Perancangan *Zeta Converter* yang dilengkapi *Power Factor Correction* pada Aplikasi Pengaturan Kecepatan Motor *Brushless* DC

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General Outline

Pendahuluan

Penjelasan Sistem

Hasil dan Analisis

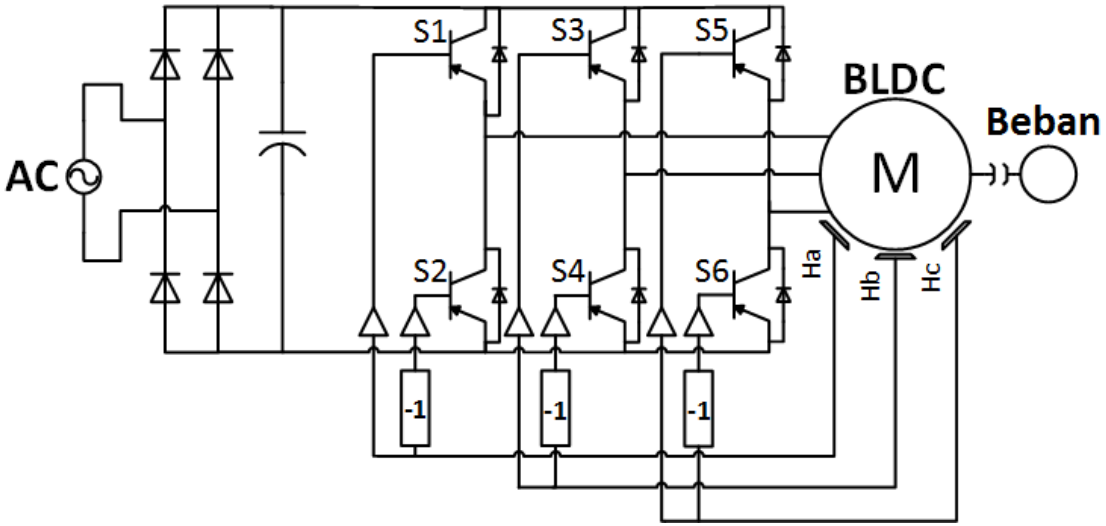
Pendahuluan

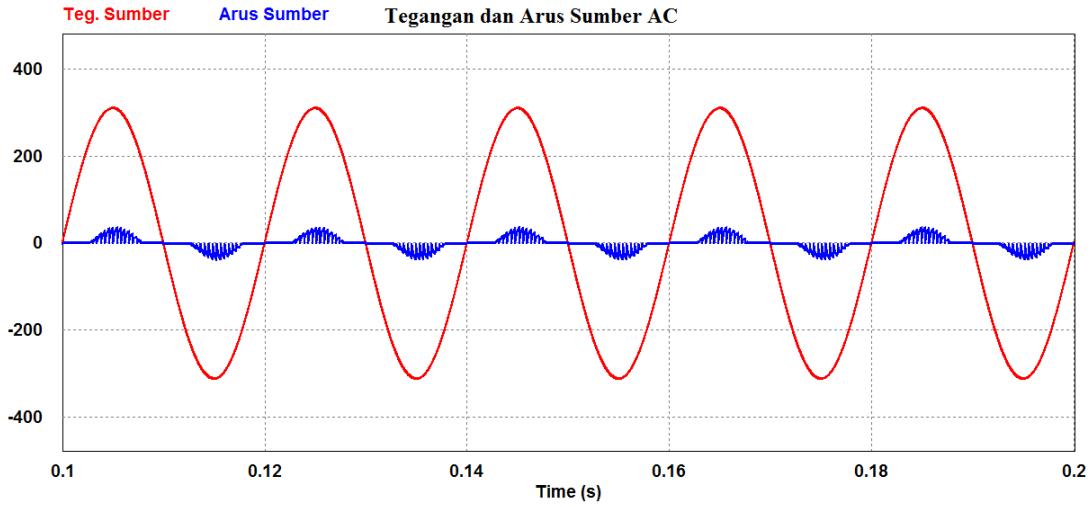
Preface

Latar Belakang

- Penggunaan Motor *Brushless* DC yang semakin banyak digunakan
- Pengoperasian dengan cara konvensional yang menyebabkan kurang baiknya kualitas daya
- Perbaikan kualitas daya dalam menggunakan metode yang baik pada pengaplikasiannya

Latar Belakang





Metode Konvensional

THD_i	73,33%
PF	0,803

Tujuan

- Performa dalam memperbaiki *power factor* dan mengurangi harmonisa arus
- Perbandingan mode operasi konverter
- Respon motor terhadap variasi kecepatan dan beban
- Perbandingan sistem kontrol PFC yang berbeda

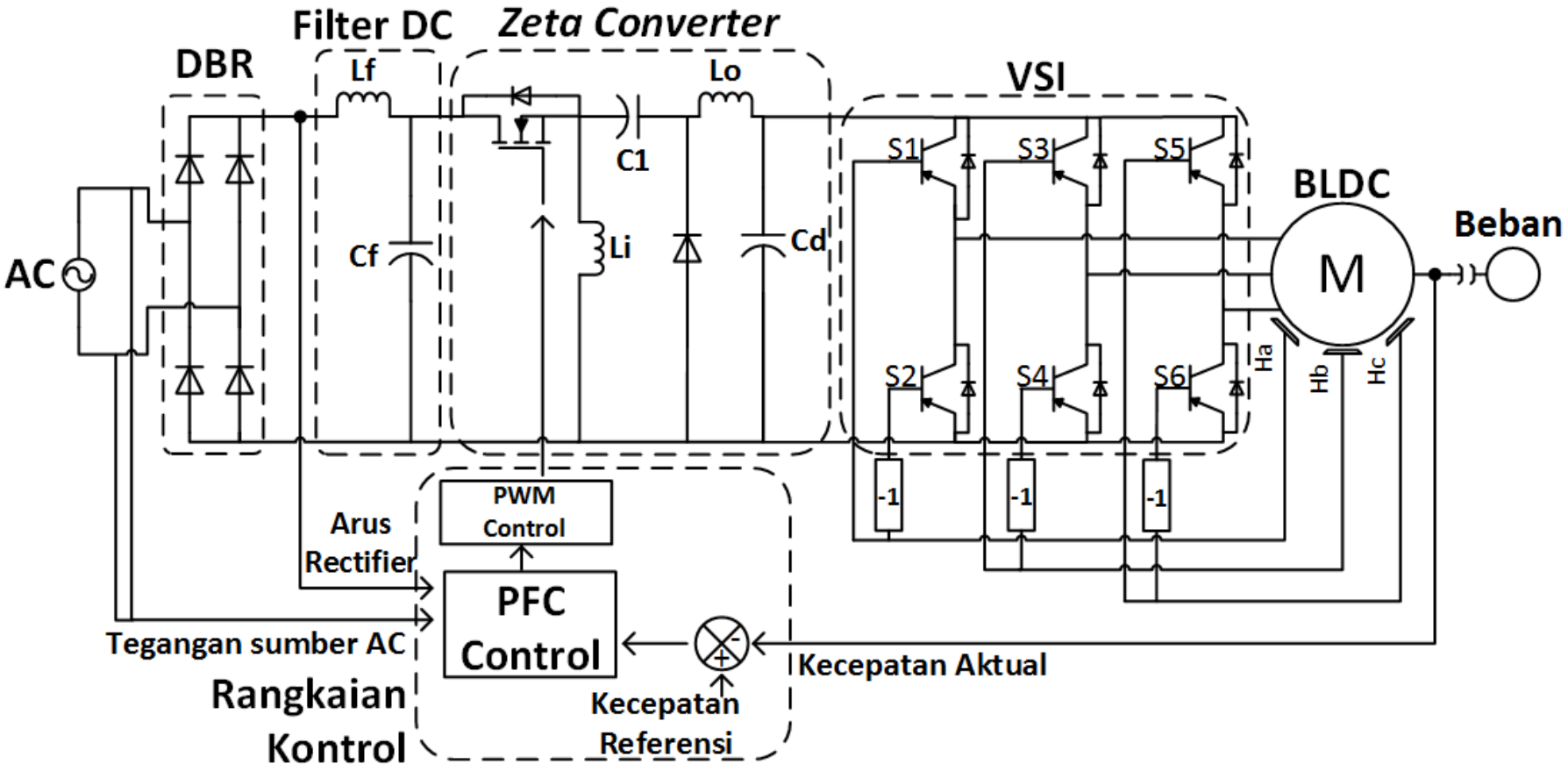
Batasan Masalah

- Simulasi dan analisis menggunakan simulator PSIM
- *Zeta Converter* digunakan pada mode DCM dan CCM dengan kontrol PFC *Average Current* dan *Hysteresis Current*
- Pengujian motor dengan kecepatan dan beban bervariasi pada kontrol PFC *Average Current*
- Performa dalam meningkatkan *power factor* dianalisa dari harmonisa yang telah direduksi

Penjelasan Sistem

System Explanation

Konfigurasi Sistem



Parameter Motor *Brushless* DC

MOOG Components BN42-53IP Winding Code 03

Parameter	Nilai
Voltage	100Vdc
Rated Power	874 W
No Load Speed	2920 rpm
Rated Speed	2820 rpm
Rated Current	10.2 A
Rated Torque	2.9588 Nm
Peak Torque	18.0744 Nm
Stall Torque	3.6649 Nm
R (resistansi terminal)	0.408Ω
L (induktansi terminal)	1.71mH
Torque Constant (Nm/amp)	0.3269
Speed Constant (rpm/V)	29.2397
No. of Poles (P)	8
Rotor Inertia	0.00049399 $kg.m^2$
Mech. Time Constant	1.9ms
Timing	120°

