

Improved Space Vector PWM Technique Operating in Over-modulation Region for Induction Machine Drive

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INTRODUCTION:

There are mainly two methods, to generate gating pulses for VSI.
They are

- ▶ Sine PWM technique
- ▶ Space Vector PWM technique

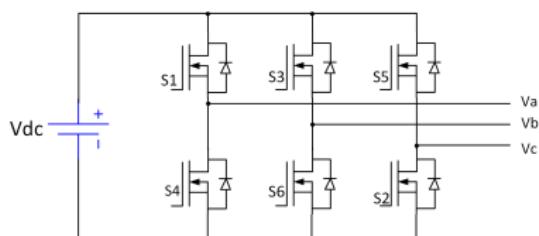


Figure: Circuit Diagram of VSI

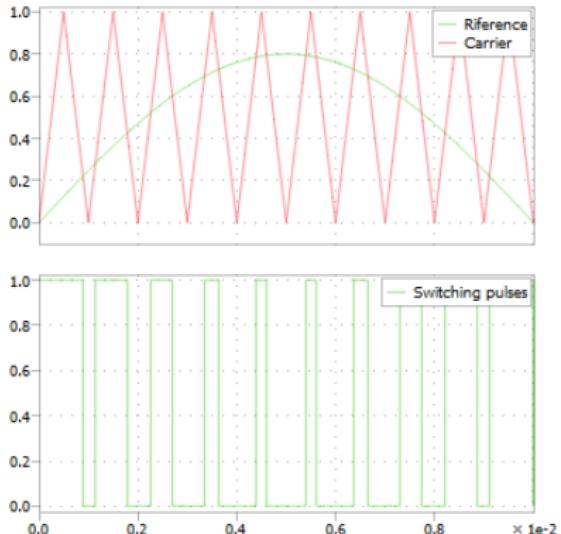


Figure: SPWM Technique

SPACE VECTOR PWM:

Voltage Vectors	Switching Signals			Pole Voltages			Line - Line Voltages		
	A	B	C	Vao	Vbo	Vco	Vab	Vbc	Vca
V0	0	0	0	0	0	0	0	0	0
V1	1	0	0	2/3	-1/3	-1/3	1	0	0
V2	1	1	0	1/3	1/3	-2/3	0	1	0
V3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V4	0	1	1	-2/3	1/3	1/3	-1	0	1
V5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V6	1	0	1	1/3	-2/3	1/3	1	-1	0
V7	1	1	1	0	0	0	0	0	0

$$\vec{V}_{\text{Ref}} = \frac{2}{3}[V_a(t)e^{j0} + V_b(t)e^{j\frac{2\pi}{3}} + V_c(t)e^{j\frac{4\pi}{3}}] \quad (1)$$

STATOR FLUX RIPPLE OVER A SUB-CYCLE:

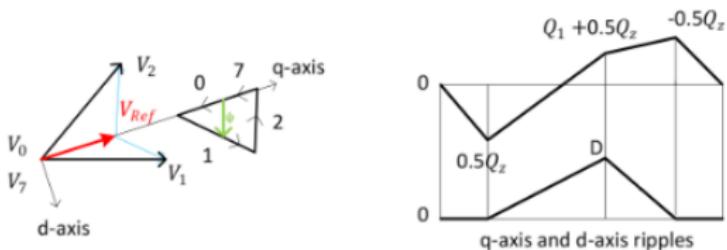


Figure: Stator Flux Ripple Vector for 0127 Sequence

- ▶ Flux ripple calculated by integrating error voltage vector

$$V_{Err} = V_{\text{applied}} - V_{\text{Ref}} \quad (2)$$

$$V_{Err1} = \sin(\alpha) + j[\cos(\alpha) - V_{\text{Ref}}] \quad (3)$$

$$V_{Err2} = -\sin(60^\circ - \alpha) + j[\cos(60^\circ - \alpha) - V_{\text{Ref}}] \quad (4)$$

$$V_{Err0} = -jV_{\text{Ref}} \quad (5)$$

CONTINUE...:

$$Q_1 = [\cos(\alpha) - V_{\text{Ref}}] T_1 \quad (6)$$

$$Q_2 = [\cos(60^\circ - \alpha) - V_{\text{Ref}}] T_2 \quad (7)$$

$$Q_z = -V_{\text{Ref}} T_0 \quad (8)$$

$$D = \sin(\alpha) T_1 \quad (9)$$

$$\begin{aligned} F_{0127}^2 &= \frac{1}{3}(0.5Q_z)^2 \frac{T_0}{2T} + \frac{1}{3}[(0.5Q_z)^2 + 0.5Q_z(0.5Q_z + Q_1) \\ &\quad +(0.5Q_z + Q_1)^2] \frac{T_1}{T} + \frac{1}{3}[(-0.5Q_z)^2 - 0.5Q_z(0.5Q_z + Q_1) \\ &\quad +(0.5Q_z + Q_1)^2] \frac{T_2}{T} + \frac{1}{3}(-0.5Q_z)^2 \frac{T_0}{2T} + \frac{1}{3}D^2 \frac{(T_1 + T_2)}{T} \end{aligned}$$

CONTINUE...:

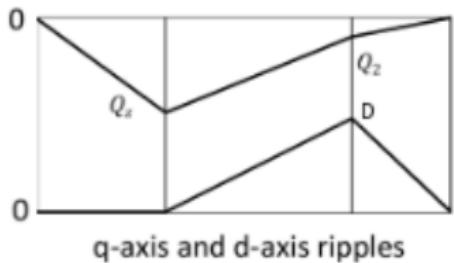
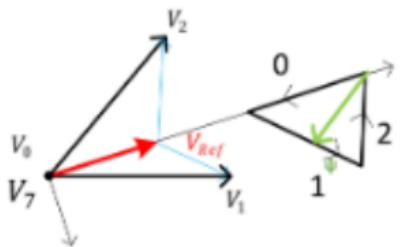


Figure: Stator Flux Ripple Vector for 012 Sequence

$$\begin{aligned} F_{012}^2 = & \frac{4}{27} Q_z^2 \frac{T_0}{T} + \frac{4}{27} [Q_z^2 + Q_z(Q_z + Q_1) + (Q_z + Q_1)^2] \frac{T_1}{T} \\ & + \frac{4}{27} [(Q_z + Q_1)^2] \frac{T_2}{T} + \frac{4}{27} D^2 \frac{(T_1 + T_2)}{T} \end{aligned}$$

CONTINUE...:

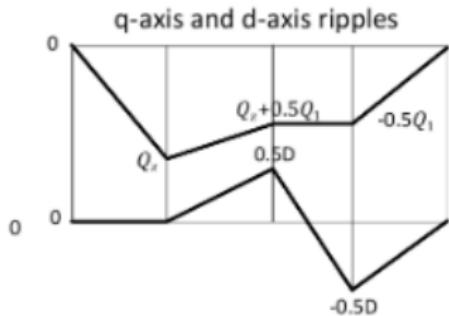
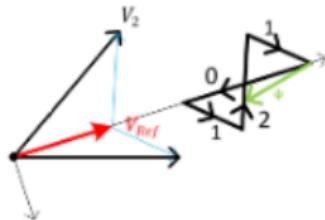
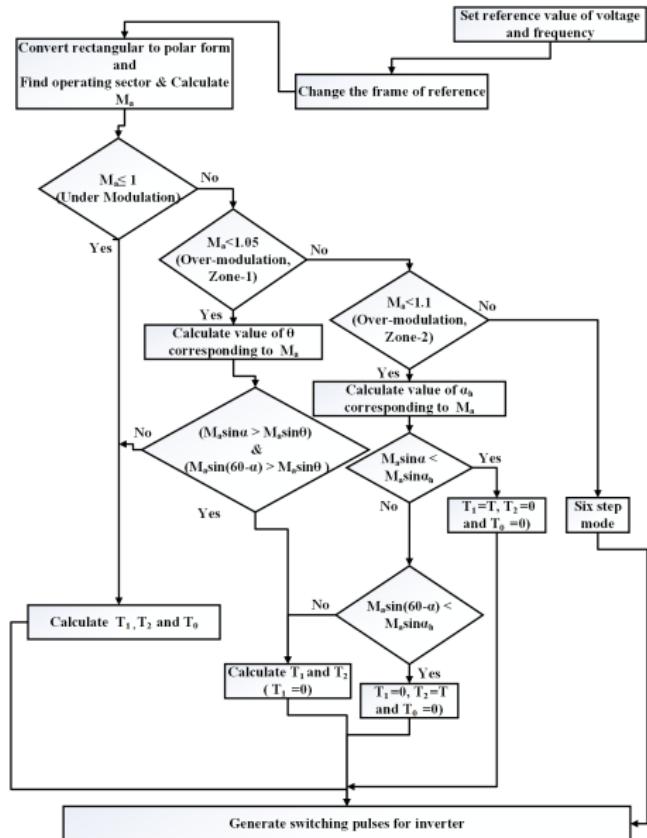


