 229 Space vector locations (SVL).
  - 384 triangles.
- Use only sampled reference values.
  - Only v_α and v_β required.
  - No angle information required.
  - No offline computation of timings.
  - Can be used in closed loop application.
- Calculate PWM timings using Volt-sec balance.
  - $\mathbf{V_R} T_s = \mathbf{V_1} T_1 + \mathbf{V_2} T_2 + \mathbf{V_0} T_0$
  - $T_s = T_1 + T_2 + T_0$

Sector identification

Identification of 30° dodecagonal Sector S



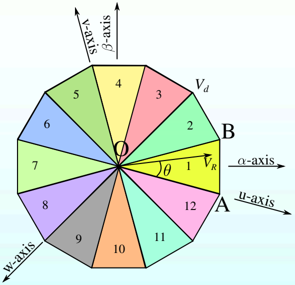
Condition		Sector
$V_u > V_v > V_w$	$V_v < 0$	1
	$V_v > 0$	2
$V_v > V_u > V_w$	$V_u < 0$	3
	$V_u > 0$	4
$V_v > V_w > V_u$	$V_w < 0$	5
	$V_w > 0$	6
$V_w > V_v > V_u$	$V_v < 0$	7
	$V_v > 0$	8
$V_w > V_u > V_v$	$V_u < 0$	9
	$V_u > 0$	10
$V_u > V_w > V_v$	$V_w < 0$	11
	$V_w > 0$	12

- Transform V_α and V_β to V_u, V_v, V_w

$$V_u = 0.644\,V_\alpha - 0.173V_\beta$$
$$V_v = -0.173V_\alpha + 0.644V_\beta$$
$$V_w = -0.471\,V_\alpha - 0.471V_\beta$$

- Use table to identify sector
- S = 1, 2, 3 ... 11, 12

Dodecagonal Sector timings



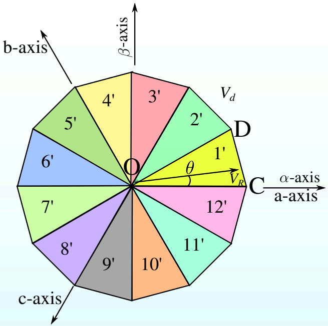
- Once 30^0 sector S is known, PWM timings can be calculated
- T_1, T_2 and T_0 are timings for OA, OB & O Triangle OAB (S=1) and $V_d = |OA|$
- $T_1 = \frac{2T_s}{V_d}[v_\alpha \sin(S\cdot 30° - 15°) - v_\beta \cos(S\cdot 30° - 15°)]$

  $T_2 = \frac{2T_s}{V_d}[-v_\alpha \sin((S-1)\cdot 30° - 15°)$
  $\quad + v_\beta \cos((S-1)\cdot 30° - 15°)]$

  $T_0 = T_s - T_1 - T_2$
- $S = 1, 2, 3 ... 12$

Sector identification

Identification of 15° shifted Sector S'

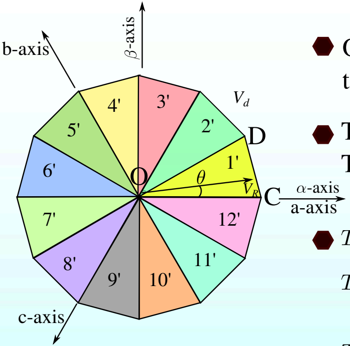


Condition		Sector
$V_a > V_b > V_c$	$V_b < 0$	1'
	$V_b > 0$	2'
$V_b > V_a > V_c$	$V_a < 0$	3'
	$V_a > 0$	4'
$V_b > V_c > V_a$	$V_c < 0$	5'
	$V_c > 0$	6'
$V_c > V_b > V_a$	$V_b < 0$	7'
	$V_b > 0$	8'
$V_c > V_a > V_b$	$V_a < 0$	9'
	$V_a > 0$	10'
$V_a > V_c > V_b$	$V_c < 0$	11'
	$V_c > 0$	12'

- Transform V_α and V_β to V_a, V_b, V_c
  a-axis is along alpha-axis
  $V_a = 0.666\ V_\alpha$
  $V_b = -0.5V_\alpha + 0.866V_\beta$
  $V_c = -0.5\ V_\alpha - 0.866V_\beta$

- Use table to identify sector S'
- S= 1', 2', 3' ... 11', 12'

15° Shifted Sector timings



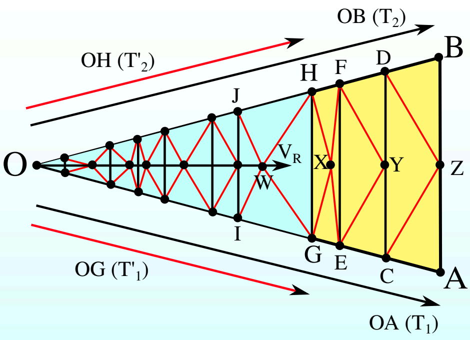
- Once 30° sector S' is known, PWM timings can be calculated
- T_{1S}, T_{2S} and T_{0S} are timings for OC, OD & O Triangle OCD (S'=1') and V_d = |OC|
- $T_{1S} = \frac{2T_s}{V_d}[v_\alpha \sin(S' \cdot 30°) - v_\beta \cos(S' \cdot 30°)]$

  $T_{2S} = \frac{2T_s}{V_d}[-v_\alpha \sin((S' - 1) \cdot 30°)$
  $+ v_\beta \cos((S' - 1) \cdot 30°)]$

  $T_{0S} = T_s - T_1 - T_2$
- S' = 1', 2', 3', ... 11', 12'

Timing Calculation - Arbitrary Triangle

Sub-sector timing calculation for Voltage reference vector V_R

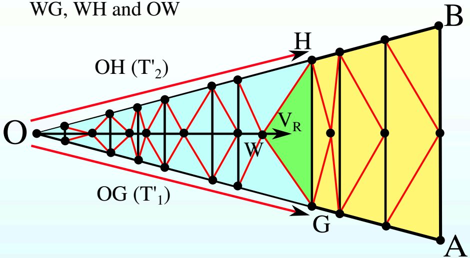


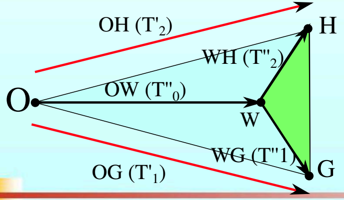
- Each 30^0 sector (OAB) is divided into smaller triangles - Sub-Sector
- Sub-sectors are formed by lines parallel to AB eg. CDO, EFO, GHO, IJO etc.
- Convert Timings for OAB to timings for OGH
- $T_1' = T_1$ (OA/OG)
  $T_2' = T_2$ (OB/OH)
  $T_0' = T_s - T_1' - T_2'$
- Scaling operation
  Changing Arm of triangle

Timing Calculation - Arbitrary Triangle

Triangle timing calculation for Voltage reference vector V_R

- For reference Vector $\mathbf{V_R}$ the Vectors to be applied are WG, WH and OW

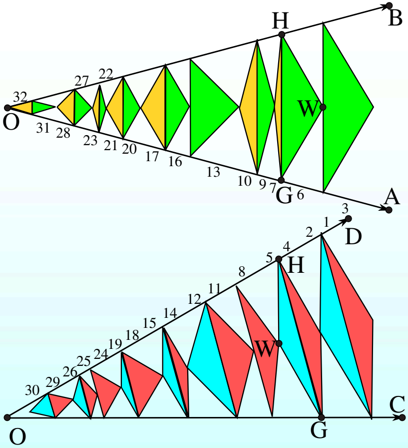




- Each Sub-sector (OGH) is divided into smaller triangles
- Convert Timings for triangle OGH to triangle WGH
- $T''_0 = T'_0/(1-k)$
  $T''_1 = T'_1 - T''_0(k/2)$
  $T''_2 = T'_2 - T''_0(k/2)$
  $k = OW/(OH \cos 15°)$
- Changing Pivot of triangle
- If T_0'', T_1'' and T_2'' are all positive, then tip of $\mathbf{V_R}$ is inside the triangle

Timing Calculation

Triangle within Sector S and 15° shifted Sector S'



Case - 1

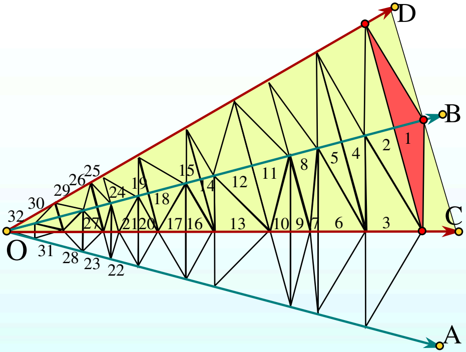
- Triangles formed inside Sector S (OAB)
- Timings for the smallest triangle depends on OAB timings T_1, T_2 and T_0
- Eg. Triangle HWG is formed within the dodecagonal sector S
  Arm = OH = OG
  Pivot = OW

Case - 2

- Triangles formed inside 15° shifted Sector S' (OCD)
- Timings for the smallest triangle depends on OCD timings T_{1S}, T_{2S} and T_{0S}
- Eg. Triangle HWG is formed within the 15° shifted sector S'
  Arm = OH = OG
  Pivot = OW

Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



Timings for Sector S (AOB)

- Timings for Sector S' (COD)

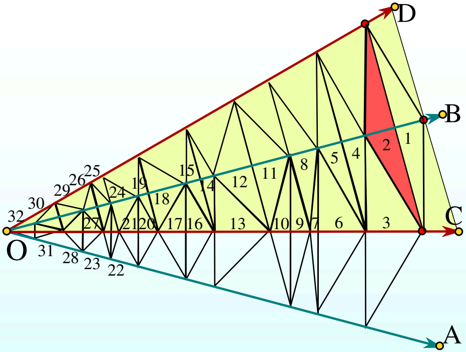
- Change of Arm
  $T'_1 = T_1 \times V_d/(\text{arm-length})$
  $T'_2 = T_2 \times V_d/(\text{arm-length})$