Parameter lainnya yang digunakan

Vs_{max}	220 V
Vs_{min}	180 V

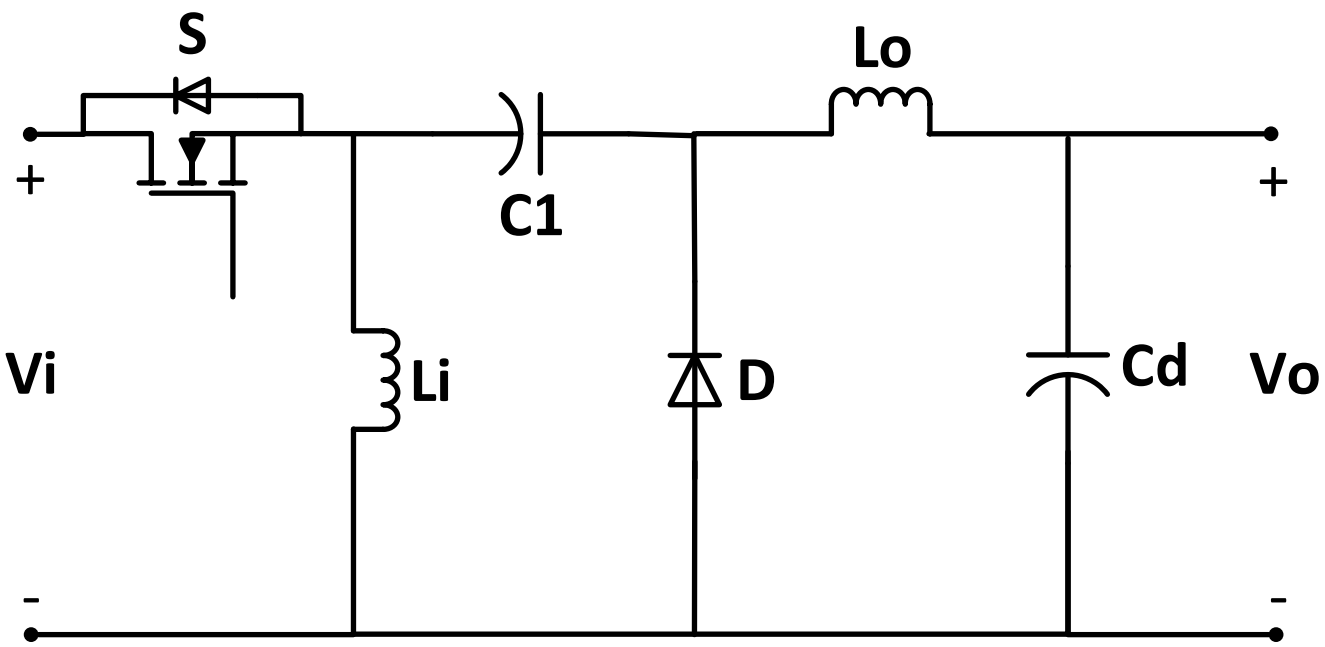
P_{max}	900 W
P_{min}	6,3 W

τ_{max}	2,9588 Nm
τ_{min}	0,5 Nm

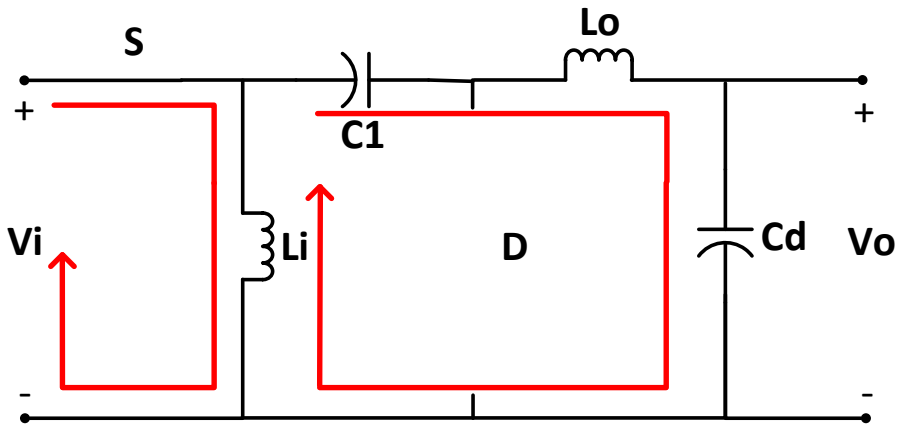
Vdc_{max}	100 V
Vdc_{min}	30 V

N_{max}	2500 rpm
N_{min}	750 rpm

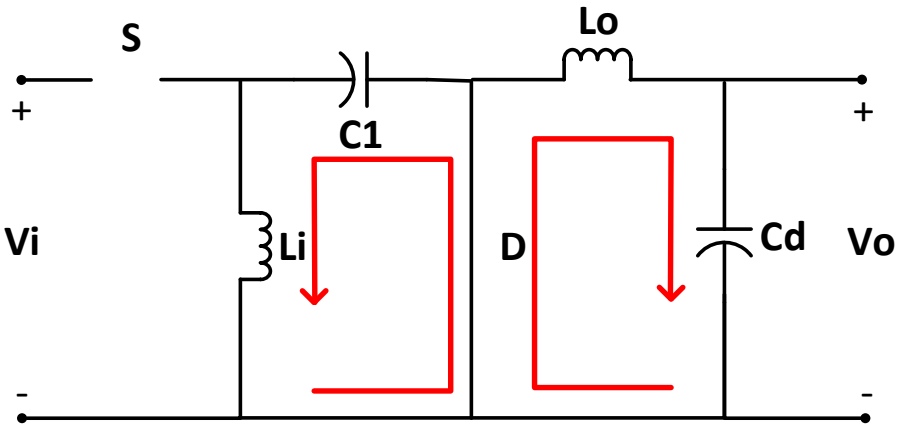
Zeta Converter



Zeta Converter



Kondisi ON



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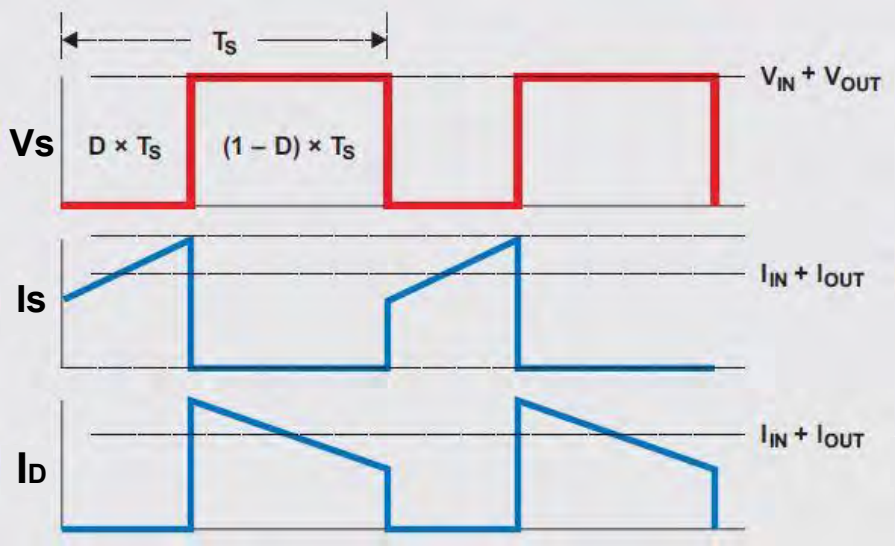
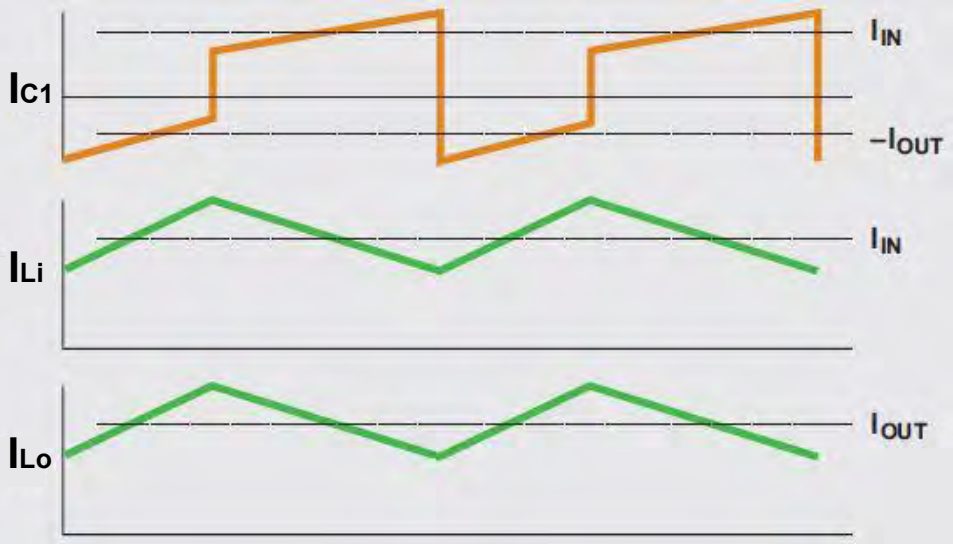