Figure: Stator Flux Ripple Vector for 0121 Sequence

$$\begin{aligned} F_{0121}^2 &= \frac{1}{3}(Q_z)^2 \frac{T_0}{T} + \frac{1}{3}[Q_z^2 + Q_z(Q_z + 0.5Q_1) + (Q_z + 0.5Q_1)^2] \frac{T_1}{2T} \\ &+ \frac{1}{3}[(-0.5Q_1)^2 - 0.5Q_1(0.5Q_1 + Q_z) + (0.5Q_1 + Q_z)^2] \frac{T_2}{T} \\ &+ \frac{1}{3}(-0.5Q_1)^2 \frac{T_1}{2T} + \frac{1}{3}(0.5D)^2 \frac{(T_1 + T_2)}{T} \end{aligned}$$

IMPLEMENTATION OF SVPWM:



MODULATION INDEX:

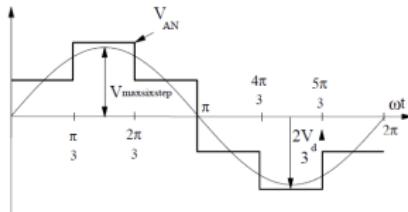


Figure: Phase and Fundamental Voltages for Six-step Operation

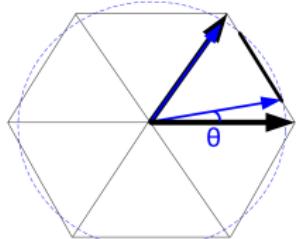
$$|V_{\text{Ref}}|_{\max} = \frac{2}{3} V_{\text{dc}} * \frac{\sqrt{3}}{2} = \frac{V_{\text{dc}}}{\sqrt{3}} \quad (10)$$

$$Ma = \frac{|V_{\text{Ref}}|}{V_{\max}} = \frac{V_{\text{Ref}}}{\frac{V_{\text{dc}}}{\sqrt{3}}} = \frac{\sqrt{3}V_{\text{Ref}}}{V_{\text{dc}}} \quad (11)$$

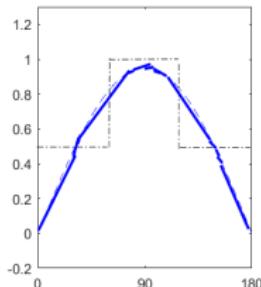
$$V_{\max6} = \frac{4}{\pi} \frac{V_{\text{dc}}}{2} = \frac{2V_{\text{dc}}}{\pi} \quad (12)$$

$$M_{a-\max} = \frac{\frac{2V_{\text{dc}}}{\pi}}{\frac{V_{\text{dc}}}{\sqrt{3}}} = \frac{2\sqrt{3}}{\pi} = 1.1 \quad (13)$$

OVER-MODULATION ZONE-1($1 < m < 1.05$):



(a) Voltage Trajectory



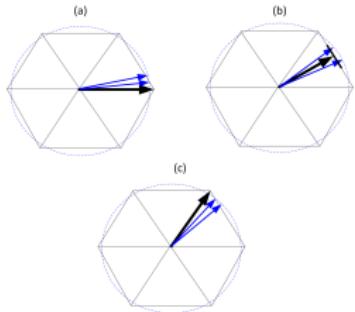
(b) Fundamental Phase Voltage

Figure: Over-modulation Zone-1 Operation

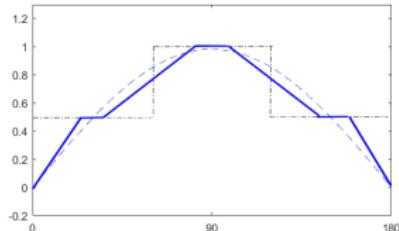
- The modified reference voltage magnitude V with respect to α is given as

$$|V| = \begin{cases} V_{ref}, & 0 \leq \alpha \leq \theta \\ \frac{\sqrt{3}}{\cos(\frac{\pi}{6} - \alpha_{ref})}, & \theta \leq \alpha \leq (\frac{\pi}{3} - \theta) \\ V_{ref}, & (\frac{\pi}{3} - \theta) \leq \alpha \leq (\frac{\pi}{3}) \end{cases}$$

OVER-MODULATION ZONE-2($1.05 < m < 1.1$):



(a) Voltage Trajectory



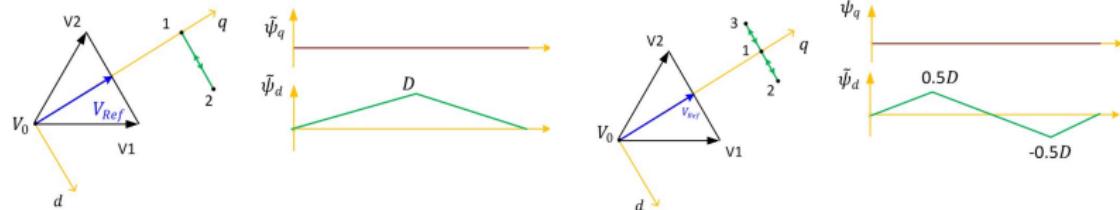
(b) Fundamental Phase Voltage

Figure: Over-modulation Zone-2 Operation

- In this zone, the angle of reference vector is varied and given as

$$\alpha = \begin{cases} 0, & 0 \leq \alpha \leq \alpha_h \\ \frac{\pi}{6} \left(\frac{\alpha - \alpha_h}{\frac{\pi}{6} - \alpha_h} \right), & \alpha_h \leq \alpha_{ref} \leq \left(\frac{\pi}{3} - \alpha_h \right) \\ \frac{\pi}{3}, & \left(\frac{\pi}{3} - \alpha_h \right) \leq \alpha \leq \left(\frac{\pi}{3} \right) \end{cases}$$

STATOR FLUX RIPPLE OVER A SUB-CYCLE IN OM REGION:



- For 12 sequence

$$\Psi_q^2 = 0 \quad (14)$$

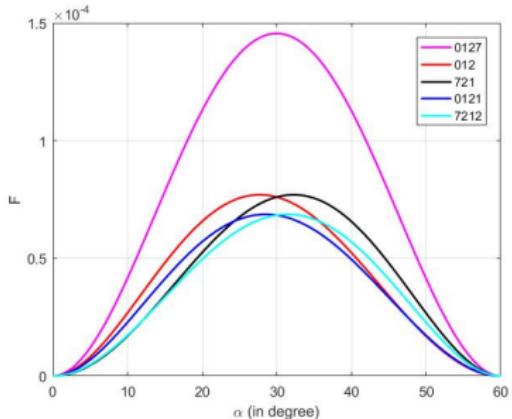
$$\Psi_d^2 = \frac{1}{3}D^2 \frac{(T_1 + T_2)}{T} = \frac{1}{3}D^2 \quad (15)$$

$$F_{12}^2 = \Psi_q^2 + \Psi_d^2 = \frac{1}{3}D^2 \quad (16)$$

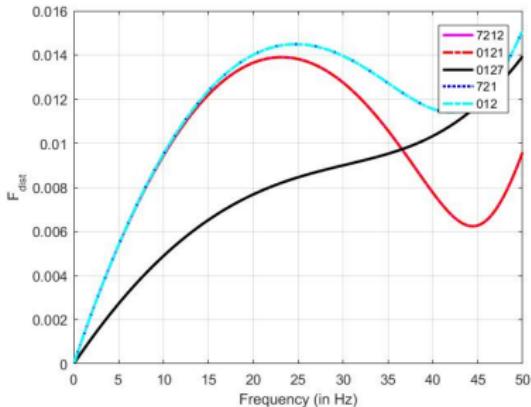
- Similarly, for 121 sequence

$$F_{121}^2 = \Psi_q^2 + \Psi_d^2 = \frac{1}{3}(0.5D)^2 \quad (17)$$

SIMULATION RESULTS:



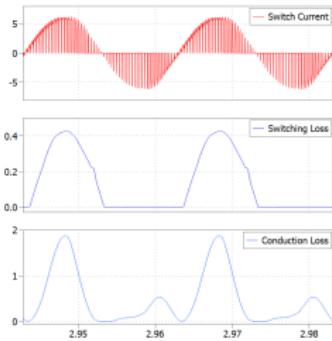
(a) RMS Stator Flux Ripple



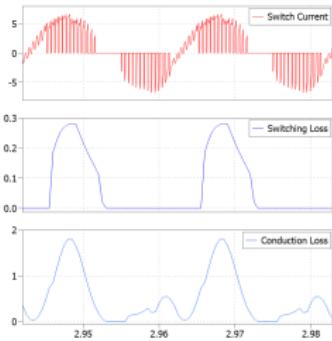
(b) Total RMS Harmonic Distortion Factor Vs Frequency Curve

Figure

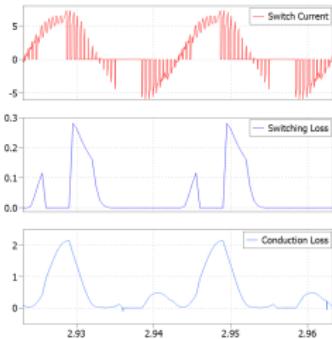
SWITCHING LOSSES AT 10NM LOAD:



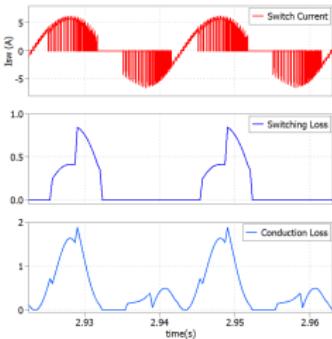
(a) 0127 Sequence



(b) 012 Sequence

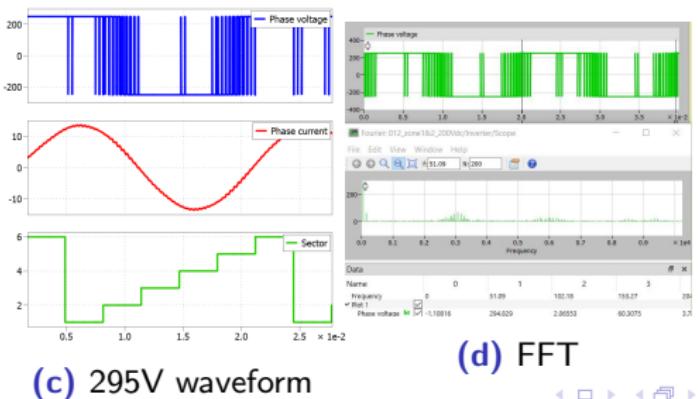
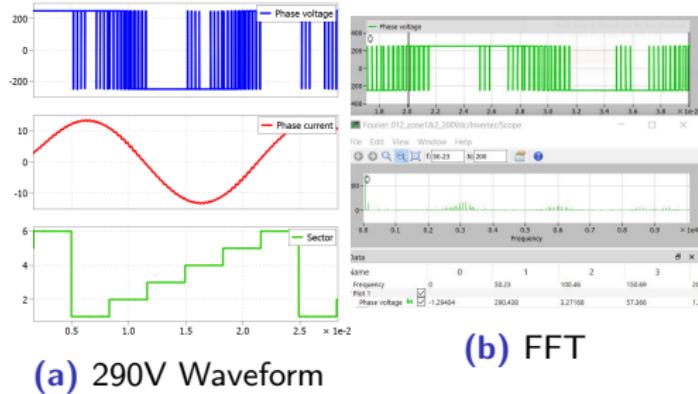


(c) 721 Sequence

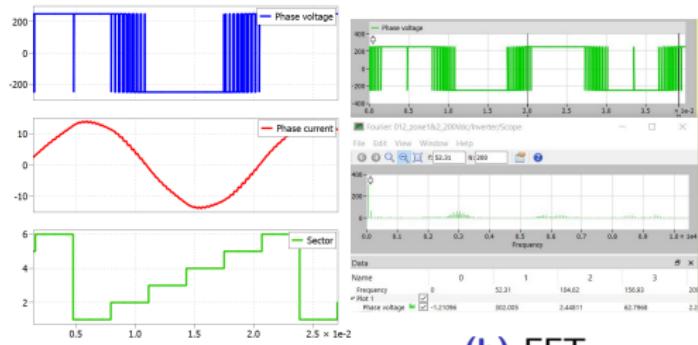


(d) 0121 Sequence

12 SEQUENCE:

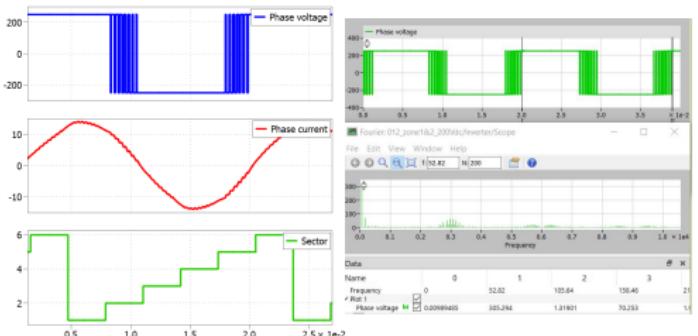


CONTINUE...:



(a) 302V Waveform

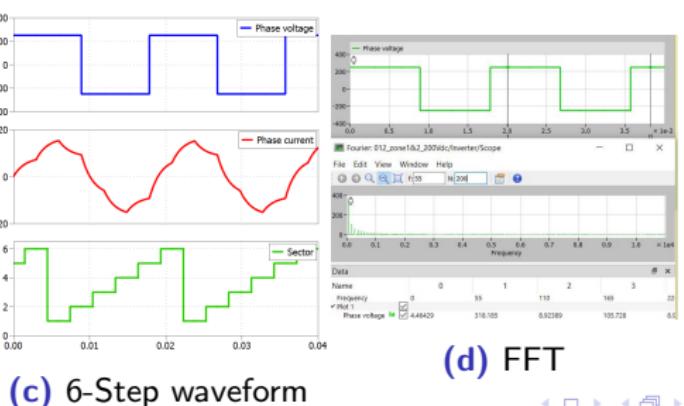
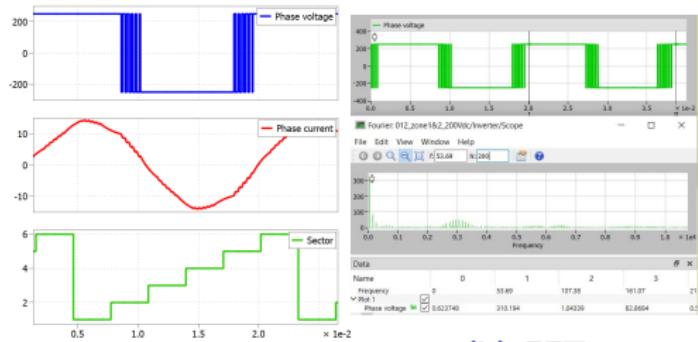
(b) FFT



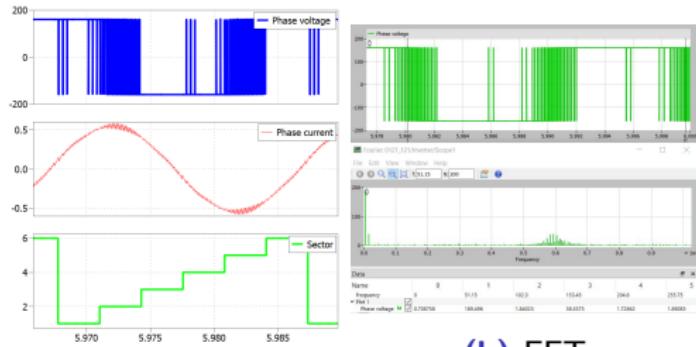
(c) 305V waveform

(d) FFT

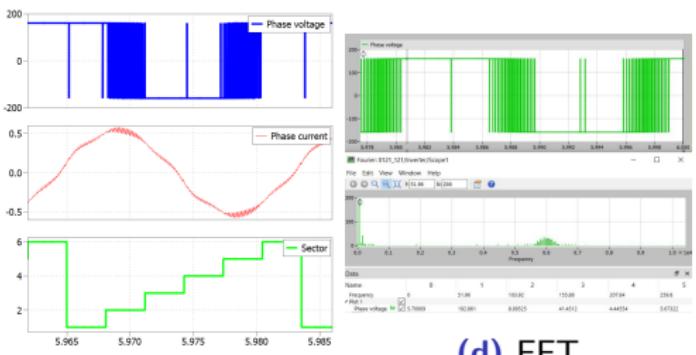
CONTINUE...:



121 SEQUENCE:

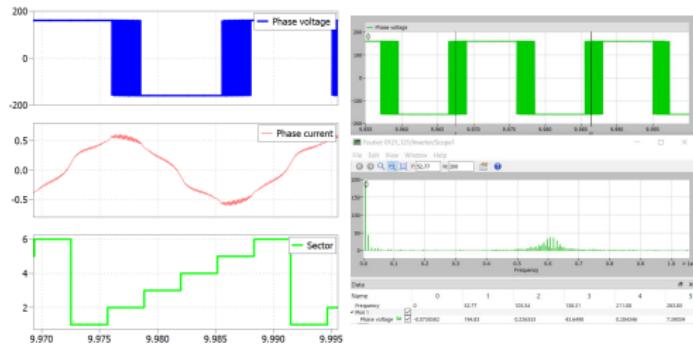


(b) FFT



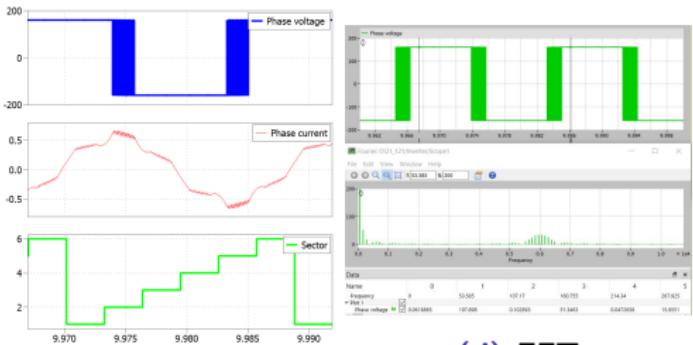
(d) FFT

CONTINUE...:



(a) 195V Waveform

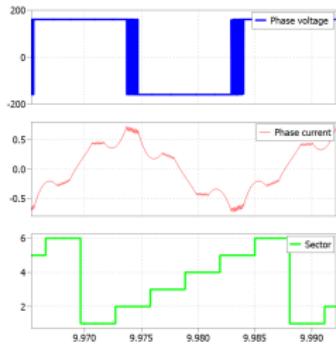
(b) FFT



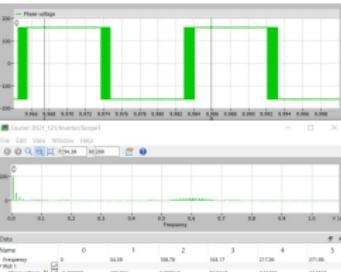
(c) 198V waveform

(d) FFT

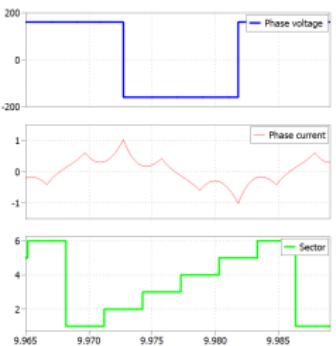
CONTINUE...:



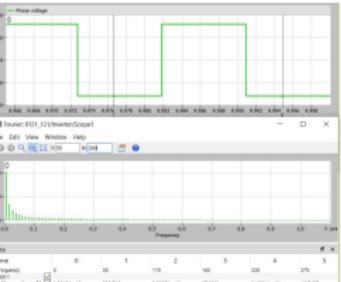
(a) 201V Waveform



(b) FFT



(c) 6-Step waveform



(d) FFT

CONTINUE...:

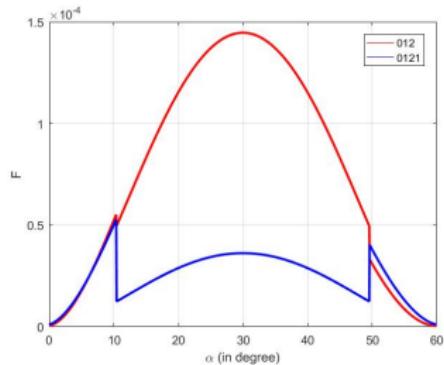
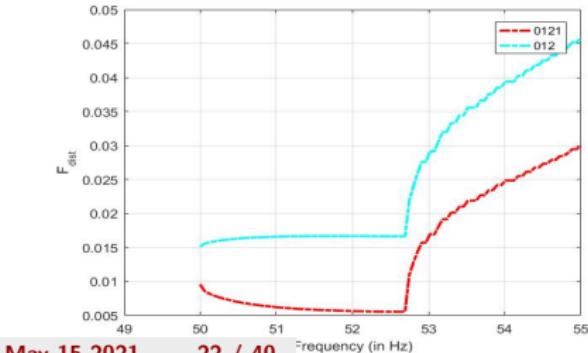
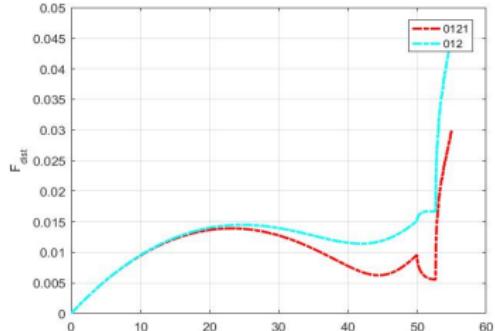


Figure: RMS Stator Flux Ripple for Modulation Index of 1.02



EXPERIMENTAL RESULTS:

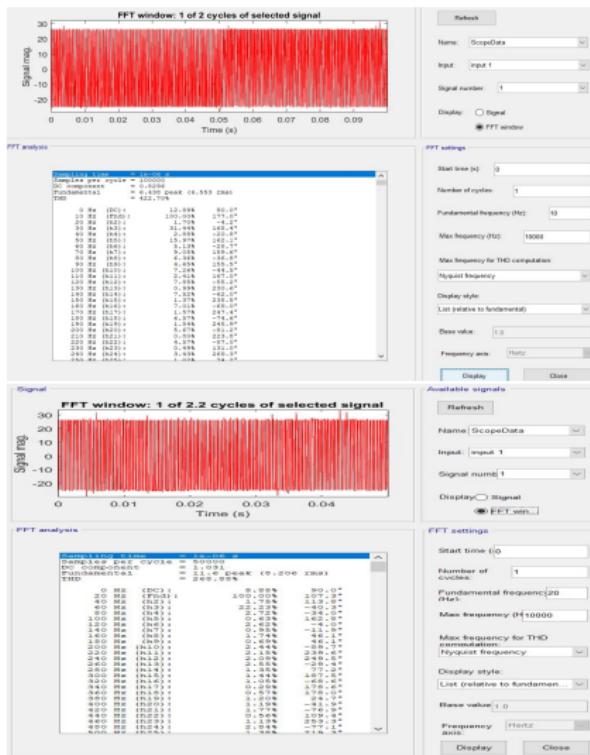
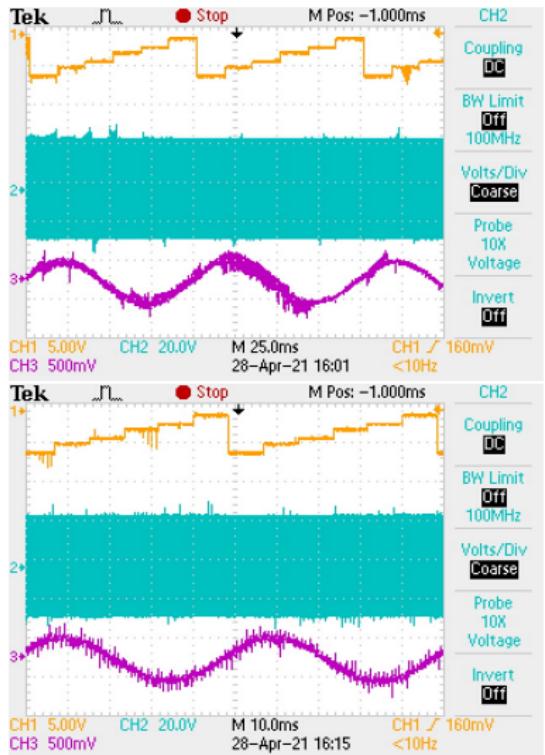