- Change of Pivot
  $T_0'' = T_0'/(1-k)$
  $T_1'' = T_1' - T_0''(k/2)$
  $T_2'' = T_2' - T_0''(k/2)$
  $k = \dfrac{\text{pivot length}}{\text{arm-length x cos } 15^{\circ}}$

- Tip of Reference vector is within the selected triangle
  IF (T"0, T"1 and T"2) > 0
  ELSE try next triangle

Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



Timings for Sector S (AOB)

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  $T'_1 = T_1 \times V_d/(\text{arm-length})$
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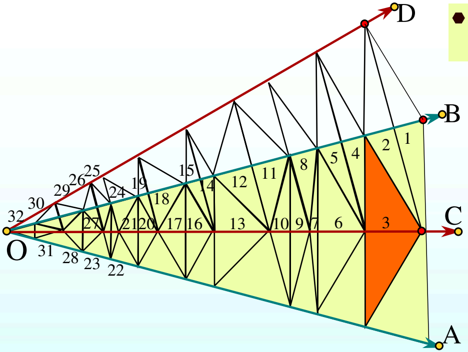
Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



- Timings for Sector S (AOB)

Timings for Sector S' (COD)

- Change of Arm

  $T'_1 = T_1 \times V_d/(\text{arm-length})$

  $T'_2 = T_2 \times V_d/(\text{arm-length})$

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  $T''_0 = T'_0/(1-k)$

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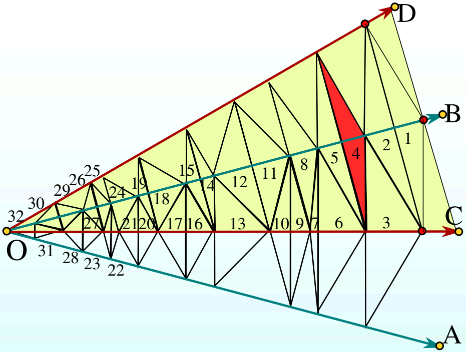
  ELSE try next triangle

Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



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- Timings for Sector S' (COD)

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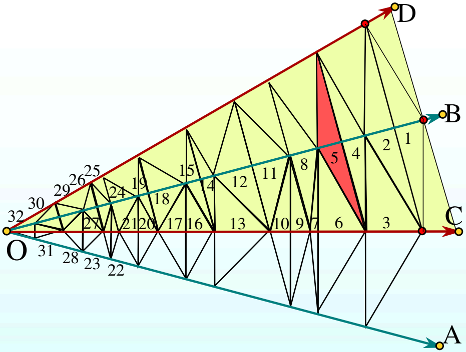
Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



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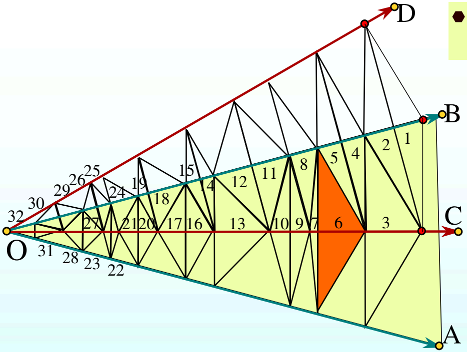
Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



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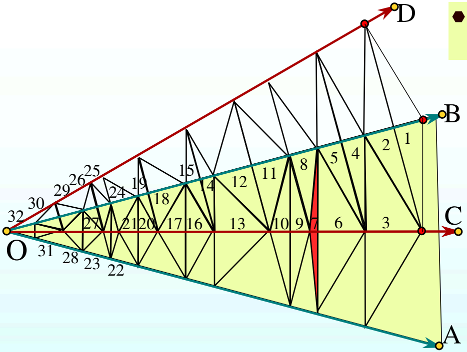

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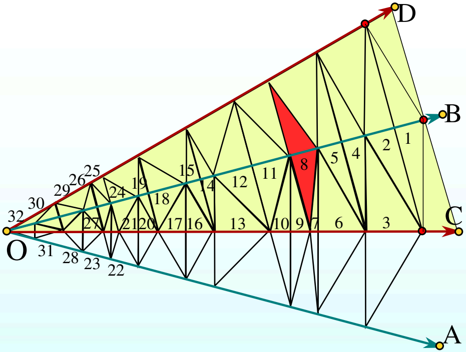
Triangle timing calculation for Voltage reference vector V_R



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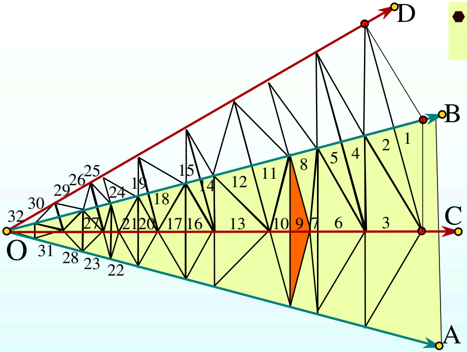

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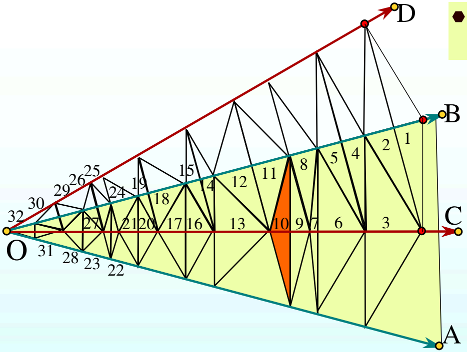

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  $T'_1 = T_1 \times V_d/(\text{arm-length})$
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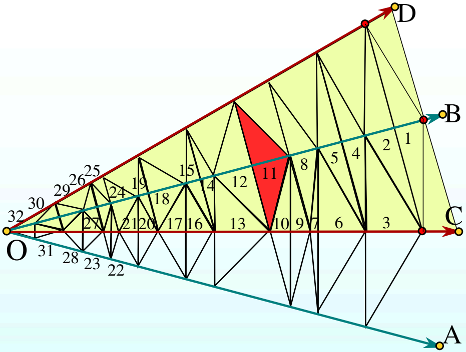
Triangle timing calculation for Voltage reference vector V_R



Timings for Sector S (AOB)

- Timings for Sector S' (COD)

- Change of Arm
  T'$_1$ = T$_1$ x V$_d$/(arm-length)
  T'$_2$ = T$_2$ x V$_d$/(arm-length)

- Change of Pivot
  $T_0'' = T_0'/(1-k)$
  $T_1'' = T_1' - T_0''(k/2)$
  $T_2'' = T_2' - T_0''(k/2)$
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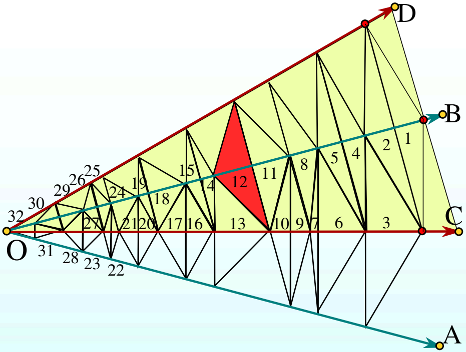

Timings for Sector S (AOB)

- Timings for Sector S' (COD)

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  $T'_1 = T_1 \times V_d/(\text{arm-length})$
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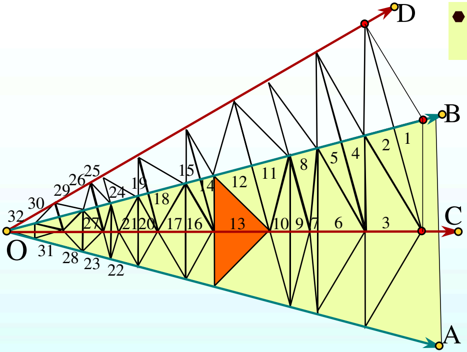

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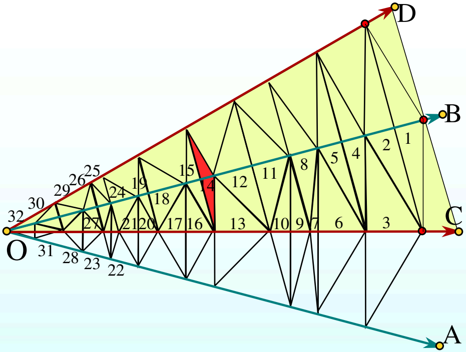

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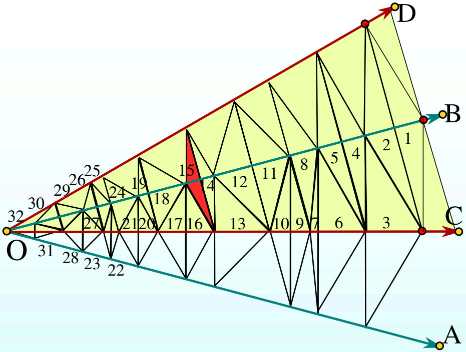

Timings for Sector S (AOB)

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  $T'_1 = T_1 \times V_d/(\text{arm-length})$
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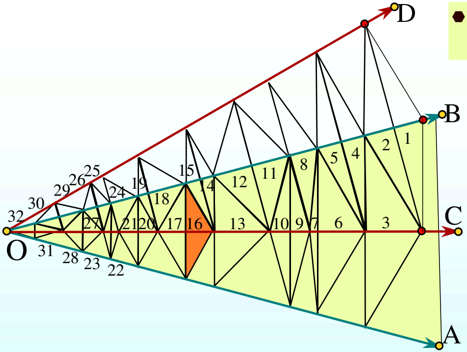

- Timings for Sector S (AOB)

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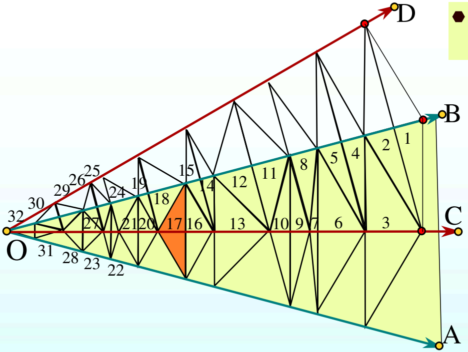
Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