Perhitungan Komponen

Persamaan Komponen

$$Li = \frac{Vin.D}{\Delta I_{Li}.fs}$$

$$C_1 = \frac{Vdc.D}{\Delta V_{C1}.fs.R_L}$$

$$C_{f\,max} = \frac{I_m}{\omega.V_m}\tan(\theta)$$

$$Lo = \frac{V_{in}.D}{\Delta I_{Lo}.f_s}$$

$$C_d = \frac{Pi}{2.\pi.f.\Delta Vdc.Vdc}$$

$$L_f = \frac{1}{4.\pi^2.f_c^2.C_f}$$

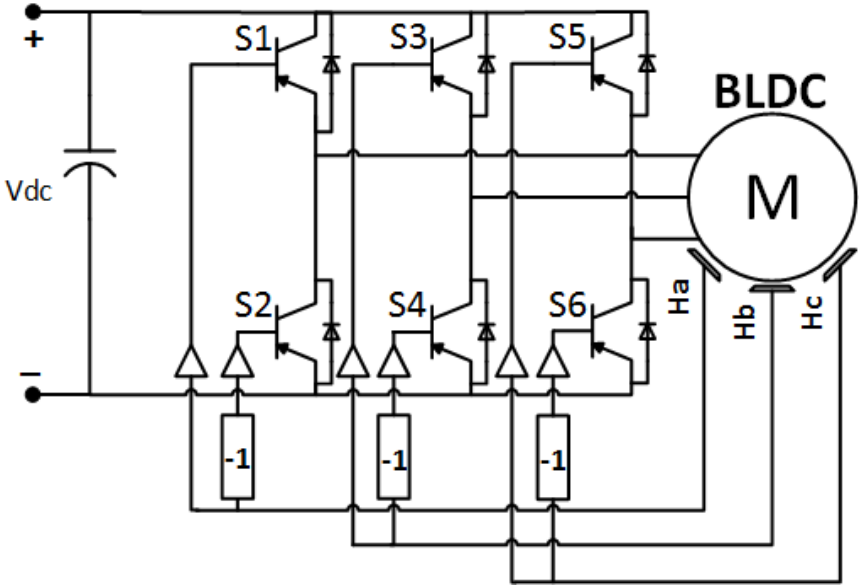
Perhitungan Komponen

Nilai Komponen

Li ccm = 3,7143mH
Li dcm = 40µH
Lo= 2.291mH
C_1= 4,05µF
C_d = 5,732mF

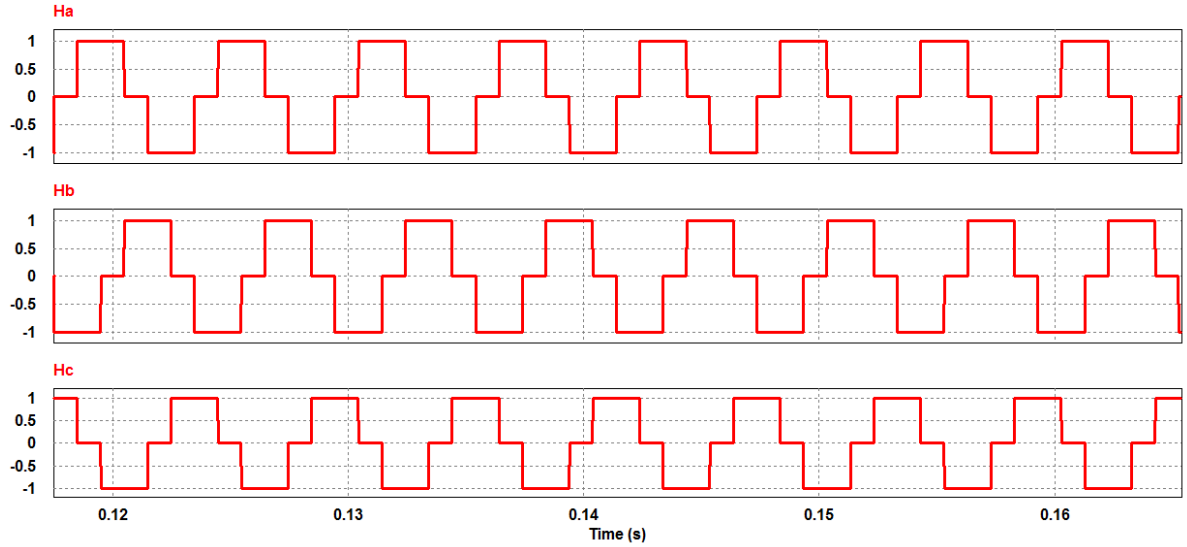
C_f = 300nF
L_f =21.13mH

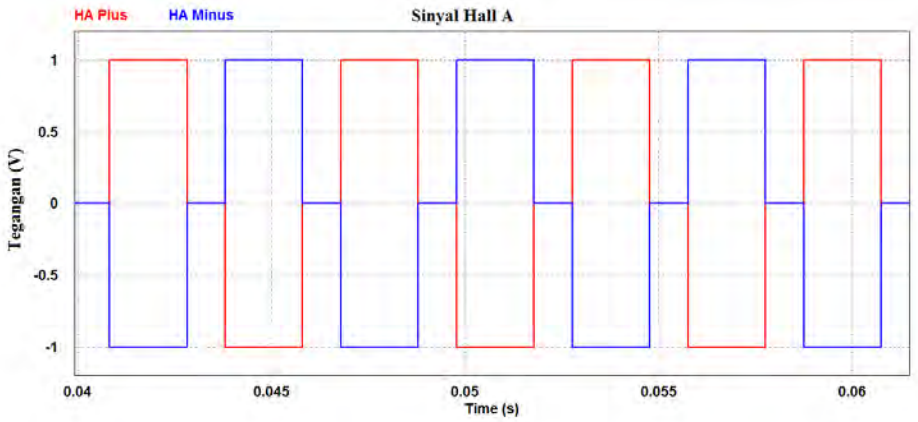
Model Kontrol Logika Motor terhadap VSI

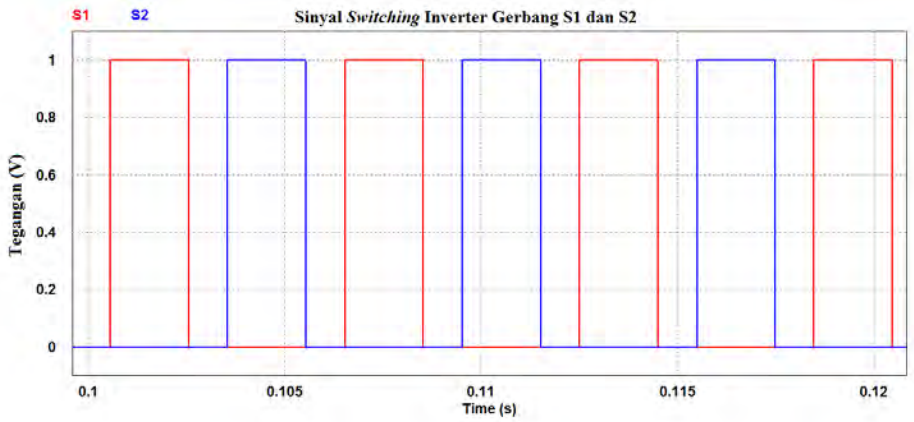


Sudut	Ha	Hb	Hc	S1	S2	S3	S4	S5	S6
0-60	0	-1	1	0	0	0	1	1	0
60-120	1	-1	0	1	0	0	1	0	0
120-180	1	0	-1	1	0	0	0	0	1
180-240	0	1	-1	0	0	1	0	0	1
240-300	-1	1	0	0	1	1	0	0	0
300-360	-1	0	1	0	1	0	0	1	0