Figure: 0127 Sequence

CONTINUE...:

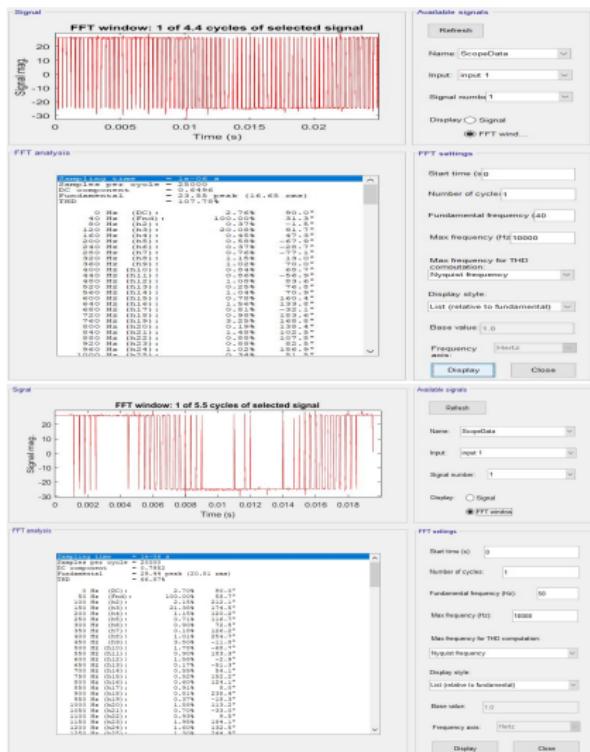
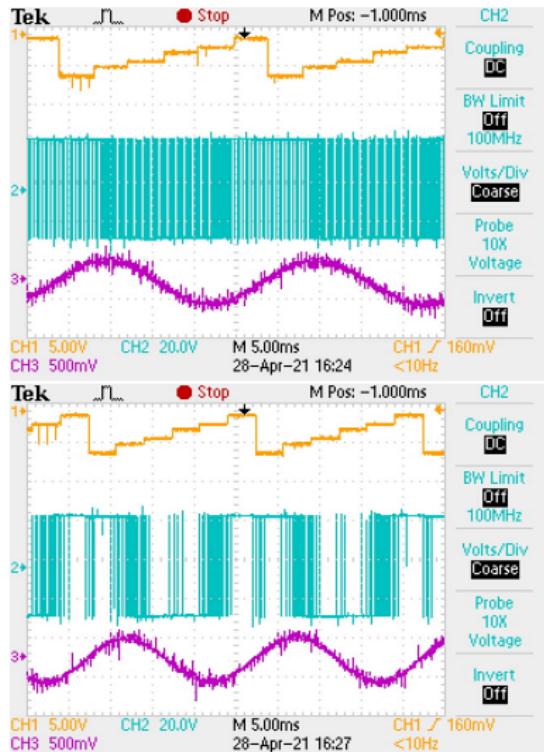
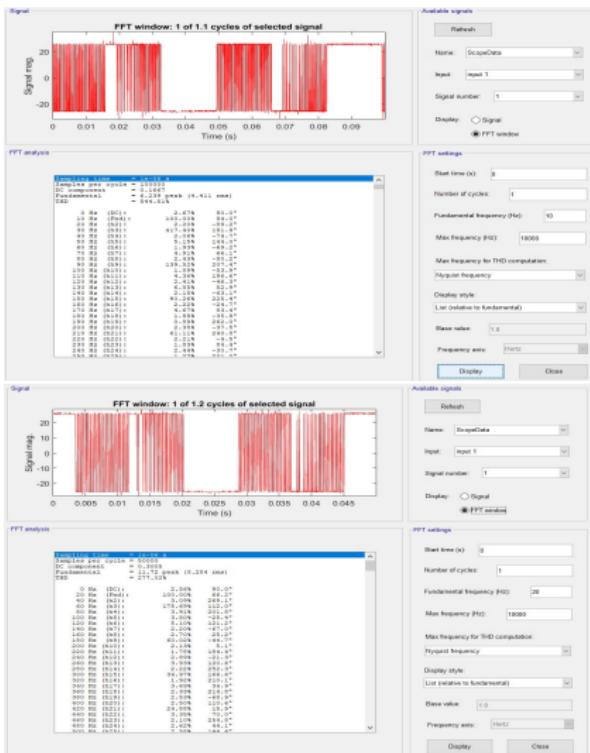
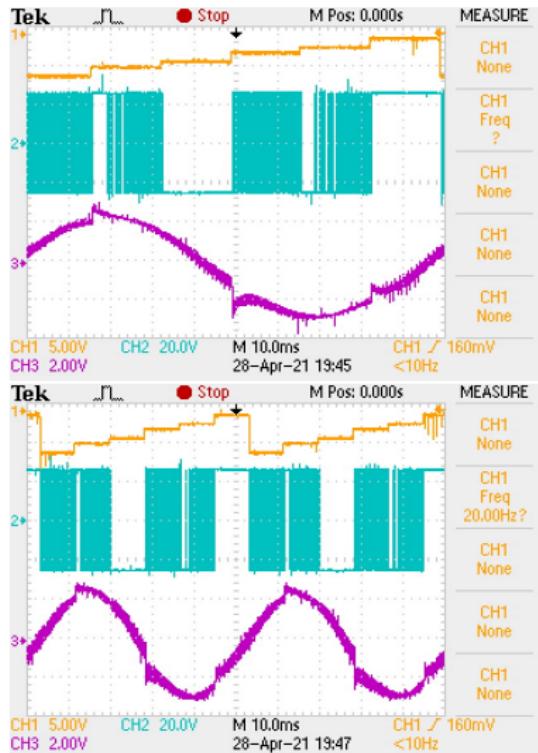
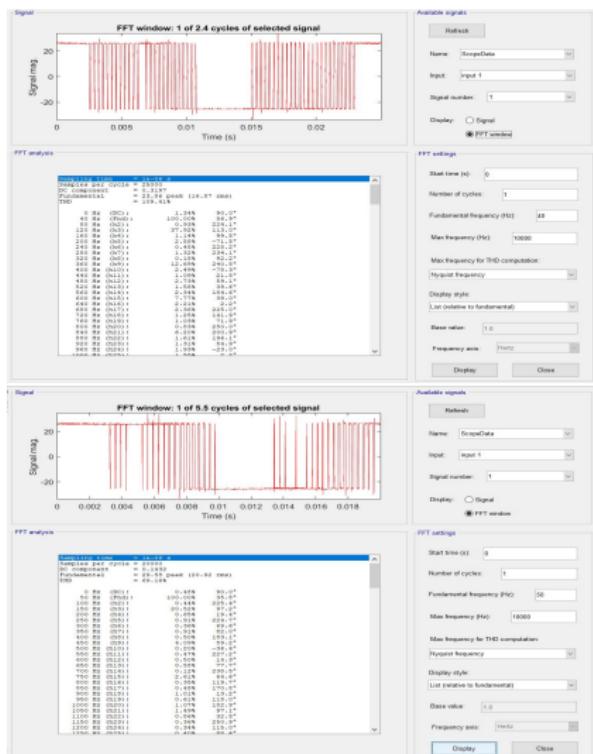
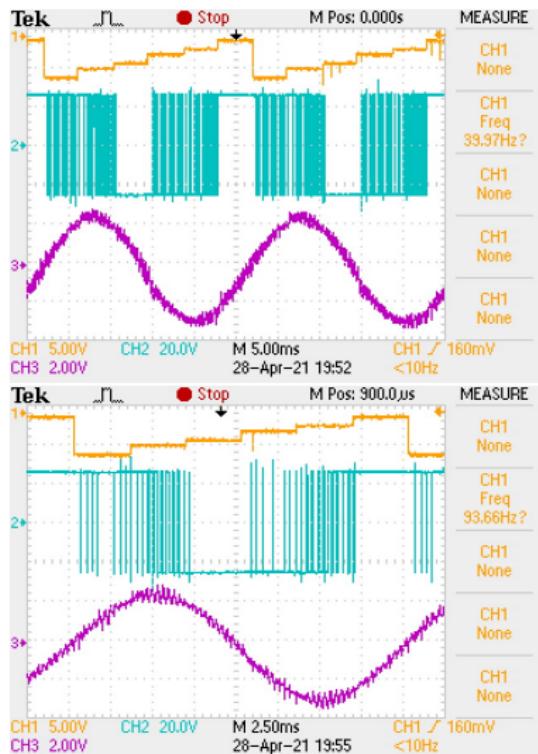