- Timings for Sector S (AOB)

Timings for Sector S' (COD)

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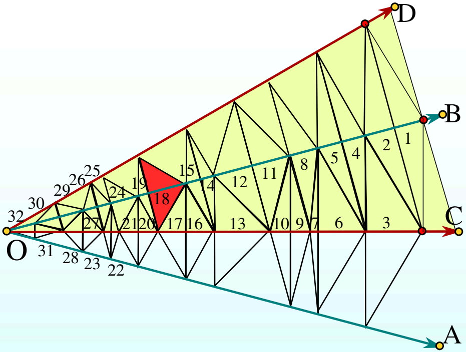
Triangle timing calculation for Voltage reference vector V_R



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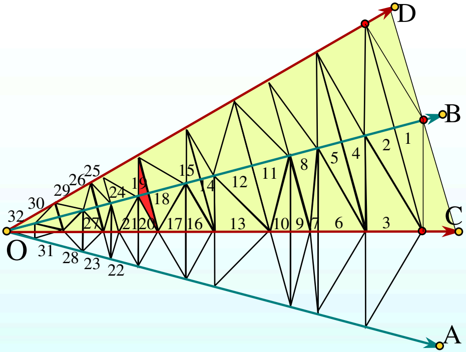

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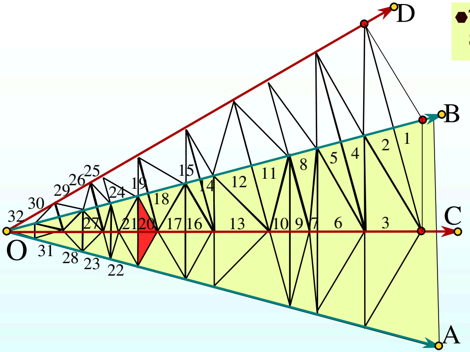

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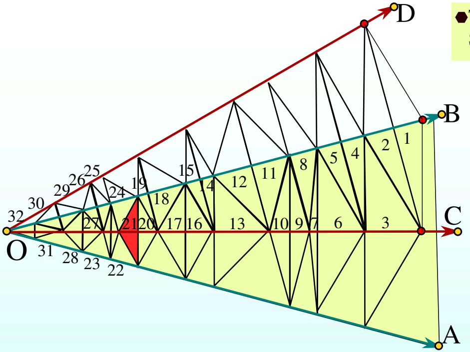

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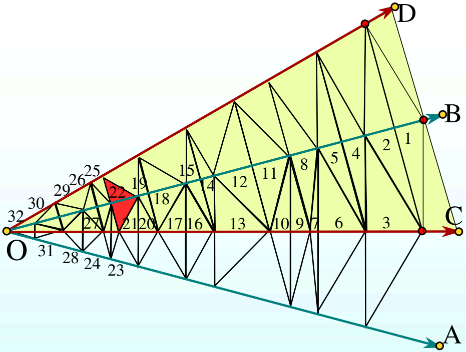

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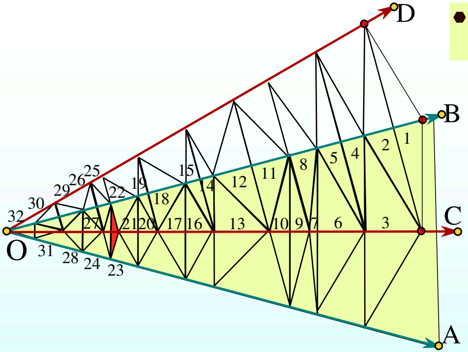

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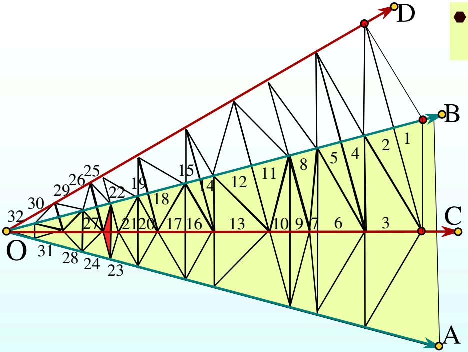
  ELSE try next triangle

Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



- Timings for Sector S (AOB)

Timings for Sector S' (COD)

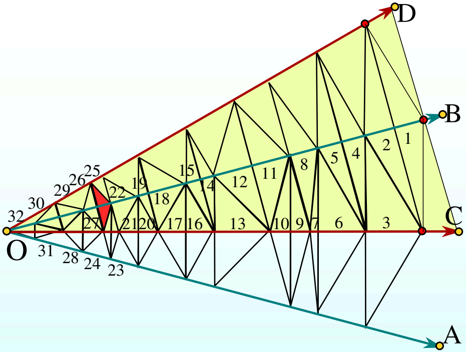
- Change of Arm
  $T'_1 = T_1 \times V_d/(\text{arm-length})$
  $T'_2 = T_2 \times V_d/(\text{arm-length})$

- Change of Pivot
  $T_0'' = T_0'/(1-k)$
  $T_1'' = T_1' - T_0''(k/2)$
  $T_2'' = T_2' - T_0''(k/2)$
  $k = \dfrac{\text{pivot length}}{\text{arm-length x cos } 15^o}$

- Tip of Reference vector is within the selected triangle
  IF (T"0, T"1 and T"2) > 0
  ELSE try next triangle

Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



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  $T'_1 = T_1 \times V_d/(\text{arm-length})$
  $T'_2 = T_2 \times V_d/(\text{arm-length})$

- Change of Pivot
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  $T''_1 = T'_1 - T''_0(k/2)$
  $T''_2 = T'_2 - T''_0(k/2)$
  $k = \dfrac{\text{pivot length}}{\text{arm-length x} \cos 15^o}$

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Timing Calculation

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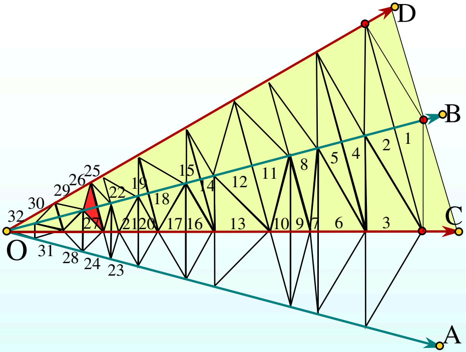

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Timing Calculation

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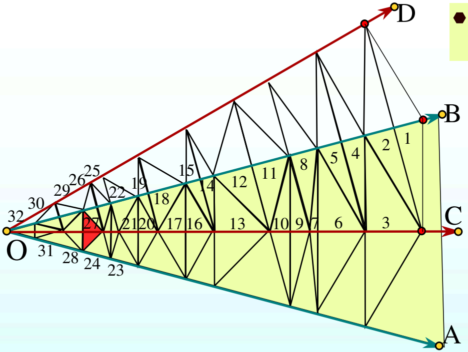

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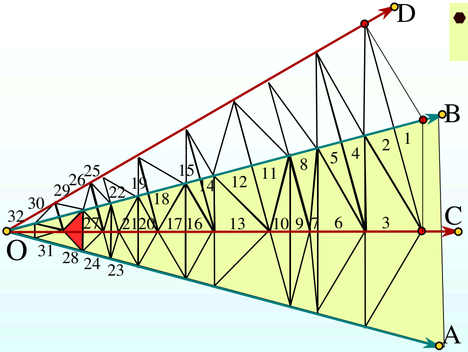
Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



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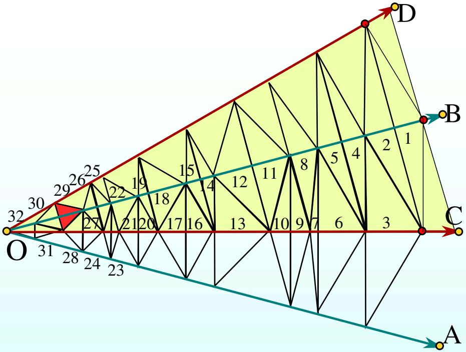

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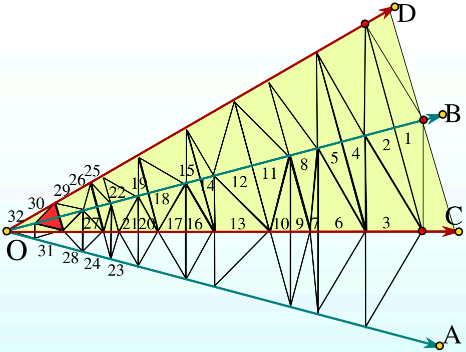

Timings for Sector S (AOB)

- Timings for Sector S' (COD)

- Change of Arm
  $T'_1 = T_1 \times V_d/(\text{arm-length})$
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- Change of Pivot
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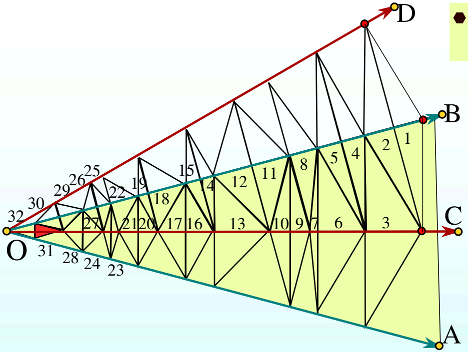

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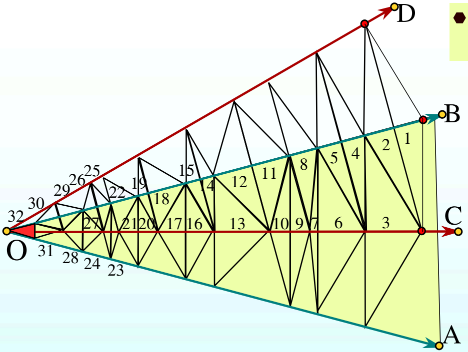
Timing Calculation