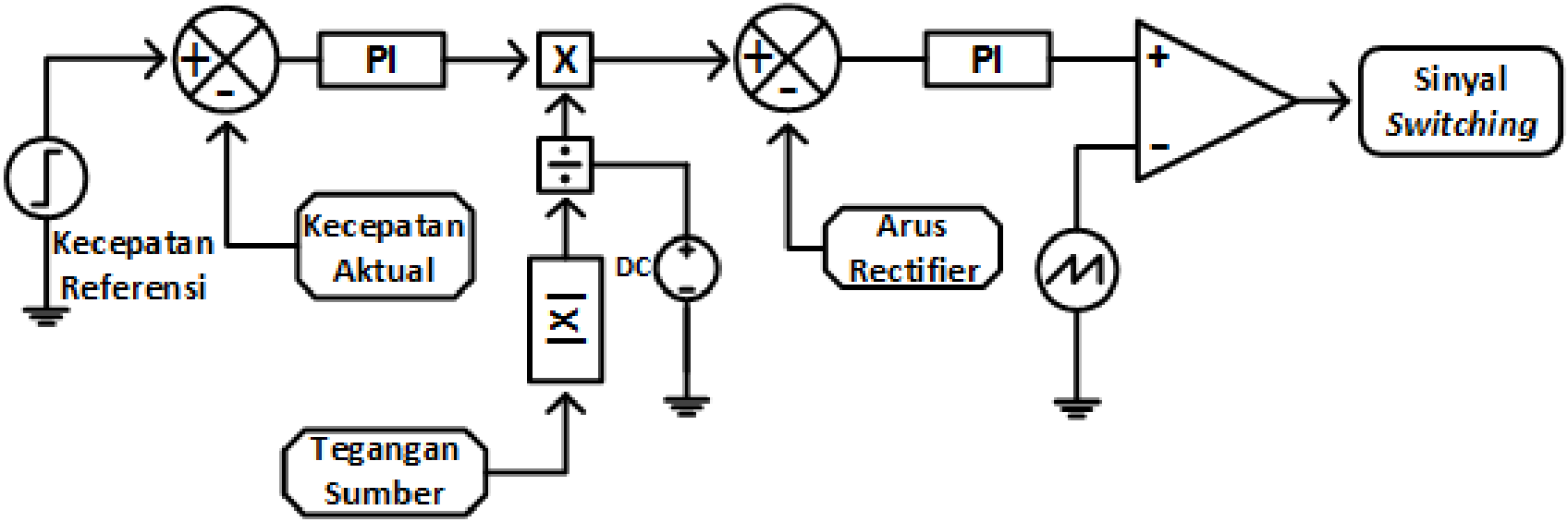
Model Kontrol Logika Motor terhadap VSI





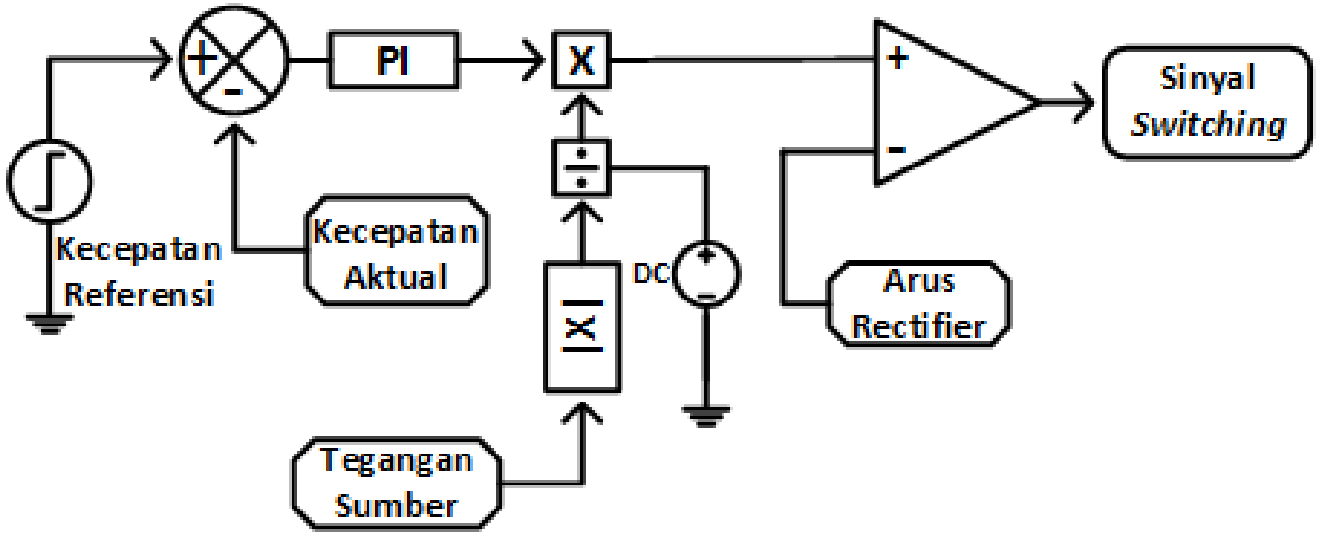


Sistem Kontrol PFC



Average Current Control

Sistem Kontrol PFC

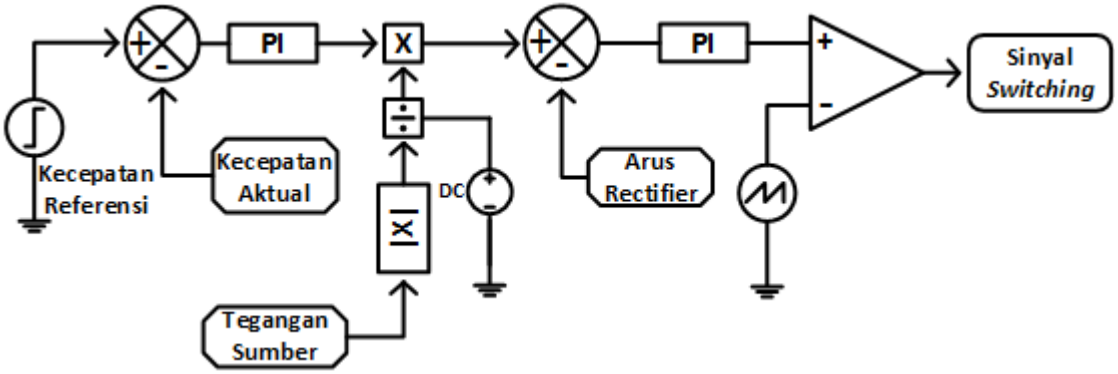


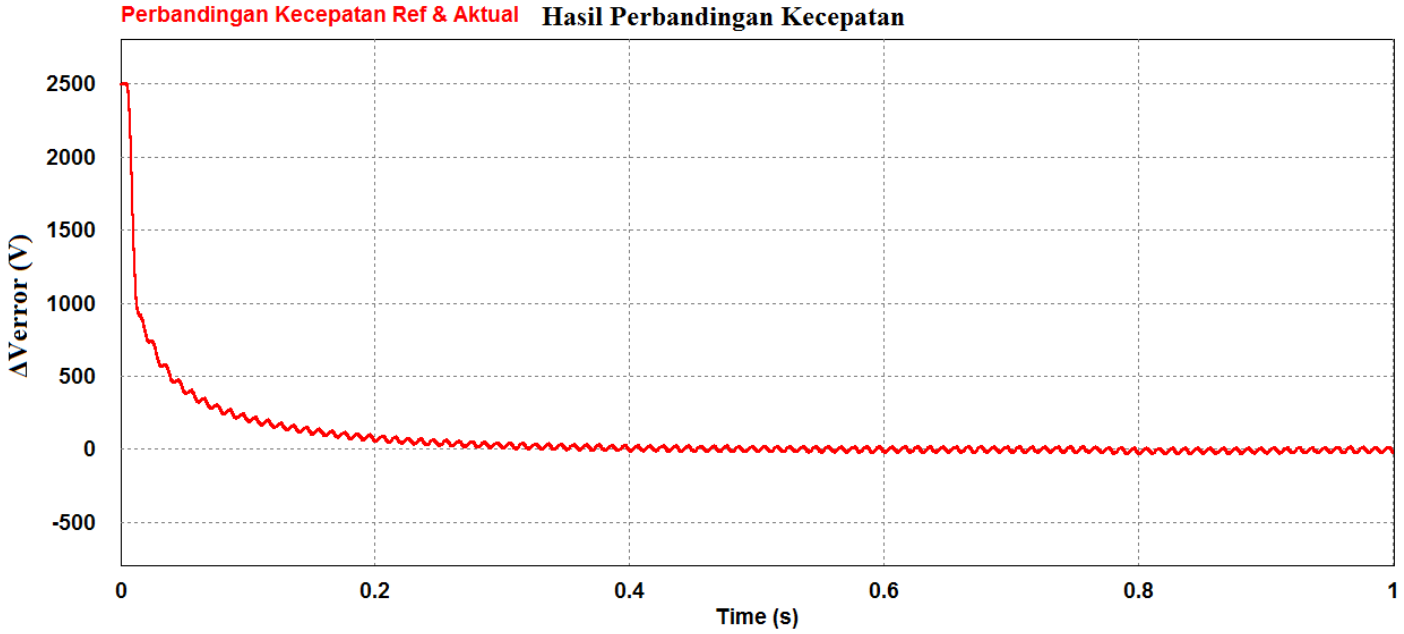
Hysteresis Current Control

Hasil dan Analisis

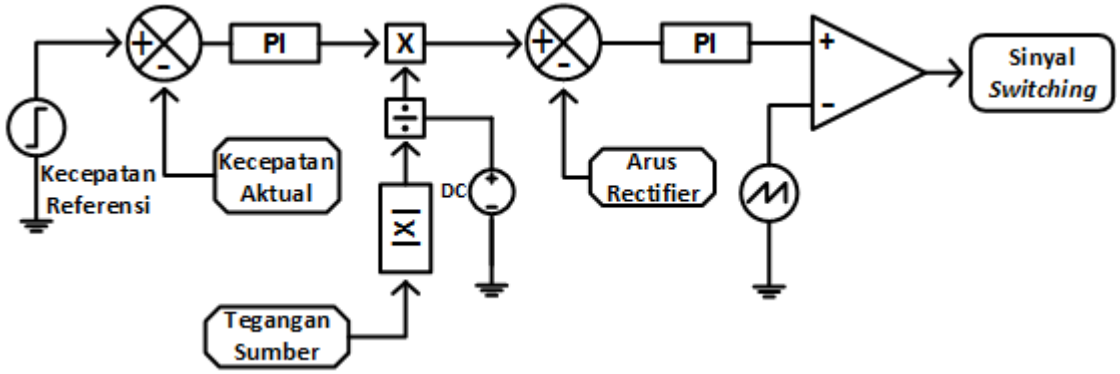
Results and Analysis

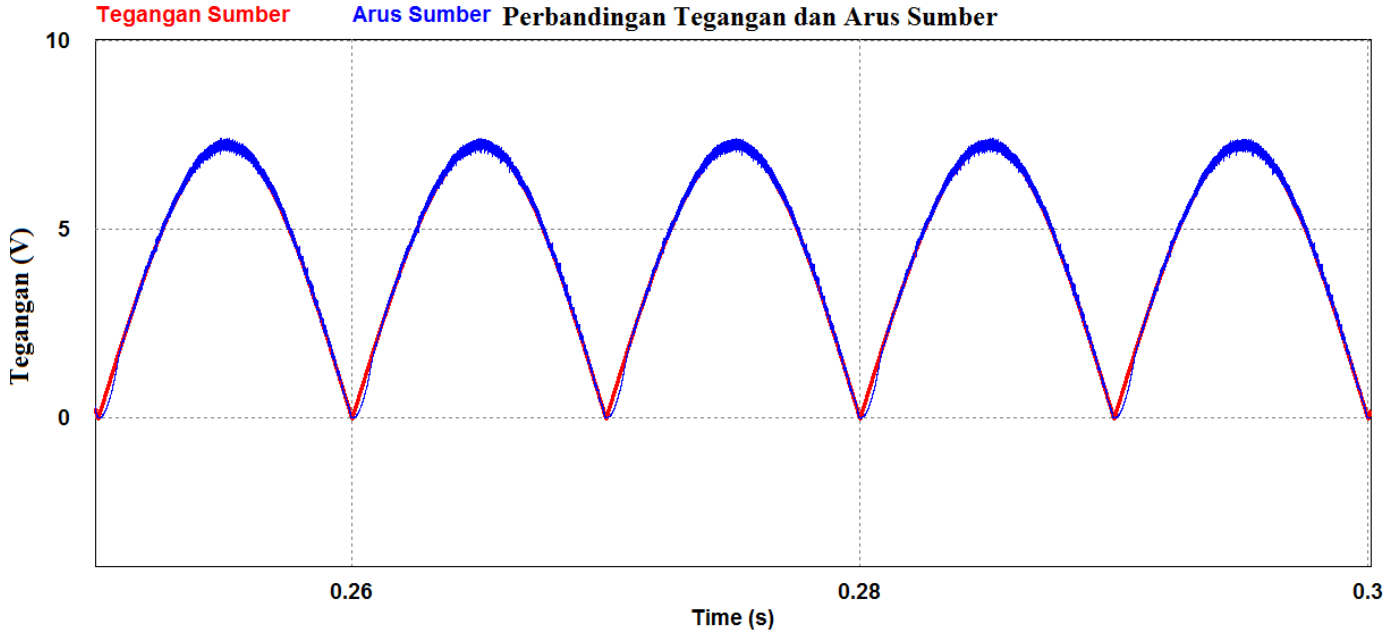
Analisis Sistem Kontrol



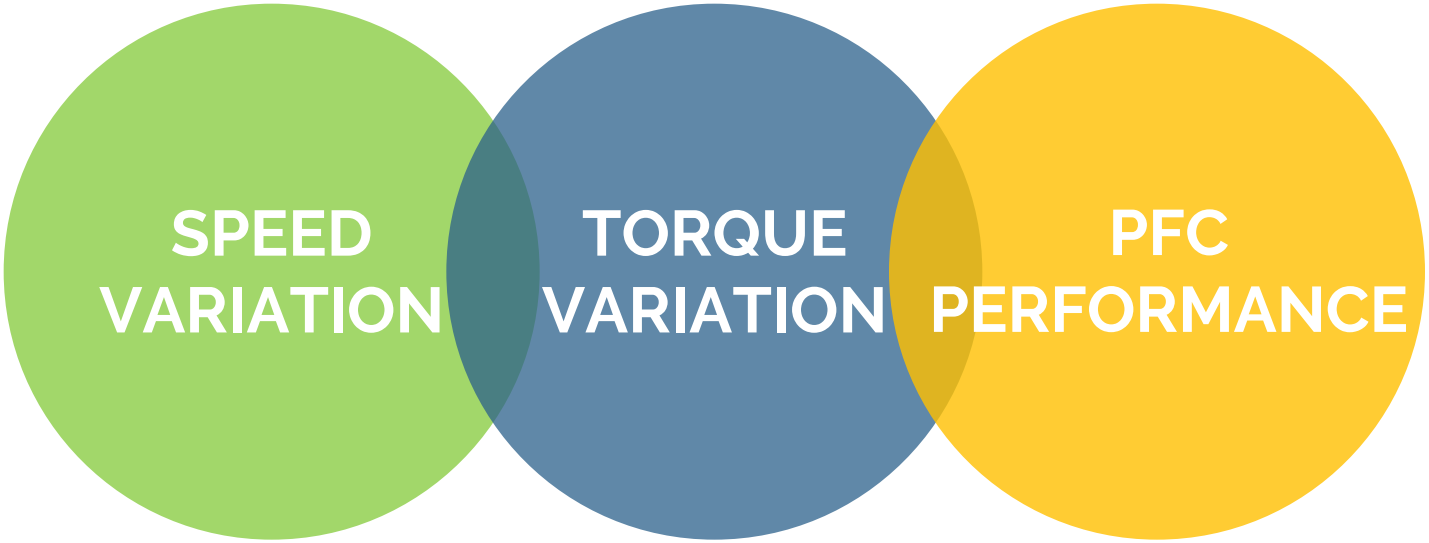


Analisis Sistem Kontrol





Pengujian Sistem

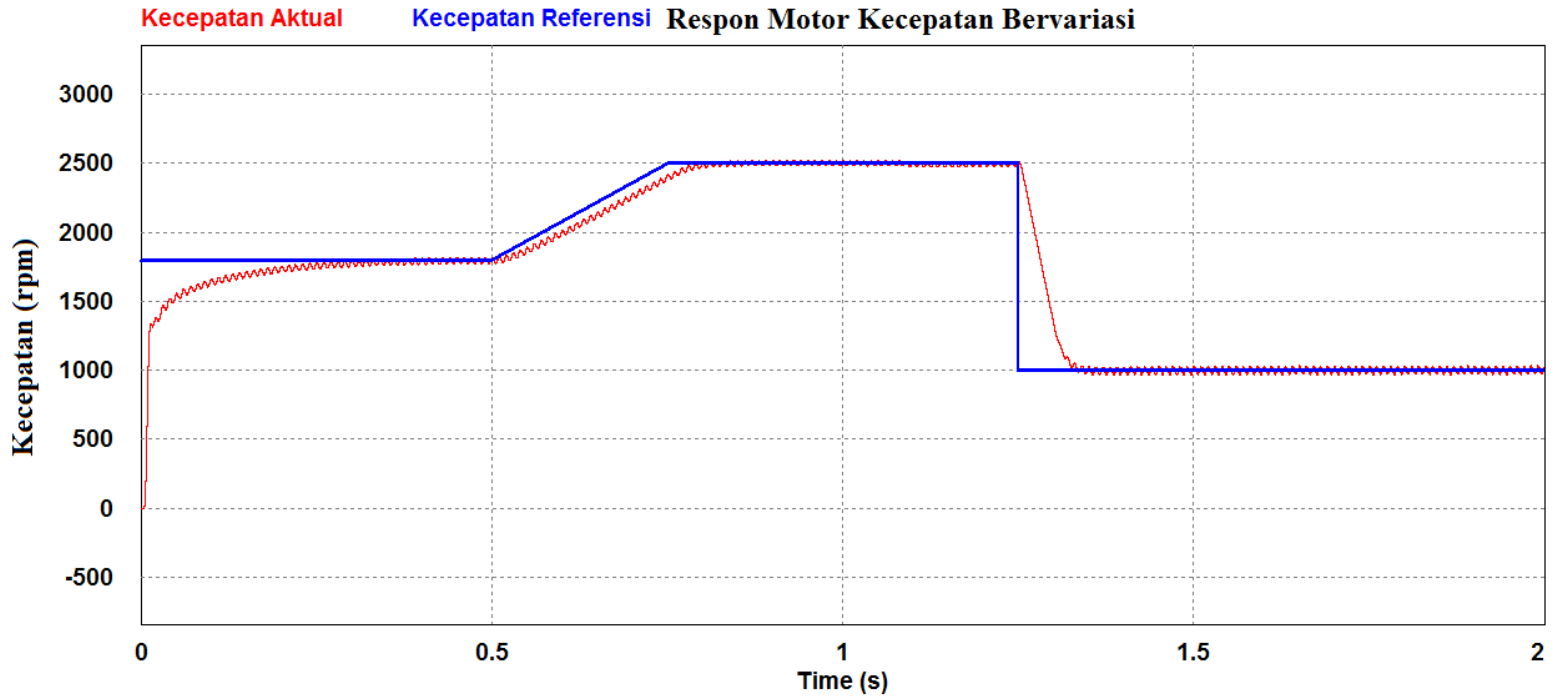