Figure: 0127 Sequence

012 SEQUENCE:



CONTINUE...:



12 SEQUENCE:

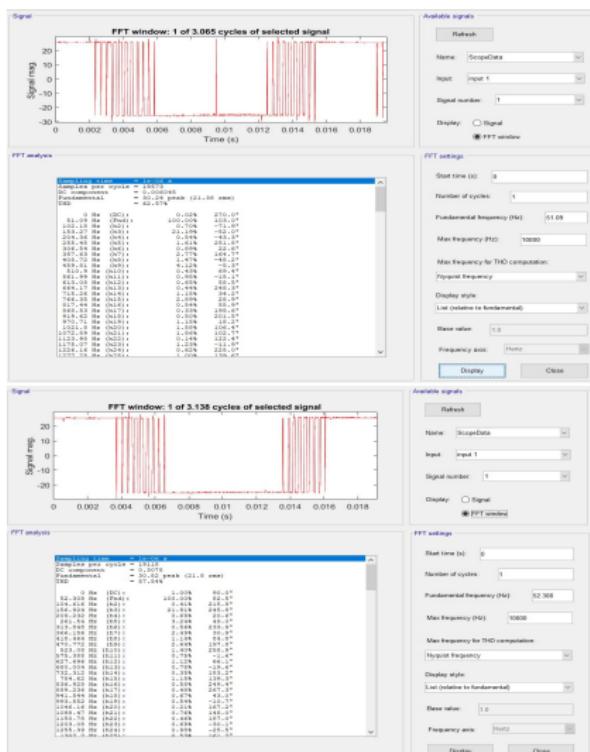
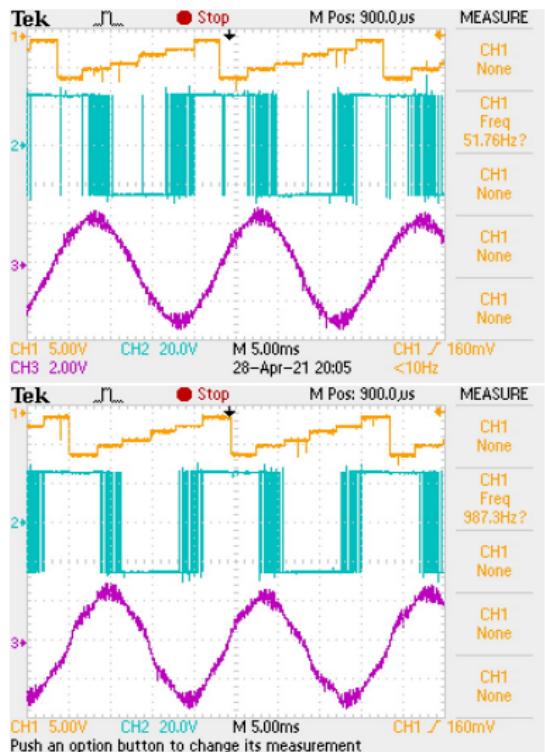


Figure: 12 Sequence

CONTINUE...:

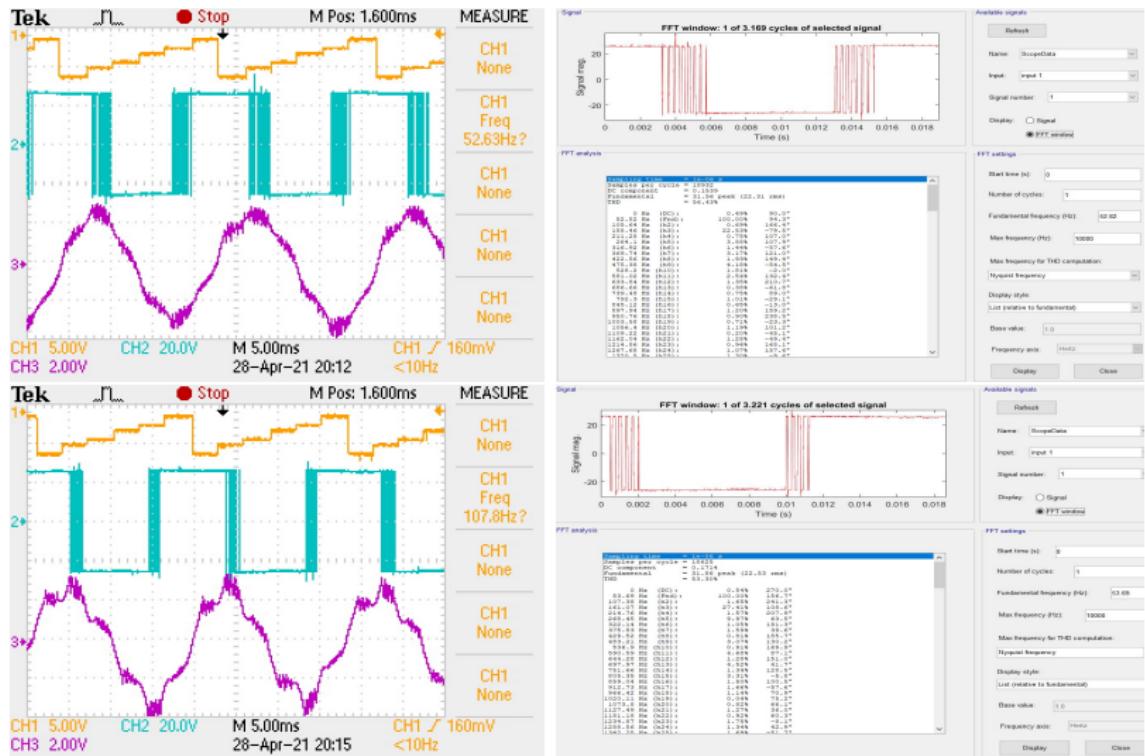


Figure: 12 Sequence

721 SEQUENCE:

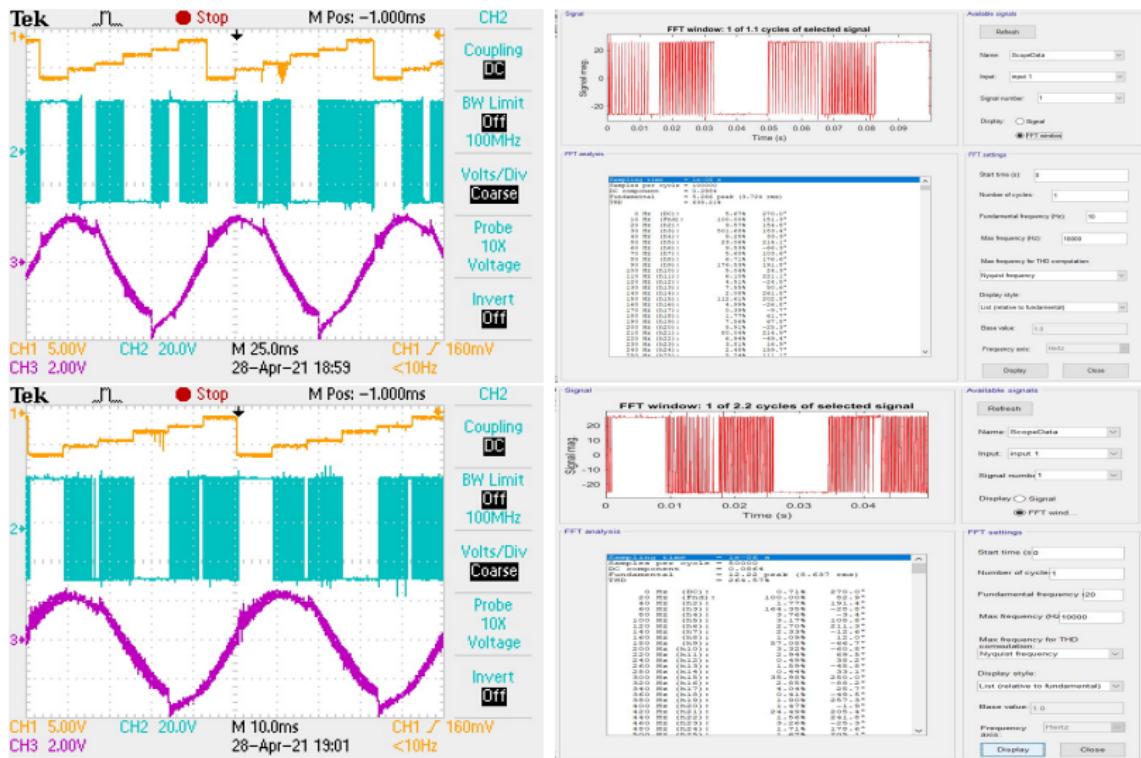


Figure: 721 Sequence

CONTINUE...:

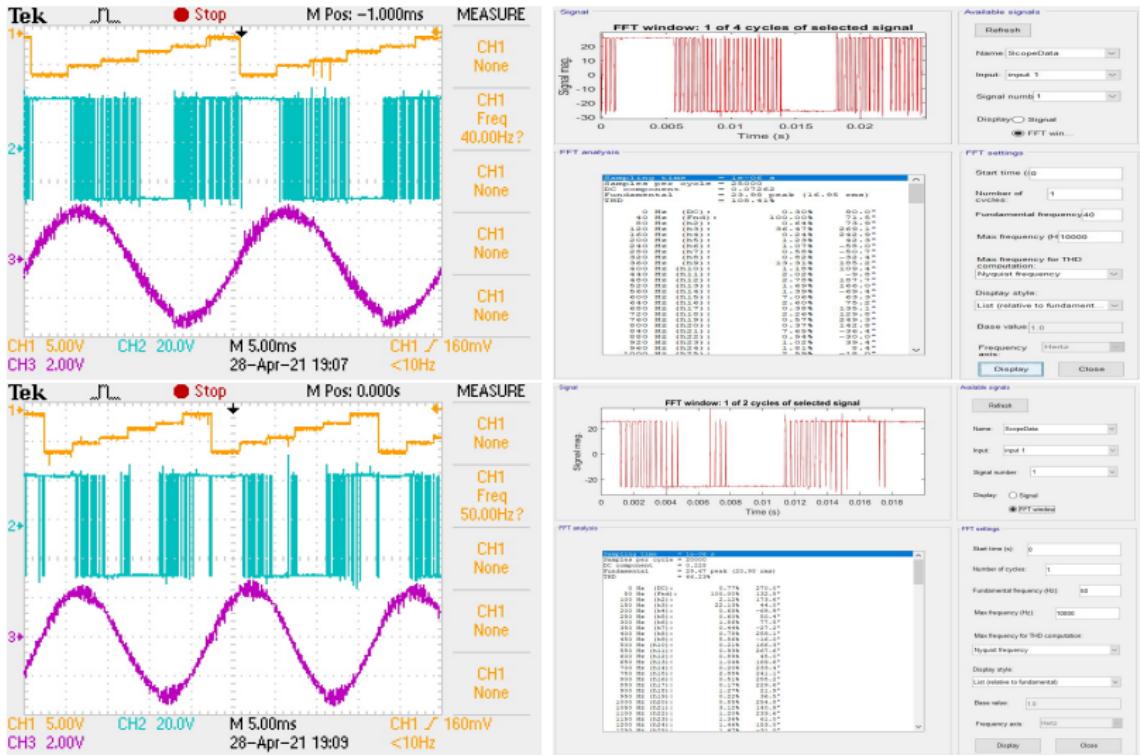


Figure: 721 Sequence

0121 SEQUENCE:

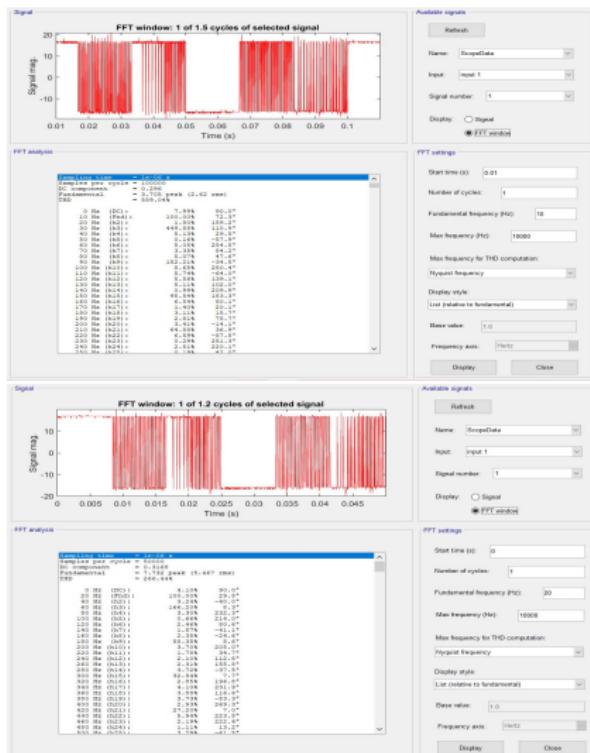
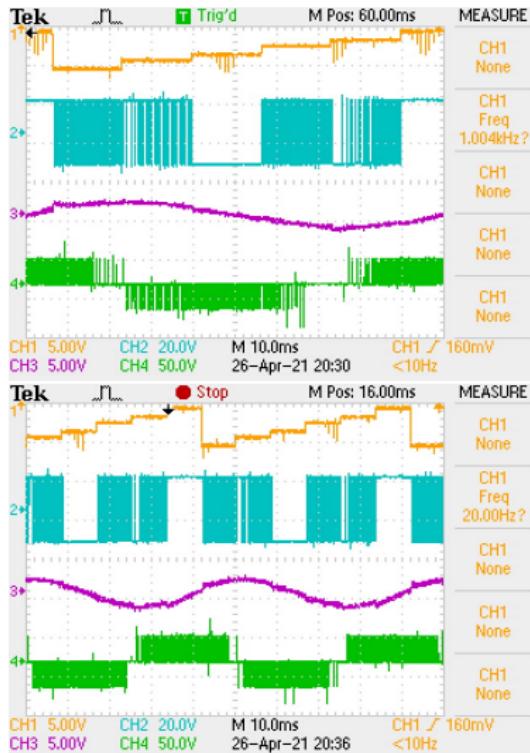


Figure: 0121 Sequence

CONTINUE...:

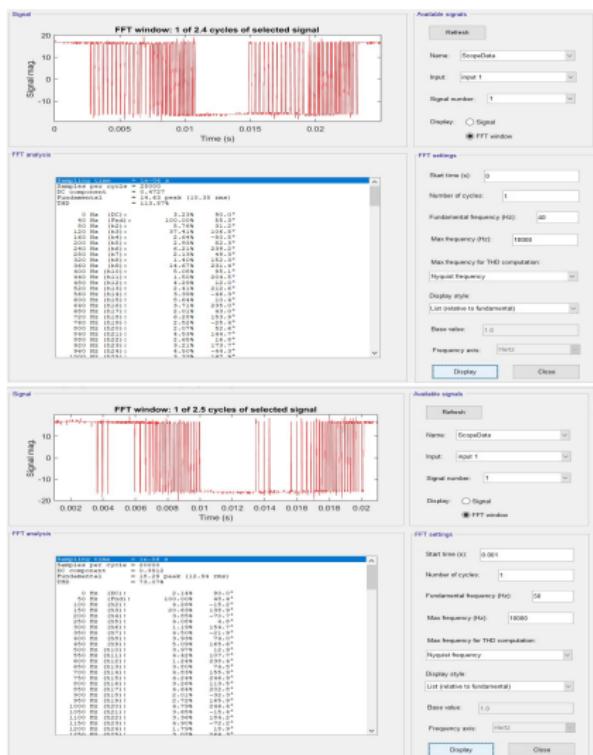
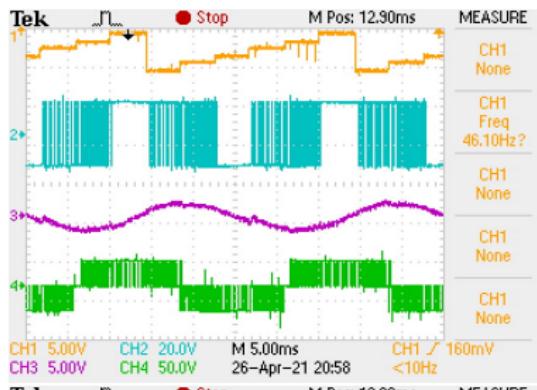
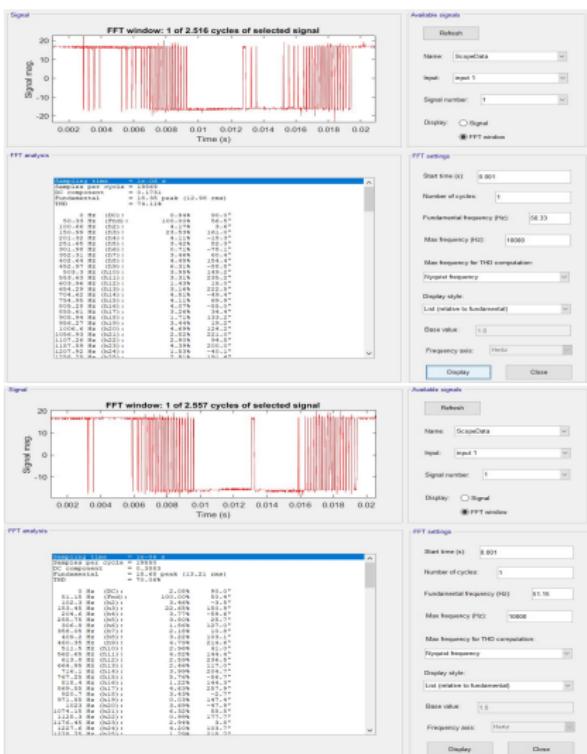
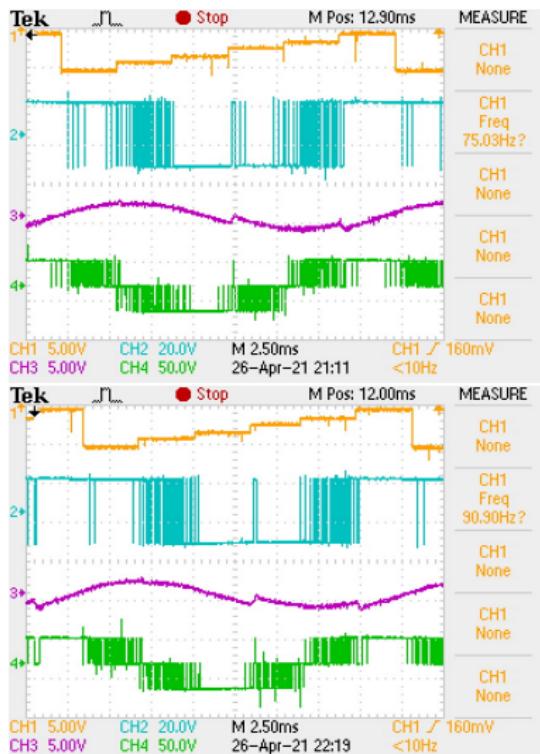


Figure: 0121 Sequence

121 SEQUENCE:



CONTINUE...:

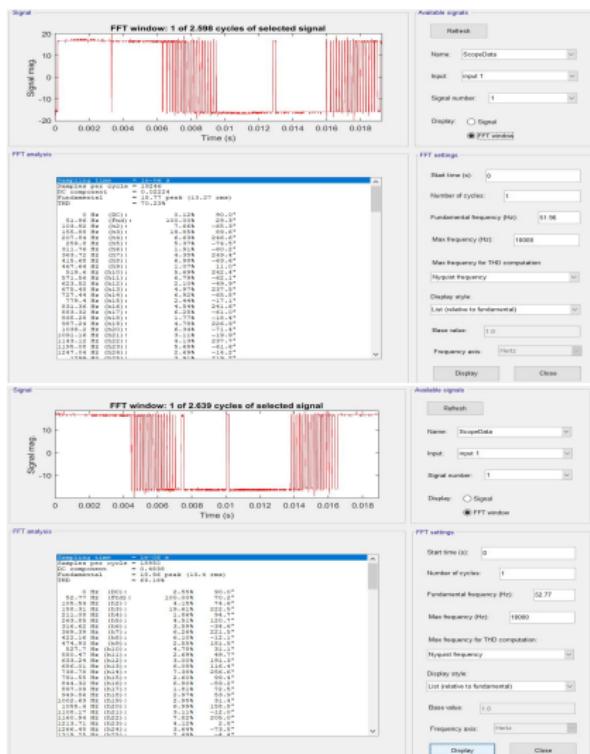
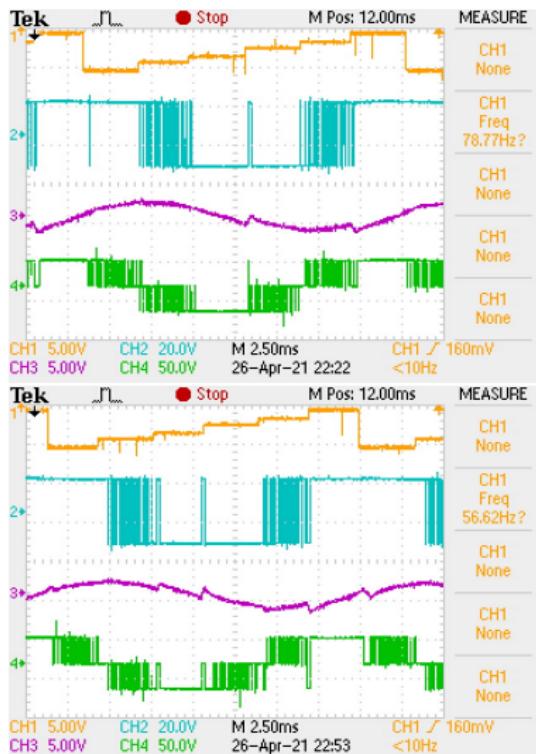


Figure: 121 Sequence

COMPARISON:

SEQUENCE		0127	012	721	0121
10 Hz	V	64.38	62.39	52.66	37.05
	THD	422.71	544.81	639.21	589.04
20 Hz	V	116	117.2	122.2	77.32
	THD	268.88	277.02	264.57	266.44
30 Hz	V	173.8	179.5	178.9	112.7
	THD	163.71	169.61	169.71	171.19
40 Hz	V	235.5	238.6	239.8	146.3
	THD	107.78	109.41	108.41	113.87
50 Hz	V	294.4	295.8	296.7	182.9
	THD	66.87	69.16	66.23	73.07

Table: Fundamental Voltage and its THD values for different sequences at different frequencies

CONTINUE...:

SEQUENCE		0127	012	721	0121
10 Hz	I	2.684	2.564	2.634	1.609
	THD	18.2	12.56	11.36	16.45
20 Hz	I	2.733	2.639	2.725	1.755
	THD	16.16	14.6	14.35	16.91
30 Hz	I	2.793	2.664	2.717	1.656
	THD	15.06	13.62	12.61	18.33
40 Hz	I	2.799	2.681	2.775	1.632
	THD	15.52	10.35	10.03	20.94
50 Hz	I	2.878	2.667	2.785	1.718
	THD	12.67	9.23	8.85	25.89

Table: Fundamental current and its THD values for different sequences at different frequencies

CONTINUE...:

V _{Ref}	Voltage	THD	Current	THD
290	295.6	66.62	2.696	8.28
295	302.4	62.57	2.657	9.94
302	308	57.54	2.589	11.8
305	315.6	56.43	2.838	15.64
310	318.6	53.3	2.703	20.16

Table: Fundamental voltage, current and Their THD values for 12 sequence in over-modulation at different reference voltages

V _{Ref}	Voltage	THD	Current	THD
186	183.5	74.11	1.604	22.17
189	189.8	70.06	1.573	29.19
192	187.7	70.23	1.732	24.33
195	189.6	69.16	1.653	23.66

Table: Fundamental voltage, current and Their THD values for 121 sequence in over-modulation at different reference voltages

FUTURE WORK:

- ▶ The unwanted pulses in over-modulation region get nullified to get better voltage and current waveforms.
- ▶ We can integrate this improved space vector PWM technique to Renewable energy resources also.

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Thank You