Triangle timing calculation for Voltage reference vector V_R



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- Change of Pivot

  $T_0'' = T_0'/(1-k)$

  $T_1'' = T_1' - T_0''(k/2)$

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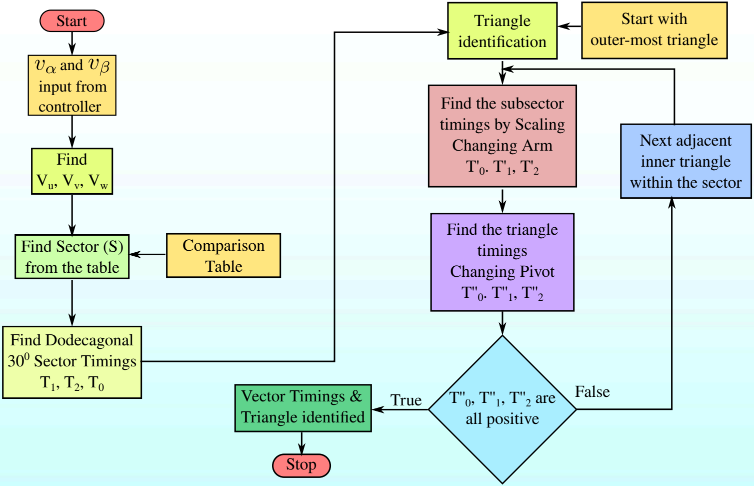
- Tip of Reference vector is within the selected triangle

  IF (T"0, T"1 and T"2) > 0

  ELSE try next triangle

Timing Calculation

Algorithm flowchart



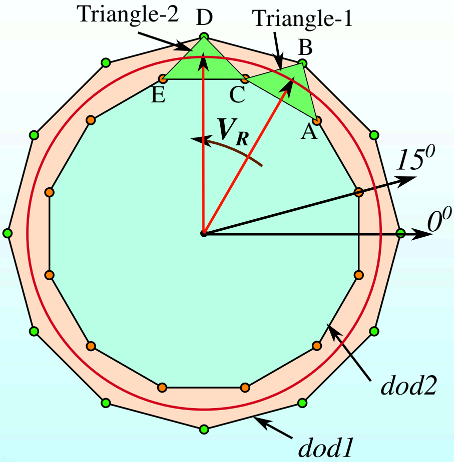
Timing Calculation

Summary

1. Identify sector S from v_α and v_β (S = 1 to 12)
2. Identify 15° shifted sector S' from v_α and v_β (S' = 1' to 12')
3. Obtain timings for Sector S and S'
4. Each dodecagonal sector $\implies$ 32 smaller triangles
5. Assume the Tip of reference vector V_R lies in outermost triangle
   - Change "Arm" of the Triangle – Scaling operation
   - Change "Pivot" of the Triangle – Find the sub-sub sector
   - If the calculated values of T_1'', T_2'' and T_0'' are all positive
     - Identify Triangle with Sector number (S) and the sub-sub-sector number
   - Else try again assuming adjacent triangle

Switching Technique

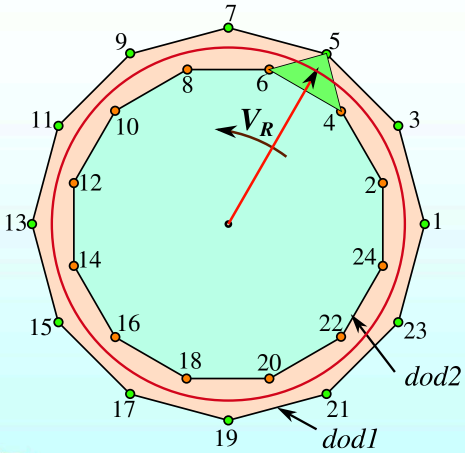
Generation of 24 stepped phase voltage waveform



- The reference vector rotates anticlockwise
- Tip of V_R lies between 2 dodecagons (*dod1* & *dod2*) which are 15^0 displaced
- Tip of VR lies in Triangle-1 After 30^0 in Triangle-2
- Vector locations switched
  A-B-C - C-D-E
  Triangle-1 Triangle-2
- Only 2 switchings per sample

Switching Technique

Generation of 24 stepped phase voltage waveform



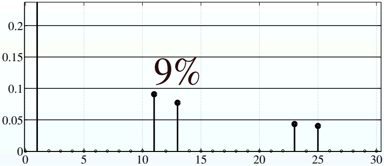
- The reference vector rotates anticlockwise
- Tip of V_R lies between 2 dodecagons (*dod1* & *dod2*) which are 15^0 displaced
- Tip of VR lies in Triangle-1 After 30^0 in Triangle-2
- Vector locations switched

  A-B-C - C-D-E

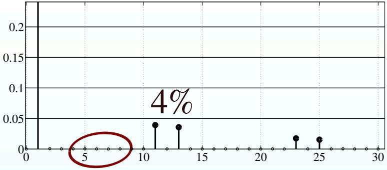
  Triangle-1 Triangle-2
- Only 2 switchings per sample
- SVL switching sequence 1, 2, 3, 4 ... 21, 22, 23, 24 Each point is 15^0 displaced

Harmonic Suppression

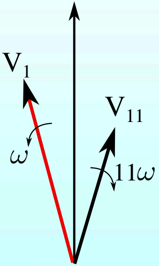
11th and 13th harmonic suppression due to 24-stepped phase voltage



12 step operation of
Dodecagonal SV structure



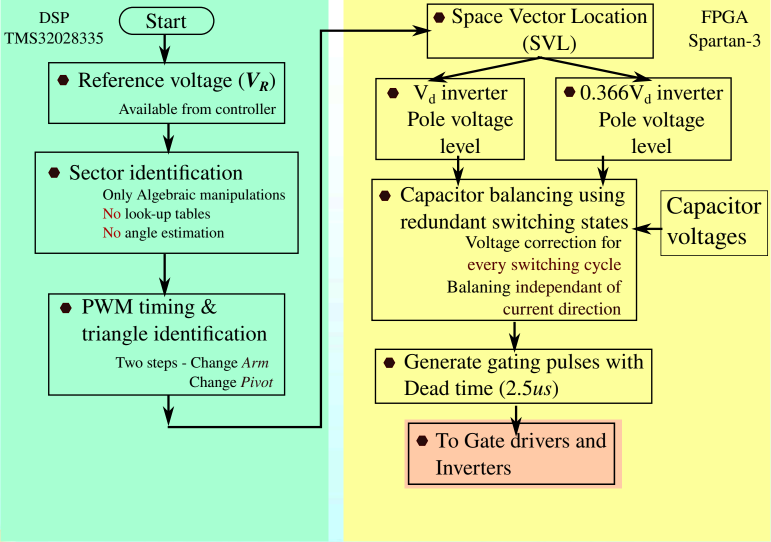
Proposed 24-step operation of
Dodecagonal SV structure



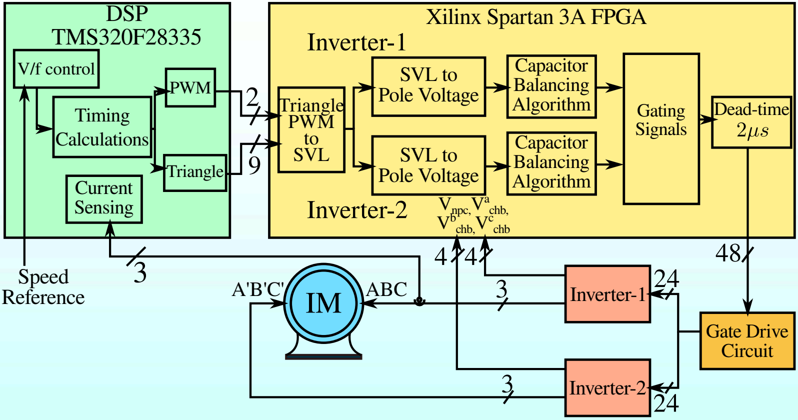
- Each SVL is 15^0 displaced. 11^{th} harmonic voltage moves by $(-11 \times 15^0) = (15^0+180^0)$ when fundamental moves 15^0. After 15^0 movement of the fundamental, the 11^{th} harmonic generated (by new vector switched) will be 180^0 phase displaced.
  Hence 11^{th} harmonic is supressed.

- Similarly, 13^{th} harmonic is also supressed.

Flowchart and Control Scheme



Flowchart and Control Scheme



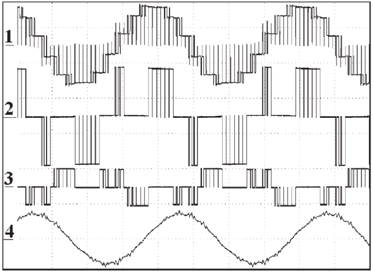
Results

Experimental Conditions

- Motor Specs : 3.7KW, 415V, 50Hz, 4-pole IM
- Power Semiconductor Devices used : 75A, 1200V IGBT half-bridge modules (SKM75GB12T4)
- Control : DSP (TMS320F28335), FPGA (SPARTAN XC3S200)
- Sensors used : LV 25-P
- PWM method : Synchronous PWM - 12 samples per cycle
- Simulation : Matlab-Simulink

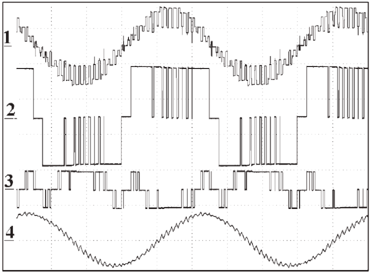
Results

Experimental results of 20Hz and 40Hz operation of conventional dodecagonal SV structure



1. Phase voltage, 100 V/div.
2. Pole voltage of INV1, 100 V/div.
3. Pole voltage of INV2, 100 V/div.
4. Phase current 2 A/div.

x-axis: 10ms/div.