Pengujian Kontrol Kecepatan Motor

Mode DCM (Variasi Kecepatan)

Waktu	Kecepatan Referensi
0 – 0,5 sekon	1800 rpm
0,75 – 1,25 sekon	2500 rpm
1,25 – 2 sekon	1000 rpm

Perubahan	Waktu
1800 ke 2500 rpm	0,075 sekon
2500 ke 1000 rpm	0,1 sekon

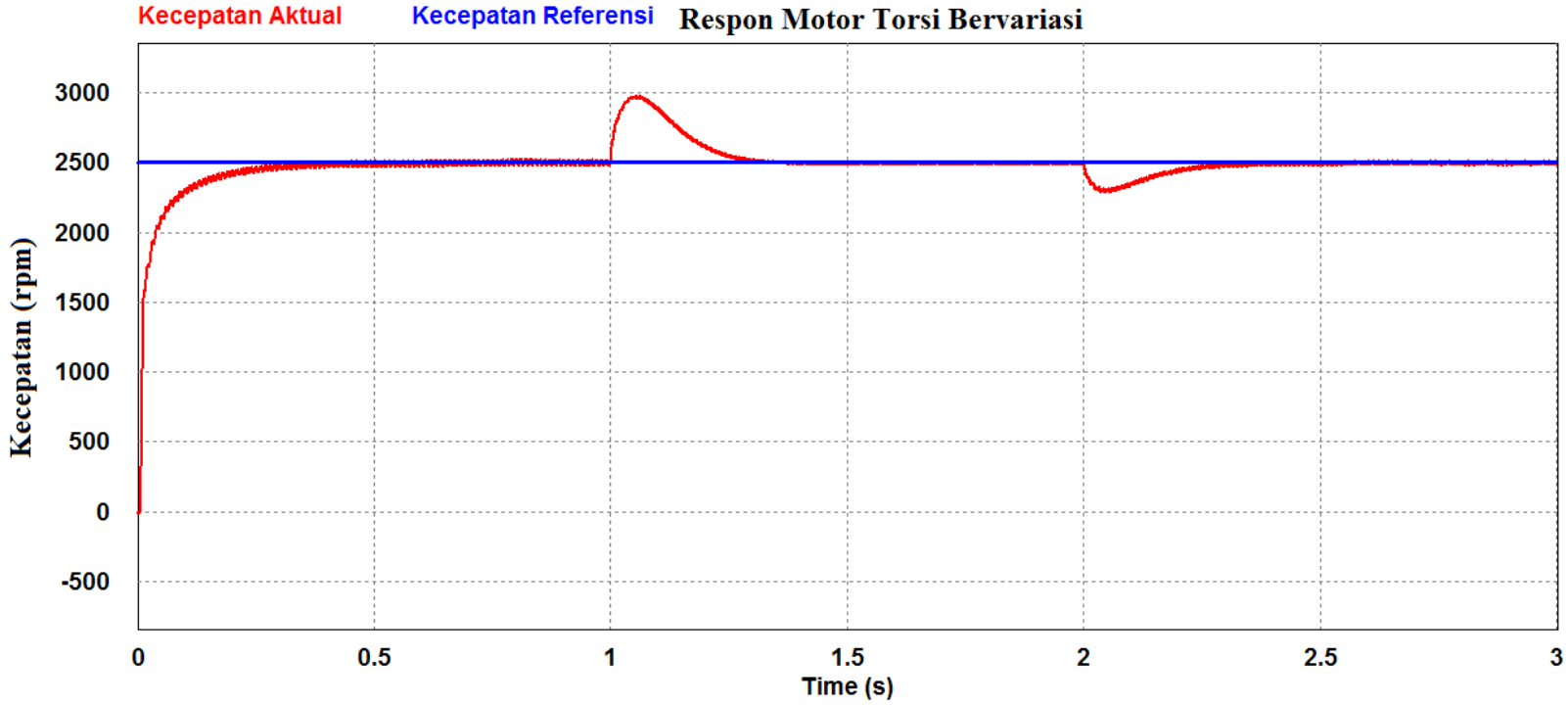


Pengujian Kontrol Kecepatan Motor

Mode DCM (Variasi Beban)

Waktu	Torsi Beban
0 – 1 sekon	2,9588 Nm
1 – 2 sekon	0,5 Nm
2 – 3 sekon	1,5 Nm

Perubahan	Waktu
2,9588 ke 0,5 Nm	0,45 sekon
0,5 ke 1,5 Nm	0,475 sekon

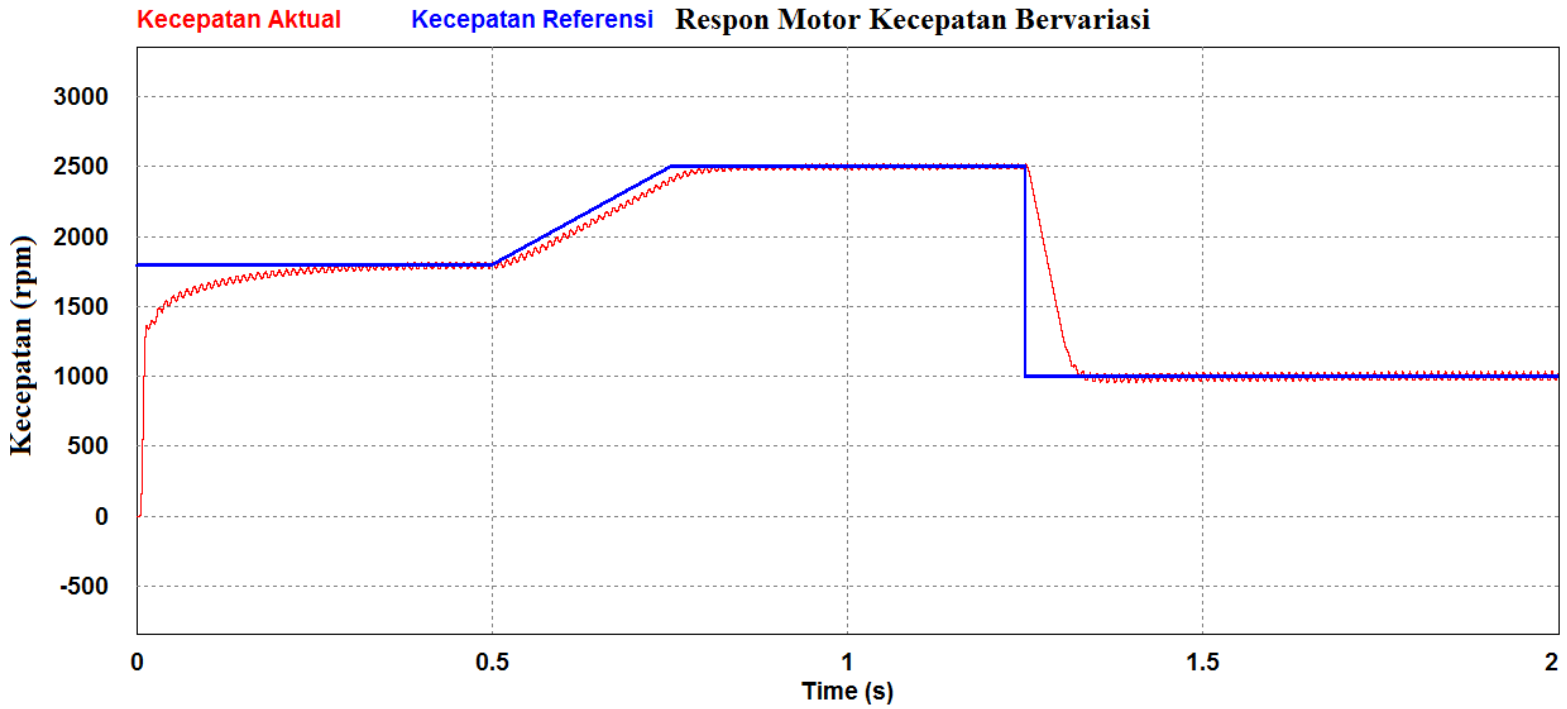


Pengujian Kontrol Kecepatan Motor

Mode CCM (Variasi Kecepatan)