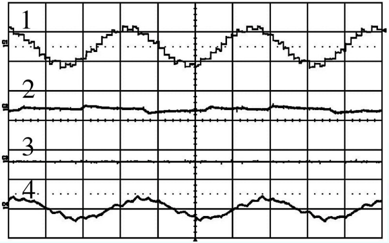
1. Phase voltage, 100 V/div.
2. Pole voltage of INV1, 100 V/div.
3. Pole voltage of INV2, 100 V/div.
4. Phase current 2 A/div.

x-axis: 5ms/div.

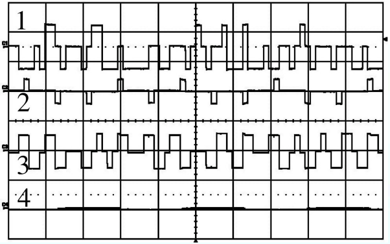
A. Das, K. Sivakumar, R. Ramchand, C. Patel, and K. Gopakumar, “A combination of hexagonal and 12-Sided polygonal voltage space vector PWM control for im drives using cascaded two-level inverters,” IEEE Trans. Ind. Electron., vol. 56, no. 5, pp. 1657–1664, May 2009.

Results

Experimental results 15Hz operation



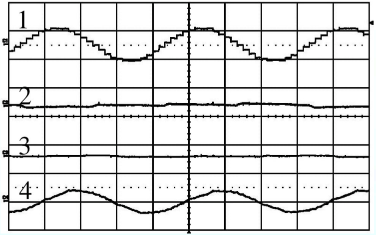
Voltage and current wave-forms of phase-A
1) phase voltage Vaa , 100V/div;
2) capacitor voltage ripple of A-phase
CHB capacitor of Inverter-1, 5V/div;
3) capacitor ripple voltage of A-phase
CHB capacitor of Inverter-2, 5V/div;
4) Phase current Ia , 1A/div.



Voltages levels and switching of individual modules of Phase-A
1) Inverter-1 NPC 200V/div;
2) Inverter-1, CHB 100V/div;
3) Inverter-2 NPC, 50V/div;
4) Inverter-2 CHB (No switching), 20V/div.
x-axis: 20ms/div.

Results

Experimental results 25Hz operation



Voltage and current wave-forms of phase-A
1) phase voltage Vaa , 200V/div;
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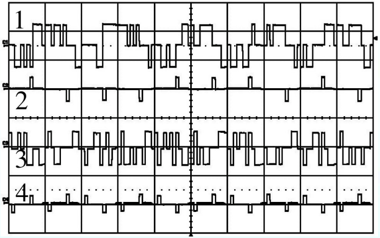
4) Phase current Ia , 1A/div.



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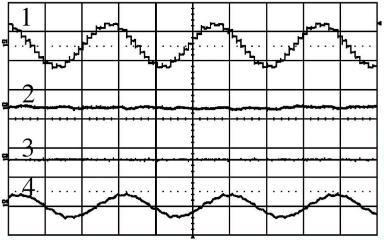
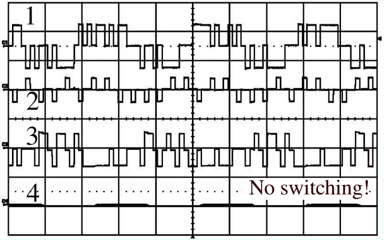
1) Inverter-1 NPC 200V/div;
2) Inverter-1, CHB 100V/div;
3) Inverter-2 NPC, 50V/div;
4) Inverter-2 CHB (No switching), 20V/div.
x-axis: 10ms/div.

Results

Experimental results 35Hz operation



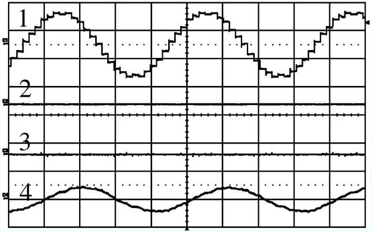


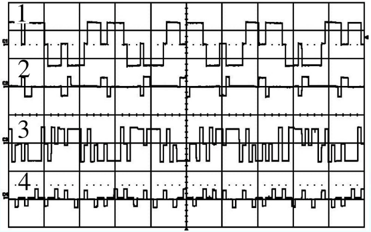
Voltage and current wave-forms of phase-A
1) phase voltage Vaa , 200V/div;
2) capacitor voltage ripple of A-phase
CHB capacitor of Inverter-1, 5V/div;
3) capacitor ripple voltage of A-phase
CHB capacitor of Inverter-2, 5V/div;
4) Phase current Ia , 1A/div.

Voltages levels and switching of individual modules of Phase-A
1) Inverter-1 NPC 200V/div;
2) Inverter-1, CHB 100V/div;
3) Inverter-2 NPC, 50V/div;
4) Inverter-2 CHB (No switching), 20V/div.
x-axis: 10ms/div.

Results

Experimental results 45Hz operation





Voltage and current wave-forms of phase-A

1) phase voltage Vaa , 200V/div;
2) capacitor voltage ripple of A-phase CHB capacitor of Inverter-1, 5V/div;
3) capacitor ripple voltage of A-phase CHB capacitor of Inverter-2, 5V/div;
4) Phase current Ia , 1A/div.

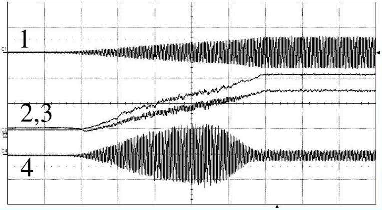
Voltages levels and switching of individual modules of Phase-A

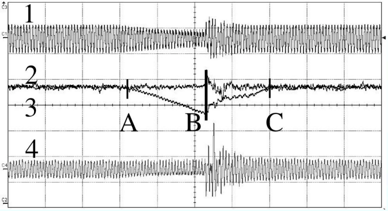
1) Inverter-1 NPC 200V/div;
2) Inverter-1, CHB 100V/div;
3) Inverter-2 NPC, 50V/div;
4) Inverter-2 CHB (No switching), 20V/div.

x-axis: 5ms/div.

Results

Transient operation





Voltage and current waveforms of Phase-A during starting up of the motor, (40 Hz)

1. Phase Voltage, 200 V/div.
2. Voltage across the CHB capacitor (Inverter-1), 100V/div.
3. Voltage across the CHB capacitor (Inverter-2), 50 V/div.
4. Phase current, 2 A/div.

x-axis: 0.5 s/div

Disabling the charge control scheme of CHB capacitors of phase-A at time 'A' and re-establishing the charge control at 'B', 40 Hz operation. x-axis: 0.5 s/div

1. Phase Voltage, 200V/div.
2. CHB capacitor voltage (Inverter-1), 50 V/div.
3. CHB capacitor voltage (Inverter-2), 20 V/div
4. Phase current, 2 A/div;

Results

Switching frequency of individual modules and Voltage THD %

F_{mod}	Inverter-1		Inverter-2		%THD
	NPC	CHB	NPC	CHB	Phase Voltage
10	100	70	70	40	6.98
13	117	78	156	117	7.32
16	160	96	160	0	8.39
21	168	147	231	126	10.96
25	200	75	300	250	7.69
30	300	120	270	0	10.90
36	432	360	288	0	9.70
40	280	200	320	240	9.05
48	96	0	336	0	9.92
49.8	99	0	396	0	6.80
50hz(12 steps)	50	0	150	0	13.29

- Switching of each inverter module is very less
- For some operating conditions, the CHB modules do not switch

Summary

- Space vector structure with **nineteen** concentric dodecagons
- Power Circuit Topology
  - Standard NPC and H-Bridge modules are used
  - Inherent capacitor balancing for CHB
  - No pre-charging circuitry required for start-up
  - In case of CHB device failure, CHB can be bypassed and system can handle full power
- Generic timing calculation method for SV structure
  - Needs only v_α and v_β
  - No look-up table, off-line computation, angle estimation required
  - Can be used with closed loop systems

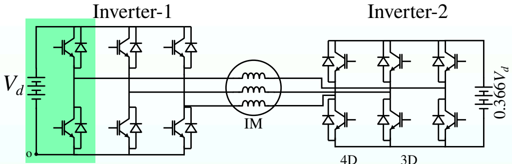
Summary

- New switching technique
  - 24 stepped waveform for **all operating conditions**
  - Less switching of individual NPC and CHB modules (Switching frequency $\approx$ 300Hz)
  - Reduction in switching losses
- Phase Voltage Harmonics - Elimination and suppression
  - Completely eliminates $6n \pm 1$ harmonics in phase voltages and currents
  - Suppression of 11^{th} and 13^{th} harmonics in phase voltages and currents
  - Phase Voltage THD $\approx$ 10%
- Reduction in dv/dt of the phase voltage
  - Lesser EMI/EMC issues
- Hence, the proposed system is well suited for medium voltage and high power motor drive applications

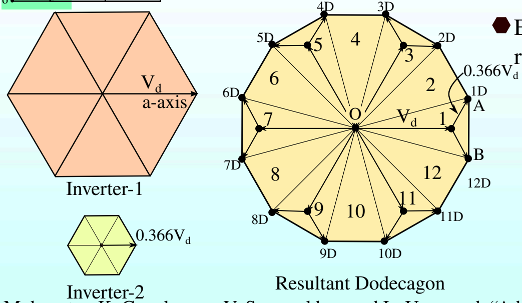
Carrier based PWM Timing Calculations for Multilevel Dodecagonal Space Vector Structures

Power Circuit Topology

Two Level Dodecagonal SV Structure



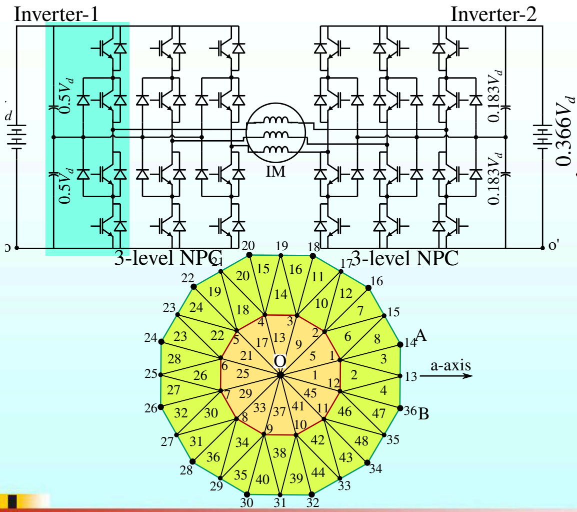
- Complete elimination of fifth and seventh harmonics in motor phase voltages and currents
- Extension of Linear Modulation range