Waktu	Kecepatan Referensi
0 – 0,5 sekon	1800 rpm
0,75 – 1,25 sekon	2500 rpm
1,25 – 2 sekon	1000 rpm

Perubahan	Waktu
1800 ke 2500 rpm	0,075 sekon
2500 ke 1000 rpm	0,1 sekon

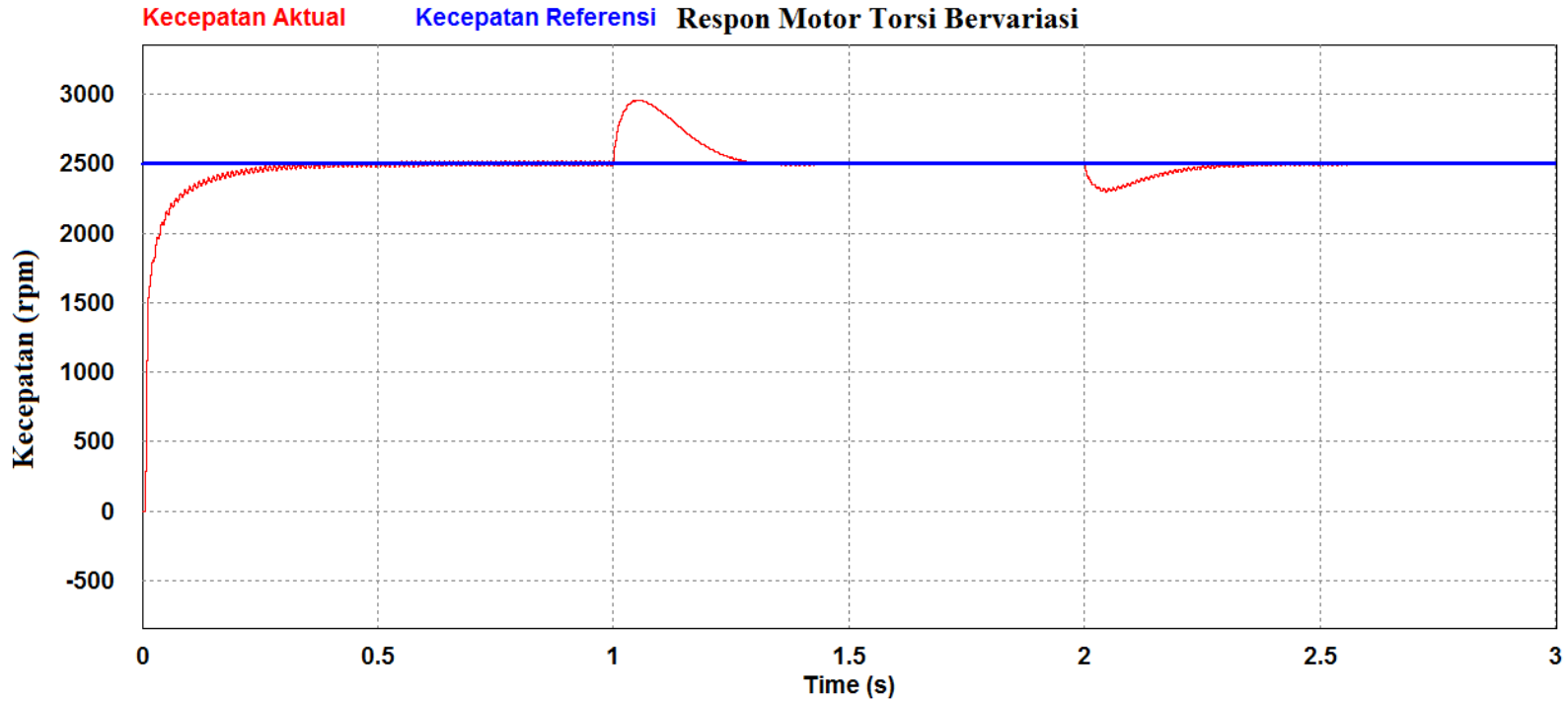


Pengujian Kontrol Kecepatan Motor

Mode CCM (Variasi Beban)

Waktu	Torsi Beban
0 – 1 sekon	2,9588 Nm
1 – 2 sekon	0,5 Nm
2 – 3 sekon	1,5 Nm

Perubahan	Waktu
2,9588 ke 0,5 Nm	0,35 sekon
0,5 ke 1,5 Nm	0,4 sekon



Pengujian Performa PFC

- Kecepatan bervariasi

Average Current Control

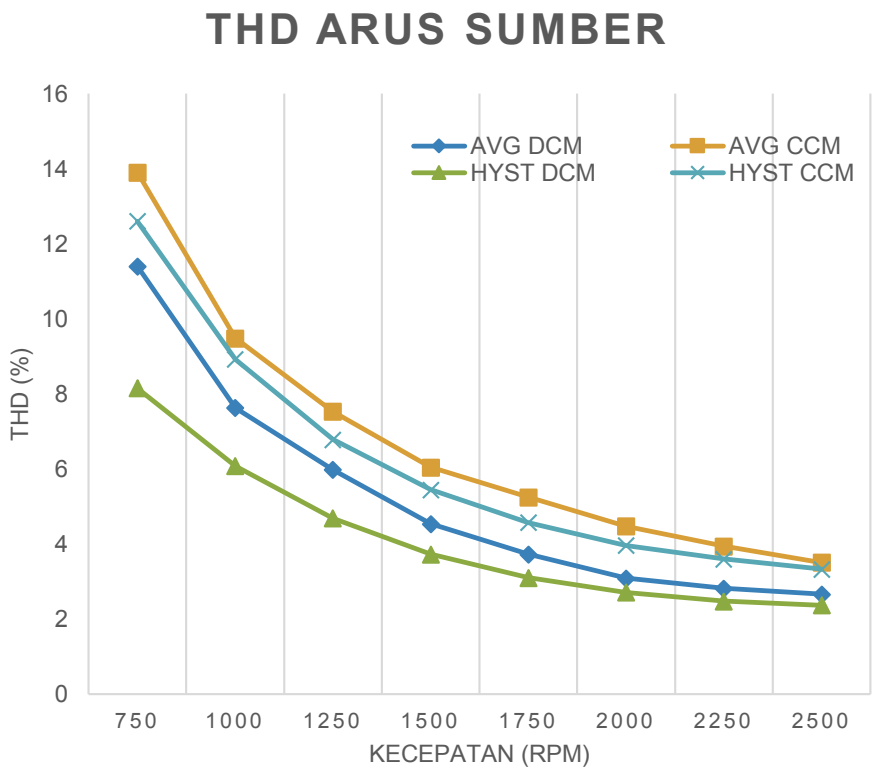
Kecepatan (rpm)	DCM		CCM	
	THDi (%)	PF_{true}	THDi (%)	PF_{true}
750	11.4	0.9916	13.9	0.9876
1000	7.63	0.9963	9.48	0.994
1250	5.98	0.9977	7.53	0.9965
1500	4.54	0.9986	6.04	0.9977
1750	3.73	0.999	5.25	0.9983
2000	3.09	0.9993	4.47	0.9987
2250	2.82	0.9994	3.94	0.999
2500	2.66	0.9995	3.51	0.9991

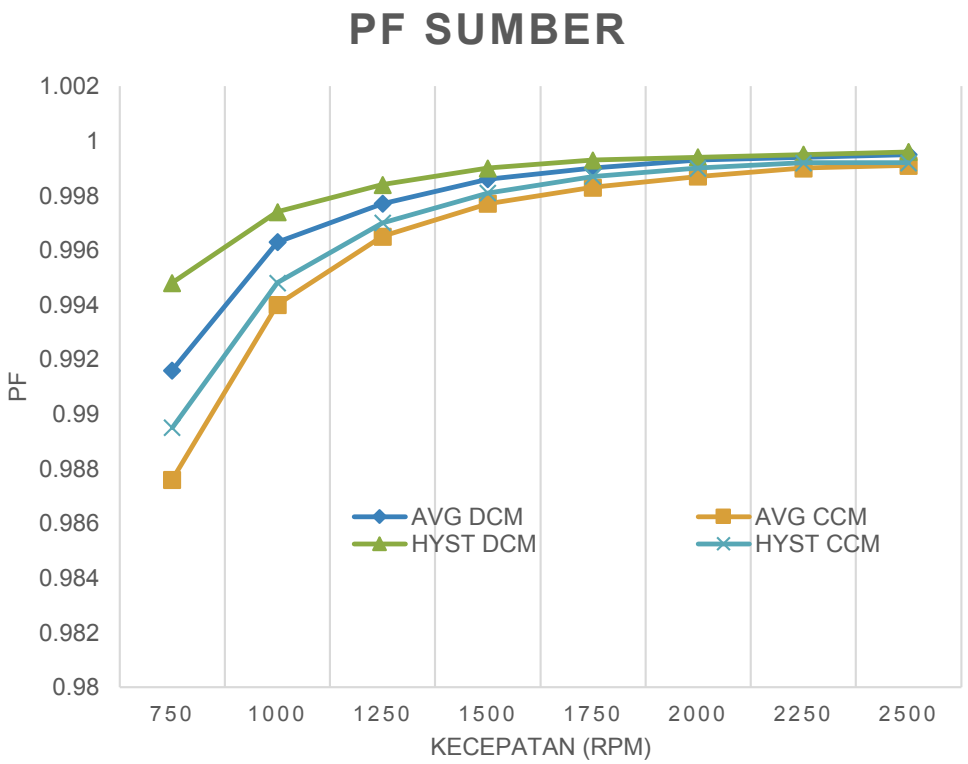
Hysteresis Current Control

Kecepatan (rpm)	DCM		CCM	
	THDi (%)	PF_{true}	THDi (%)	PF_{true}
750	8.15	0.9948	12.6	0.9895
1000	6.08	0.9974	8.92	0.9948
1250	4.69	0.9984	6.78	0.997
1500	3.73	0.9990	5.45	0.9981
1750	3.1	0.9993	4.57	0.9987
2000	2.71	0.9994	3.96	0.999
2250	2.48	0.9995	3.6	0.9992
2500	2.37	0.9996	3.33	0.9992

Pengujian Performa PFC

- Kecepatan bervariasi





Pengujian Performa PFC

- Tegangan sumber bervariasi

Average Current Control

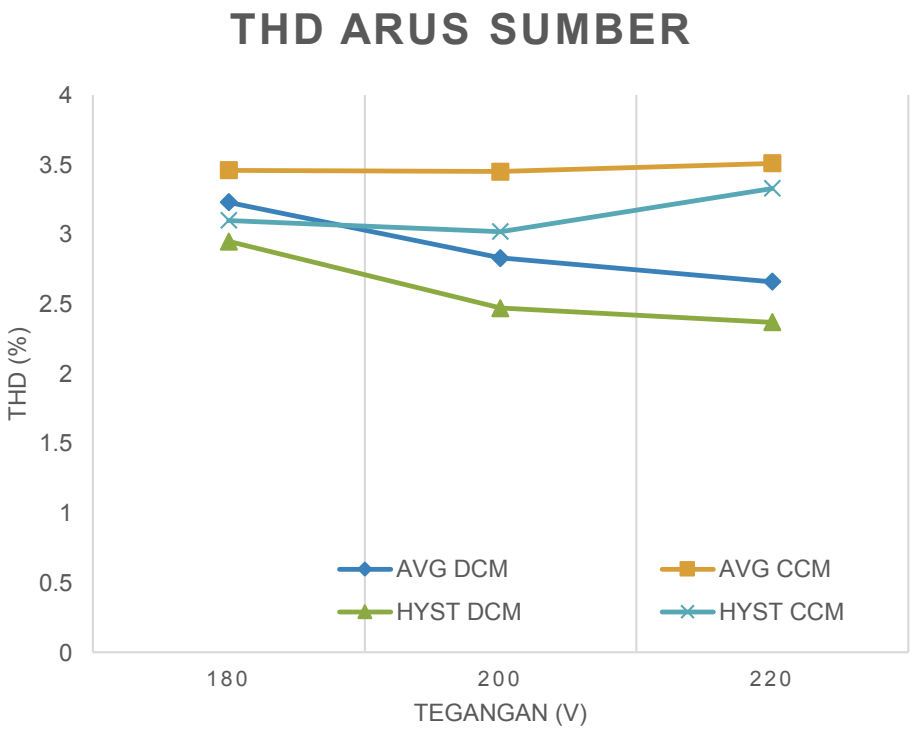
Tegangan (V)	DCM		CCM	
	THDi (%)	PF_{true}	THDi (%)	PF_{true}
180	3.23	0.9991	3.46	0.9991
200	2.83	0.9994	3.45	0.9992
220	2.66	0.9995	3.51	0.9991

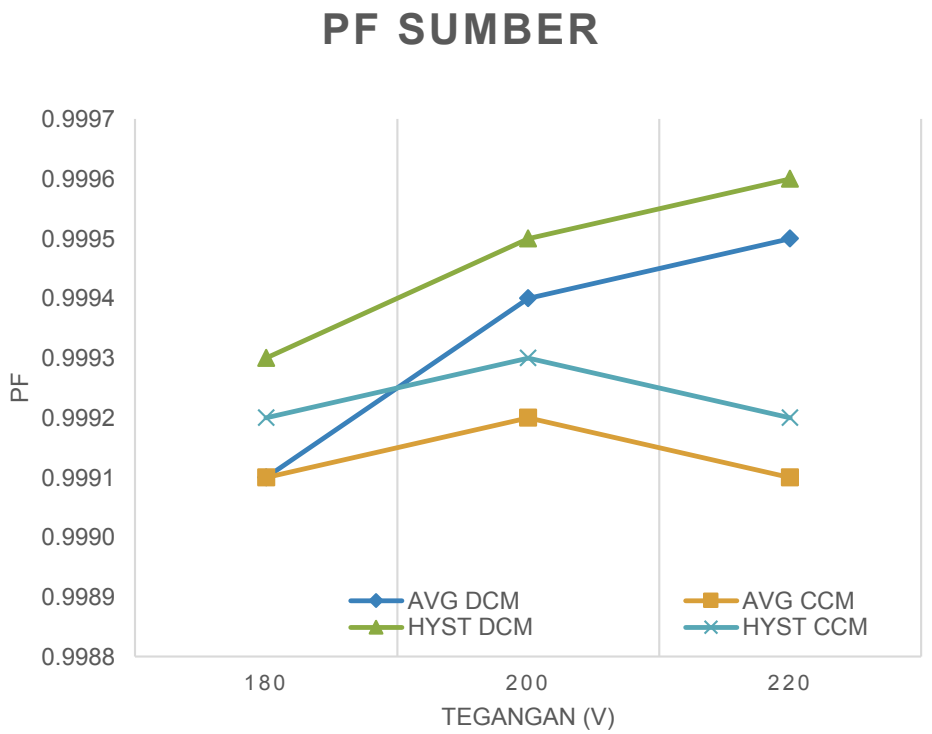
Hysteresis Current Control

Tegangan (V)	DCM		CCM	
	THDi (%)	PF_{true}	THDi (%)	PF_{true}
180	2.95	0.9993	3.1	0.9992
200	2.47	0.9995	3.02	0.9993
220	2.37	0.9996	3.33	0.9992

Pengujian Performa PFC

- Tegangan sumber bervariasi





Kesimpulan

Sistem ini dapat memperbaiki kualitas daya dari nilai THD sebesar 73,33% dan *power factor* sebesar 0,803 menjadi nilai THD berkisar antara 2-3% dan *power factor* hingga 0,999.

Pengujian sistem pengaturan kecepatan motor *brushless* DC dengan kecepatan referensi yang bervariasi dapat berjalan dengan baik karena putaran motor dapat mengikuti kecepatan referensi.

Pengoperasian motor pada kecepatan yang konstan tetap stabil pada pembebanan yang bervariasi.

Mode DCM lebih unggul dalam memperbaiki *power factor* dibandingkan dengan mode CCM. Tetapi saat pengaturan kecepatan motor, mode DCM memiliki respon lebih lambat

Metode kontrol PFC *hysterisis current* dapat mereduksi harmonisa arus sedikit lebih baik dibandingkan kontrol PFC *average current*

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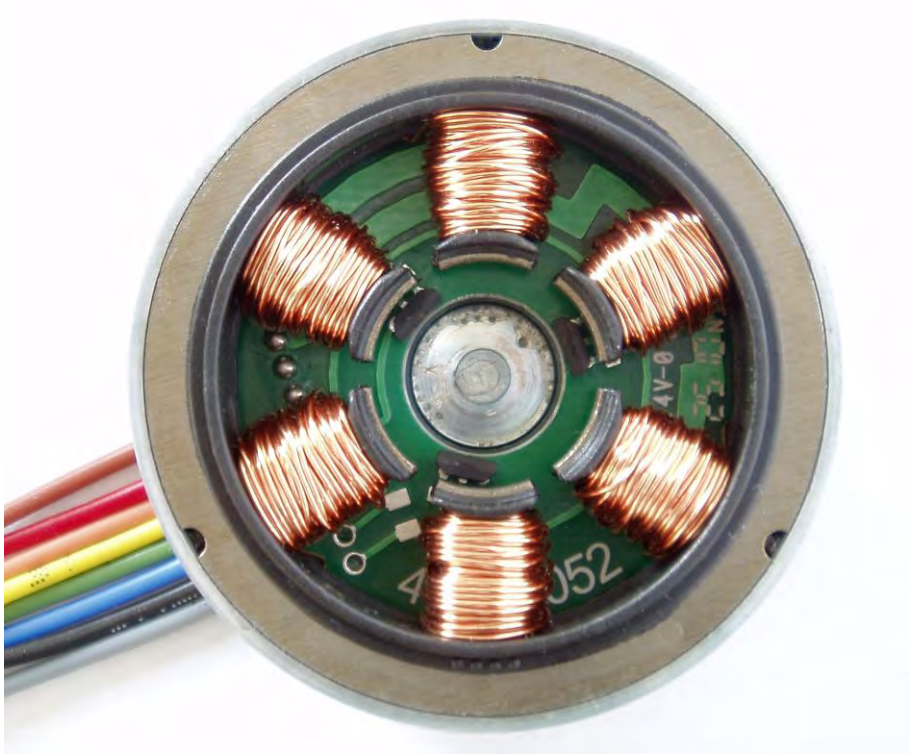
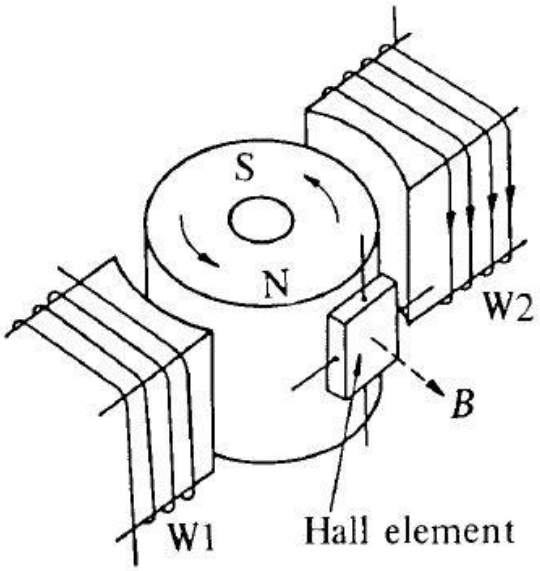
Terima kasih!

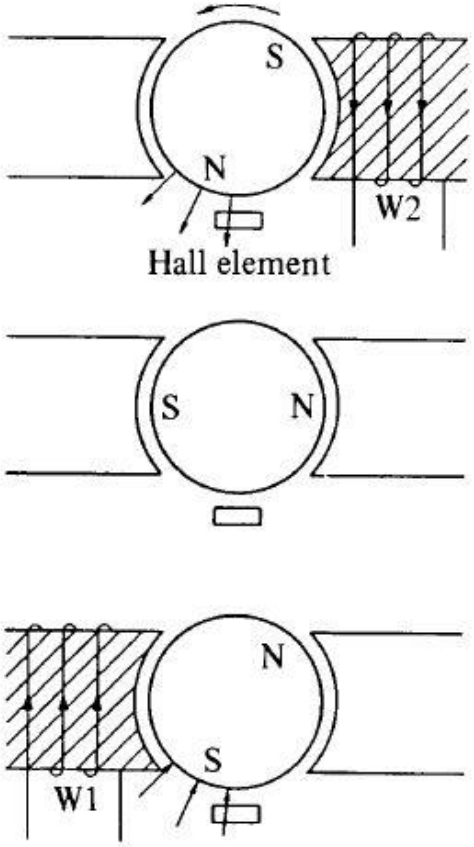
Any questions?