K. Mohapatra, K. Gopakumar, V. 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.

Power Circuit Topology

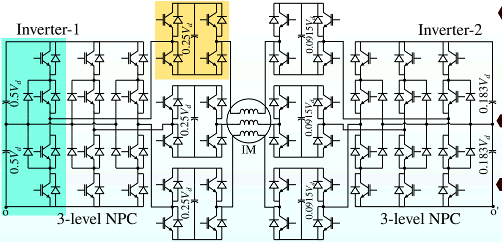
Three Level Dodecagonal SV Structure

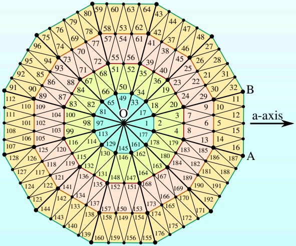


- Complete elimination of fifth and seventh harmonics in motor phase voltages and currents
- Extension of Linear Modulation range
- Reduction in dv/dt in motor phase voltage and across switches

Power Circuit Topology

Five Level Dodecagonal SV Structure

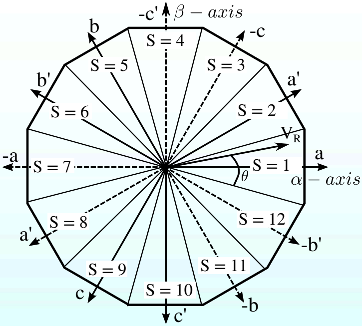




- Complete elimination of fifth and seventh harmonics in motor phase voltages and currents
- Extension of Linear Modulation range
- Furthur reduction in dv/dt in motor phase voltage and across switches
- Multilevel dodecagonal SV structure can be generalized - Symmetric triangles!

Carrier based PWM timings

Timings for a Single Dodecagon



- $T_1 = m \times \dfrac{\sin(\pi/6 - \theta)}{\sin(\pi/6)} \times T_s$
- $T_2 = m \times \dfrac{\sin\theta}{\sin(\pi/6)} \times T_s$
- $T_0 = T_s - T_1 - T_2$

$$m = \frac{\text{length of } V_R}{\text{radius of dodecagon}}$$

- Timings for each sector S=1 to 12 is represented in terms of angle and modulation index m.
- This is converted in terms of reference phase voltages

A. Das, K. Sivakumar, R. Ramchand, C. Patel, and K. Gopakumar, “A pulsewidth modulated control of induction motor drive using multilevel 12-Sided polygonal voltage space vectors,” IEEE Trans. Ind. Electron., vol. 56, no. 7, pp. 2441–2449, 2009

Carrier based PWM timings

Sector Identification for a single dodecagon

- (i) Timings for a single dodecagon
  - Sample six reference values namely v_a, v_b, v_c, v'_a, v'_b and v'_c
  - a', b' and c' axes are 30° lagging to a, b and c axes respectively
  - 30° dodecagonal sector can be identified using these six reference voltages
  - v_a, v_b, v_c, v'_a, v'_b and v'_c
  - Sector identification involves only comparisons
  - S = 1 to 12
- (ii) Timings for a smaller triangles - Sub-Sector and Sub-Sub-sector

Timings for all 12 sectors

Dodecagonal Sector identification using only sampled reference values

max. value		
T_{m1}	va>0	S = 1
	vb>0	S = 5
	vc>0	S = 9
T'_{m1}	va'>0	S = 2
	vb'>0	S = 6
	vc'>0	S = 10
T_{m2}	va<0	S = 7
	vb<0	S = 11
	vc<0	S = 3
T'_{m2}	va'<0	S = 4
	vb'<0	S = 8
	vc'<0	S = 12

- va, vb, vc, va', vb' and vc' is sampled
- For abc reference phase
  $T_{m1} = \max(v_a, v_b, v_c) - \text{mid}(v_a, v_b, v_c)$
  $T_{m2} = \text{mid}(v_a, v_b, v_c) - \min(v_a, v_b, v_c)$
- Similarly, for a', b', c' reference phase
  $T'_{m1} = \max(v_a', v_b', v_c') - \text{mid}(v_a', v_b', v_c')$
  $T'_{m2} = \text{mid}(v_a', v_b', v_c') - \min(v_a', v_b', v_c')$
  - max is maximum value
    mid is the middle value
    min is the minimum value
- Find maximum of (T_{m1}, T_{m2}, T'_{m1} and T'_{m2})
- Sector S can be identified using only sampled reference phase values using the table

Timings for all 12 sectors

Timing values T_1, T_2 for all 30° dodecagonal sectors
$k = T_s/(2V\cos 15°)$; V=radius of dodecagon

Sector-1		Sector-2		Sector-3		Sector-4	
T_1	$3k(v'_c - v_b)$	T_1	$3k(-v_b - v'_b)$	T_1	$3k(v_a - v'_b)$	T_1	$3k(v_a + v'_a)$
T_2	$3k(-v_c - v'_c)$	T_2	$3k(v_b - v'_c)$	T_2	$3k(v_b + v'_b)$	T_2	$3k(v'_b - v_a)$
T_{eff}	$3kv_a$	T_{eff}	$3kv'_a$	T_{eff}	$-3kv_c$	T_{eff}	$-3kv'_c$
Sector-5		Sector-6		Sector-7		Sector-8	
T_1	$3k(v'_a - v_c)$	T_1	$3k(-v_c - v'_c)$	T_1	$3k(v_b - v'_c)$	T_1	$3k(v_b + v'_b)$
T_2	$3k(-v_a - v'_a)$	T_2	$3k(v_c - v'_a)$	T_2	$3k(v_c + v'_c)$	T_2	$3k(v'_c - v_b)$
T_{eff}	$3kv_b$	T_{eff}	$3kv'_b$	T_{eff}	$-3kv_a$	T_{eff}	$-3kv'_a$
Sector-9		Sector-10		Sector-11		Sector-12	
T_1	$3k(v'_b - v_a)$	T_1	$3k(-v_a - v'_a)$	T_1	$3k(v_c - v'_a)$	T_1	$3k(v_c - v'_c)$
T_2	$3k(-v_b - v'_b)$	T_2	$3k(v_a - v'_b)$	T_2	$3k(v_a + v'_a)$	T_2	$3k(v'_a - v_c)$
T_{eff}	$3kv_c$	T_{eff}	$3kv_c$	T_{eff}	$-3kv_b$	T_{eff}	$-3kv'_b$

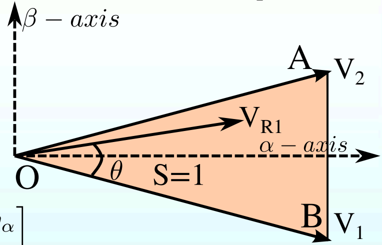
- The timings T1 and T2 can be expressed in terms of phase reference values
- For each sector, the timings are known

Timing T_1 for Sector S = 1

Example calculation

$$\overrightarrow{V_{R1}}T_s = \vec{V_1}T_1 + \vec{V_2}T_2 + \vec{V_0}T_0$$
$$= T_1 V_{dc}\angle(-15^\circ) + T_2 V_{dc}\angle 15^\circ$$
$$T_s = T_1 + T_2 + T_0$$

- Volt-Second balance
- Volt-second balance in alpha-beta frame
- Volt-second balance matrix representation



$$\frac{T_s}{V_{dc}}(v_\alpha + jv_\beta) = T_1(\cos 15^\circ - j\sin 15^\circ) + T_2(\cos 15^\circ + j\sin 15^\circ)$$

$$\frac{T_s}{V_{dc}}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} \cos 15^\circ & \cos 15^\circ \\ -\sin 15^\circ & \sin 15^\circ \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \end{bmatrix}$$

$$\begin{bmatrix} T_1 \\ T_2 \end{bmatrix} = \frac{T_s}{V_{dc}}\begin{bmatrix} \cos 15^\circ & \cos 15^\circ \\ -\sin 15^\circ & \sin 15^\circ \end{bmatrix}^{-1}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$
$$= \frac{T_s}{2V_{dc}\sin 15^\circ\cos 15^\circ}\begin{bmatrix} \sin 15^\circ & -\cos 15^\circ \\ \sin 15^\circ & \cos 15^\circ \end{bmatrix}\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}$$

Timing T_1 for Sector S = 1

Example calculation

$$T_1 = \frac{T_s}{V_{dc}} \frac{(v_\alpha \sin 15^\circ - v_\beta \cos 15^\circ)}{2 \sin 15^\circ \cos 15^\circ}$$
$$= \frac{T_s}{V_{dc}} \frac{(v_\alpha - 4 v_\beta \cos^2 15^\circ)}{2 \cos 15^\circ}$$

- T_1 in terms of v_alpha and v_beta

$$T_1 = \frac{T_s}{V_{dc}} \left\{ \frac{v_\alpha - v_\beta (2 + \sqrt{3})}{2 \cos 15^\circ} \right\}$$

- Simplification and substitution

$$T_1 = 3k(v_c' - v_b)$$
$$k = \frac{T_s}{2 V_{dc} \cos 15^\circ}$$

- Similarly, the Sector timings T_1 and T_2 can be calculated for other Sectors S = 1 to 12

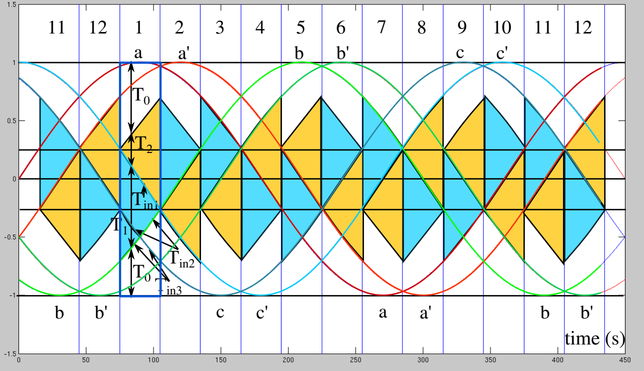
Carrier based PWM timings

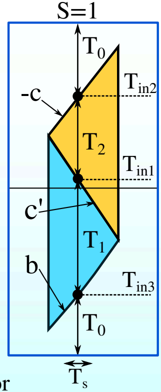
Algorithm

- Six phase voltage reference values are sampled
  $v_a, v_b, v_c, v'_a, v'_b, v'_c$
- Find $T_{\text{in}1}$, $T_{\text{in}2}$ and $T_{\text{in}3}$ where,
  $T_{\text{in}1} = \text{inner-most}(v_a, v_b, v_c, v'_a, v'_b, v'_c) \times T_s$
  $T_{\text{in}2} = 2^{\text{nd}} \text{ inner-most } (v_a, v_b, v_c, v'_a, v'_b, v'_c) \times T_s$
  $T_{\text{in}3} = 3^{\text{rd}} \text{ inner-most } (v_a, v_b, v_c, v'_a, v'_b, v'_c) \times T_s$
  where, inner-most is the minimum($|v_a|, |v_b|, |v_c|, |v'_a|, |v'_b|, |v'_c|$),
  T_s is the sampling time
  This is done for easy implementation in DSP
- The inner-most, 2^{nd} inner-most and the 3^{rd} inner-most can be found by comparing the absolute values (magnitudes) of the sampled reference values.
- Example: In Sector-1, $T_{\text{in}1} = v'_c \times T_s$, $T_{\text{in}2} = v_c \times T_s$ and $T_{\text{in}3} = v_b \times T_s$

Carrier based PWM timings

PWM timings for a Single Dodecagon

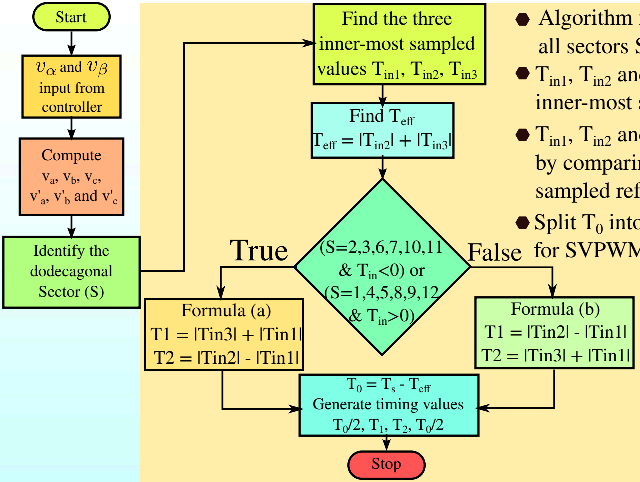




- Reference phase voltages and T_1, T_2 calculations for every sector At any time instant (Sampling Instant),
- The vertical extent of the Blue section shows the values of T_1
- The vertical extent of the Yellow section shows the values of T_2

Carrier based PWM timings

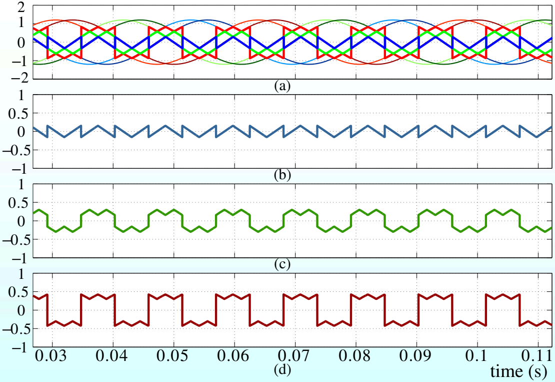
Algorithm - Flowchart



- Algorithm for finding timings for all sectors S = 1 to 12
- T_{in1}, T_{in2} and T_{in3} are three inner-most sampled references
- T_{in1}, T_{in2} and T_{in3} can be found by comparing absolute values of sampled references
- Split T_0 into 2 equal durations for SVPWM like switching

Carrier based PWM timings

for a Single dodecagon



Six reference phase voltages

Inner-most value found by minimum of absolute values of sampled values

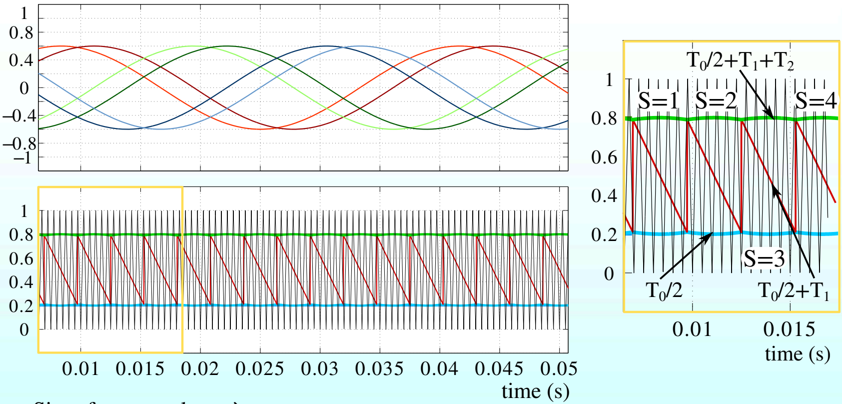
2nd Inner-most value

3rd Inner-most value

- The inner-most, 2nd inner-most and the 3rd inner-most can be found by comparing the absolute values (magnitudes) of the sampled reference values.

Carrier based PWM timings

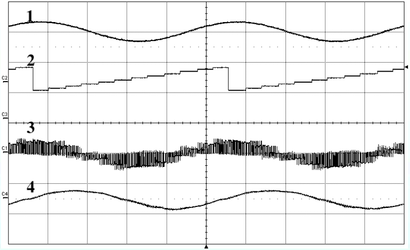
PWM Compare values and T_0 equalization



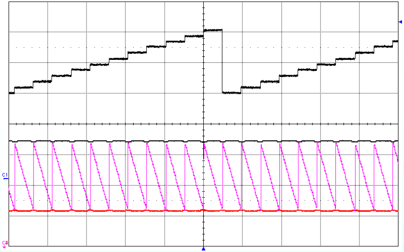
- Six reference voltages`
- Compare values to be used for carrier based switching – the sequence repeats every 30° dodecagonal sector
- SVPWM like switching is possible by dividing T0 into two equal T0/2 durations

Carrier based PWM timings

Experimental results - 2 level - 10Hz



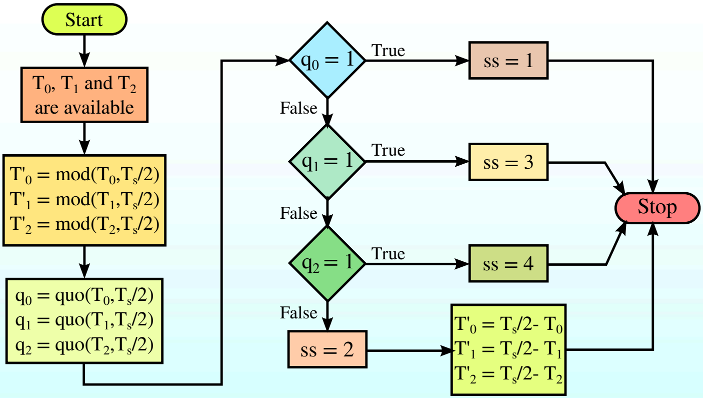
Voltage and current wave-forms of Phase-A: x-axis: 20ms/div,
1)Voltage reference waveform;
2)Sector information S = 1 to 12;
3)Phase voltage, 200 V/div;
4)Phase current, 1A/div.



Sector identification and PWM compare values after T_0 equalization

Carrier based PWM timings

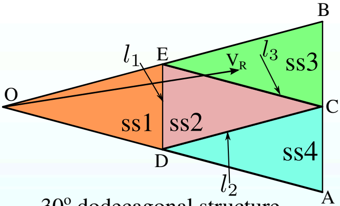
Sub-sector identification



- Algorithmic representation of the level shifted carrier based method
- mod(T0,Ts/2) is the remainder when T0 is divided by Ts/2
  quo(T0,Ts/2) is the quotient when T0 is divided by Ts/2

Carrier based PWM timings

Sub-sector identification



30° dodecagonal structure divided into 4 sub-sectors

- Assume V_R is in ss=3
- In such a case, $T_2 > T_s/2$
  So, $q_2 = 1$
- Timings
  $T'_0 = T_0$
  $T'_1 = T'_1$
  $T'_2 = T_2 - T_s/2$

- Bringing T_1, T_2, T_0 form 0 to T_s to T'_1, T'_2, T'_0 from 0 to $T_s/2$
- Sub-Sector identification

T_0, T_1 and T_2 are available

$T'_0 = \mathrm{mod}(T_0,T_s/2)$
$T'_1 = \mathrm{mod}(T_1,T_s/2)$
$T'_2 = \mathrm{mod}(T_2,T_s/2)$

$q_0 = \mathrm{quo}(T_0,T_s/2)$
$q_1 = \mathrm{quo}(T_1,T_s/2)$
$q_2 = \mathrm{quo}(T_2,T_s/2)$

- $\mathrm{mod}(T_0,T_s/2)$ is the remainder when T_0 is divided by $T_s/2$
  $\mathrm{quo}(T_0,T_s/2)$ is the quotient when T_0 is divided by $T_s/2$

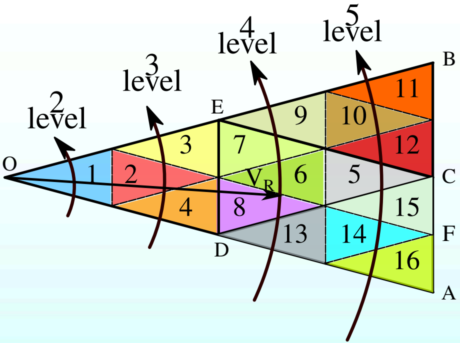
Carrier based PWM timings

Algorithm for converting Sector timings to smallest triangle timings

1. Six phase voltage reference values are sampled $v_a, v_b, v_c, v'_a, v'_b, v'_c$
2. Using only the samples, the 30° Sector S and timings (T_1, T_2) for Sector is calculated
3. Sub-sector identification (ss) and sub-sector timings (T'_1, T'_2) using sector timings
4. Sub-sub-sector identification (sss) and sub-sub-sector timings (T''_1, T''_2) using sub-sector timings

Sub-Sub-Sector identification

Sequence of the sub-sub-sector for each sector

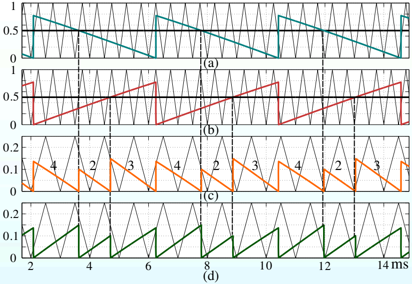


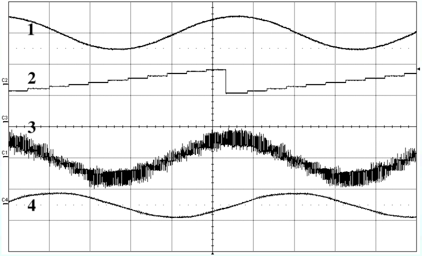
- Rotation of V_R is in anti-clockwise direction
- Sub-Sub Sectors are identified directly using the Sector timings T_1, T_2 and T_0

- The tip of V_R passes through smaller Triangles in all Sectors S = 1 - 12
- For 2-level operation, sub-sub-sector sequence is 1 - 1 - 1...
- For 3-level operation, sub-sub-sector sequence is 4 - 2 - 3...
- For 4-level operation, sub-sub-sector sequence is 13 - 8 - 6 - 7 - 9...
- For 5-level operation, sub-sub-sector sequence is 16-14-15-5-12-10-11...

Experimental Results

3 level operation - 17Hz



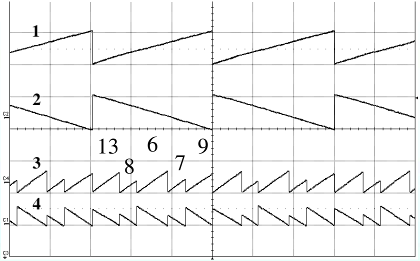


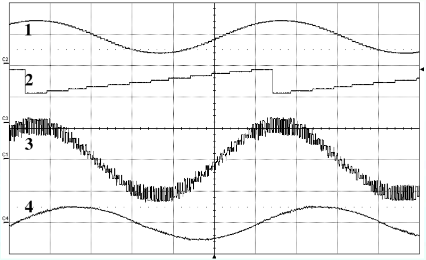
- T_1, T_2 variation for each sector:
  T_1 decreases from T_{eff} to zero
  T_2 increases from zero to T_{eff} for each Sector
- Sub-sector identification and timings
  T''_1 and T''_2 by shifting to single carrier range
  Sub-sub-sector sequence: 4-2-3...

Voltage and current wave-forms of Phase-A: x-axis: 10ms/div, y-axis: 1)Voltage reference waveform; 2)Sector information; 3)Phase voltage, 200 V/div; 4)Phase current, 1A/div

Experimental Results

4 level operation - 35Hz



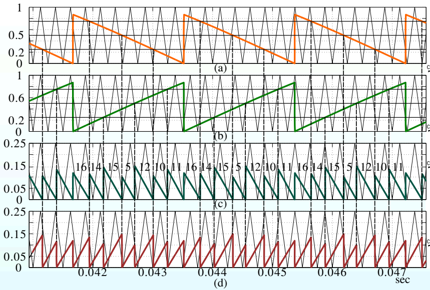


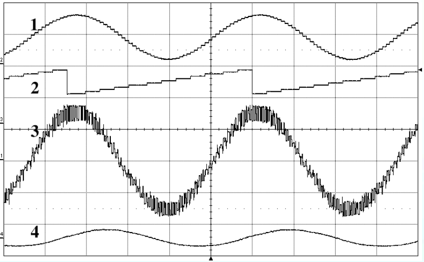
- T_1, T_2 variation for each sector:
  T_1 decreases from T_{eff} to zero
  T_2 increases from zero to T_{eff} every Sector
- Triangle identification and triangle timings
  T''_1 and T''_2 by shifting to $T_s/4$ range
  Sub-sector sequence: 13-8-6-7-9...

Voltage and current wave-forms
of Phase-A: x-axis: 10ms/div,
y-axis: 1)Voltage reference waveform;
2)Sector information;
3)Phase voltage, 200 V/div;
4)Phase current, 1A/div

Experimental Results

5 level operation - 45Hz



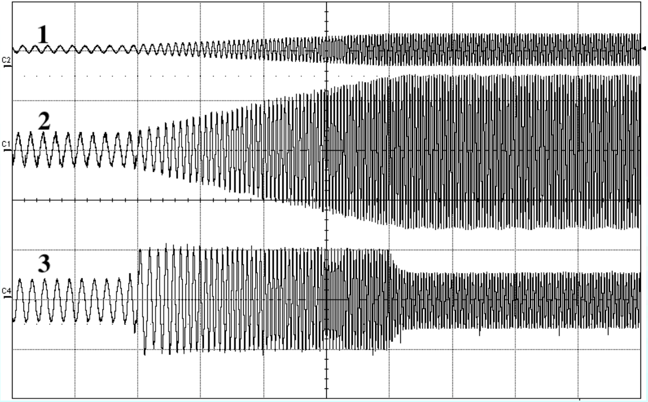


- T_1, T_2 variation for each sector:
  T_1 decreases from T_{eff} to zero
  T_2 increases from zero to T_{eff} every Sector
- Triangle identification and
  T''_1 and T''_2 by shifting to $T_s/4$ range
  Sub-sub-sector sequence:
  16-14-15-5-12-10-11...

Voltage and current wave-forms of Phase-A: x-axis: 5ms/div,
y-axis: 1)Voltage reference waveform;
2)Sector information;
3)Phase voltage, 200 V/div;
4)Phase current, 1A/div

Experimental Results

Transient operation 10Hz - 45Hz in 4 secs.



Motor is accelerated from 10Hz to 45 Hz in 4 sec. x-axis: 1s/div.

1) Reference phase Voltage

2) Inverter Phase Voltage Vaa' - 250V/div.

3) Motor Phase Current Ia - 2A/div

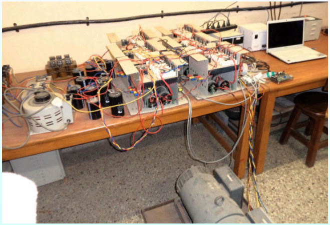
Summary

Carrier based modulation scheme for Dodecagonal SV structure

- A PWM timing calculation method using only reference voltages for Multilevel dodecagonal SV structures
- SVPWM like switching sequences can be obtained by equalizing the pivot vector time
- No iterative methods for triangle identification
  - 3 level - 4 iterations (typical) - 1 iteration (proposed)
  - 5 level - 16 iterations (typical) - 2 iteration (proposed)
  - 9 level - 64 iterations (typical) - 3 iteration (proposed)
- Tested for two, three, four and five level operation - steady state and transients

Results

Photos of the Experimental Setup



- Power Supply
- Inverter - 1
  Inverter - 2
- DSP, FPGA and Sensor PCB
- Induction Motor

Summary

Multilevel Dodecagonal SV Structure with Symmetric Triangles

- Space vector structure with Symmetric triangles
- Power Circuit Topology
  - Standard NPC and H-Bridge modules are used
  - Inherent capacitor balancing for CHB
  - No pre-charging circuitry required for start-up
  - In case of CHB device failure, CHB can be bypassed and system can handle full power
- Generic timing calculation method for SV structure
  - No iterative search required for triangle identification (Direct Hit)
  - Needs only v_α and v_β
  - No look-up table, off-line computation, angle estimation required
  - Can be used with closed loop systems

Summary

Nineteen level Dodecagonal Space Vector Structure with Scalable 24-stepped Phase Voltage

- Space vector structure with **nineteen** concentric dodecagons
- New switching technique
  - 24 stepped waveform for **all operating conditions**
  - Less switching of individual NPC and CHB modules (Switching frequency $\approx$ 300Hz)
  - Reduction in switching losses
- Phase Voltage Harmonics - Elimination and suppression
  - Completely eliminates $6n \pm 1$ harmonics in phase voltages and currents
  - **Suppression** of 11^{th} and 13^{th} harmonics in phase voltages and currents
  - Phase Voltage THD $\approx$ 10%
- Reduction in dv/dt of the phase voltage - Lesser EMI issues

Summary

- A PWM timing calculation method using only reference voltages for Multilevel dodecagonal SV structures
- SVPWM like switching sequences can be obtained by equalizing the pivot vector time
- No iterative methods for triangle identification
  - 3 level - 4 iterations (typical) - 1 iterations (proposed)
  - 5 level - 16 iterations (typical) - 2 iterations (proposed)
  - 9 level - 64 iterations (typical) - 3 iterations (proposed)
- Tested for two, three, four and five level operation - steady state and transients

Summary

Advantages

- Phase Voltage Harmonics - Elimination and suppression
- Completely eliminates $6n \pm 1$ (n = odd) harmonics in phase voltages and currents
- Extension in linear modulation range due to dodecagonal switching
- Lesser dv/dt due to smaller identical triangles
  - in phase voltages
  - across power switches
- Lesser EMI/EMC issues
- Hence, the proposed system is well suited for medium voltage and high power motor drive applications