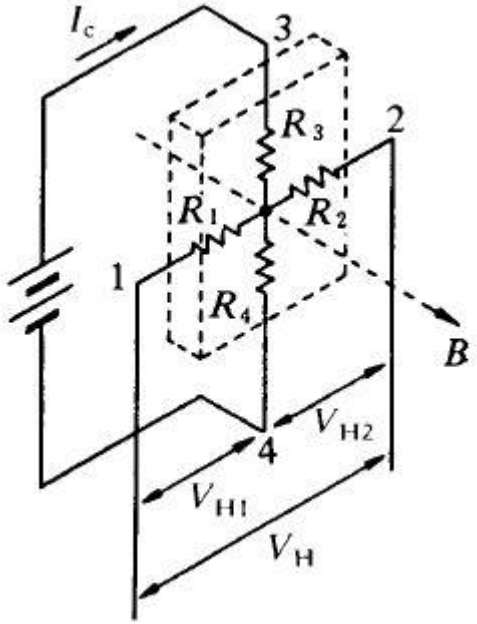
Motor *Brushless* DC

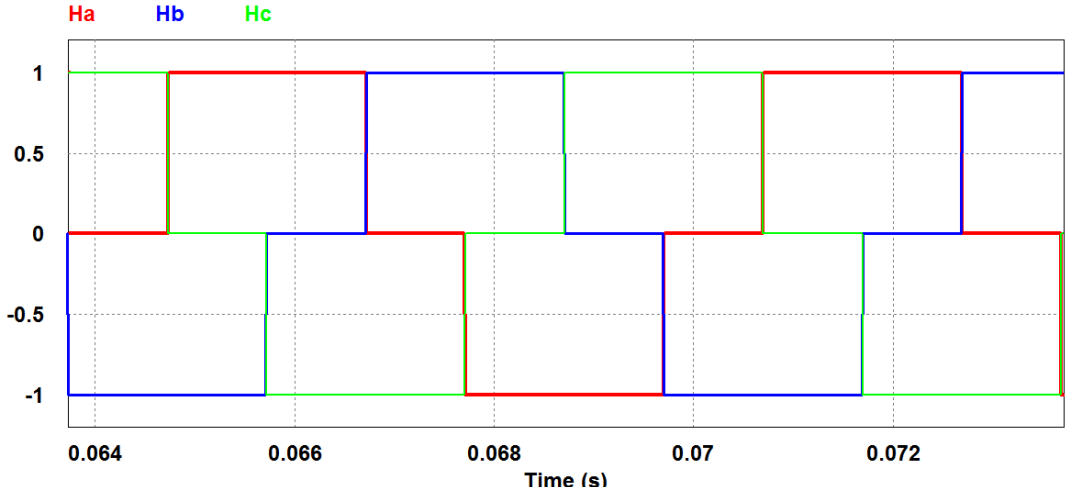


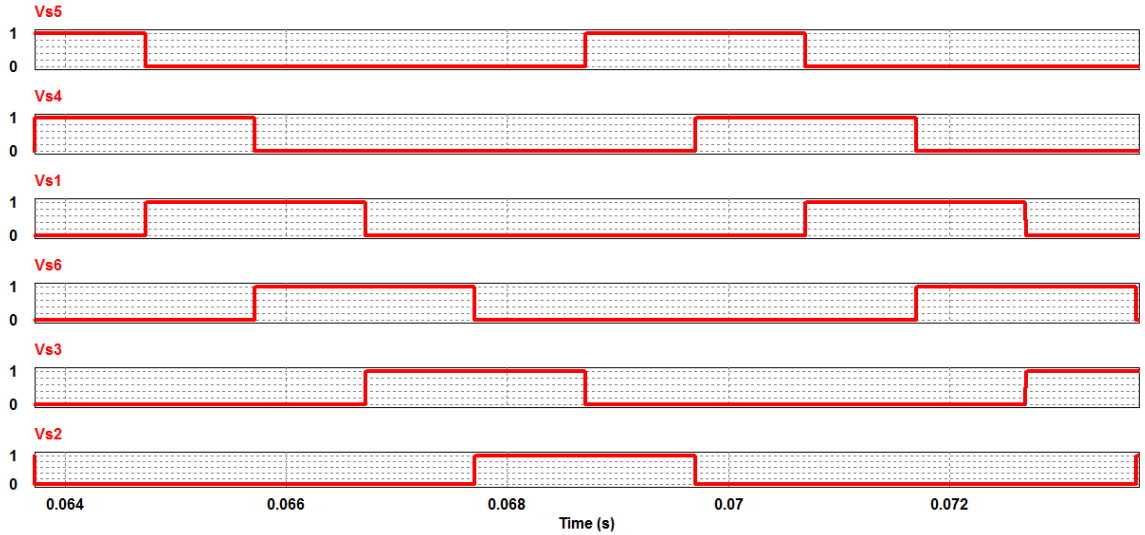
Hall Element



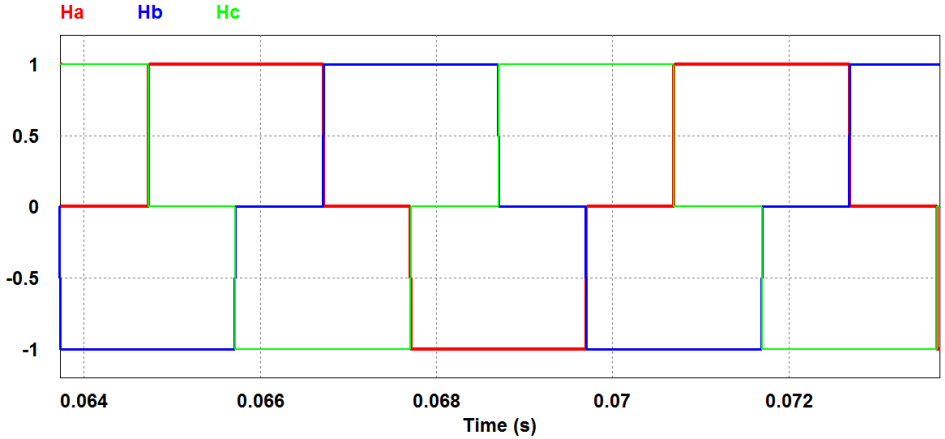




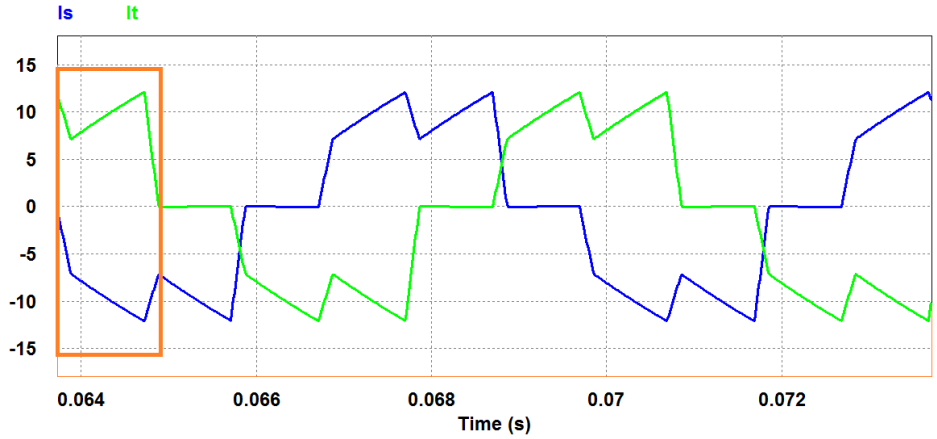


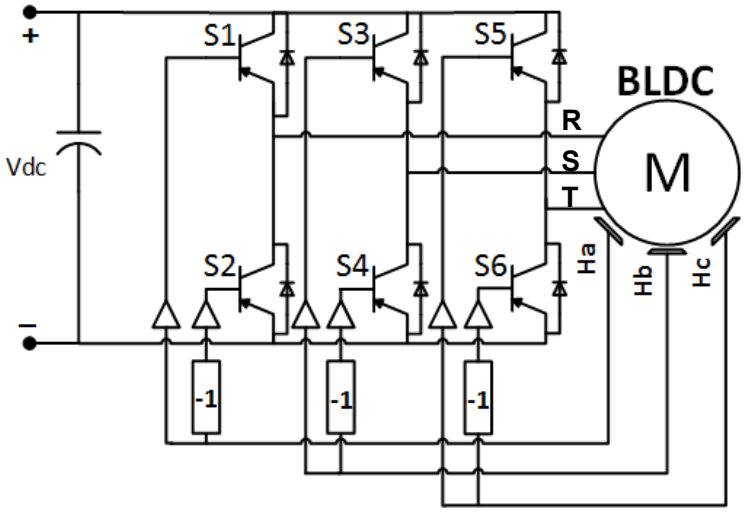


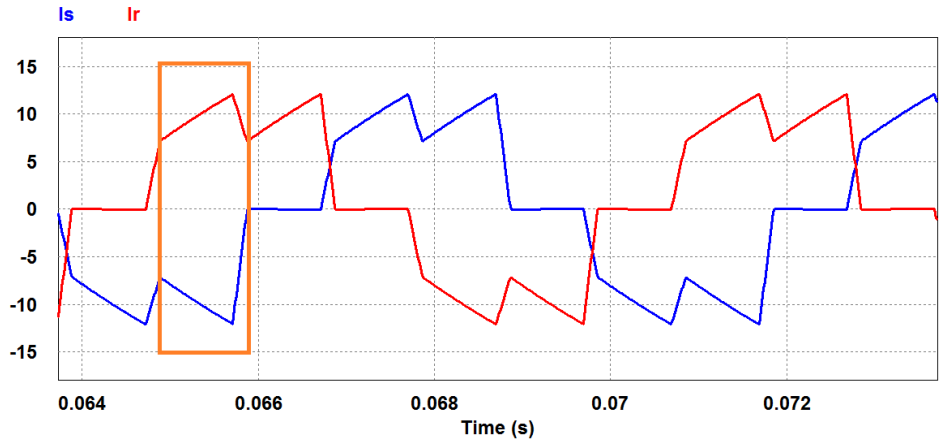
Sudut	Ha	Hb	Hc	S1	S2	S3	S4	S5	S6
0-60	0	-1	1	0	0	0	1	1	0
60-120	1	-1	0	1	0	0	1	0	0
120-180	1	0	-1	1	0	0	0	0	1
180-240	0	1	-1	0	0	1	0	0	1
240-300	-1	1	0	0	1	1	0	0	0
300-360	-1	0	1	0	1	0	0	1	0

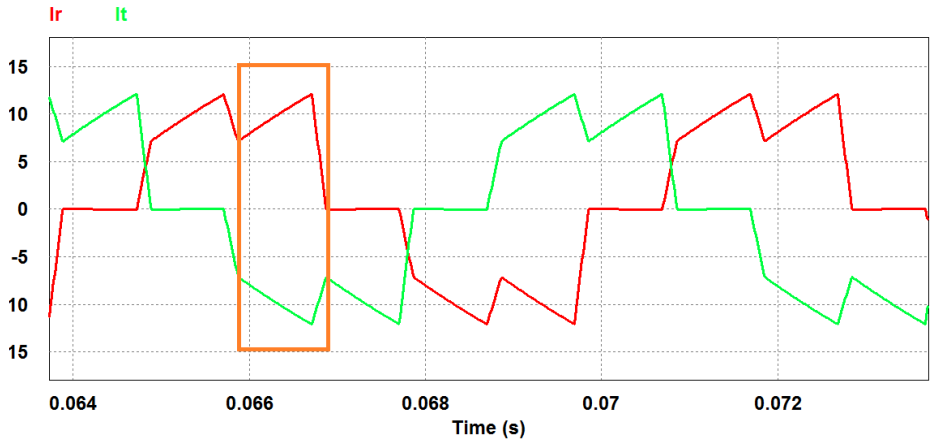


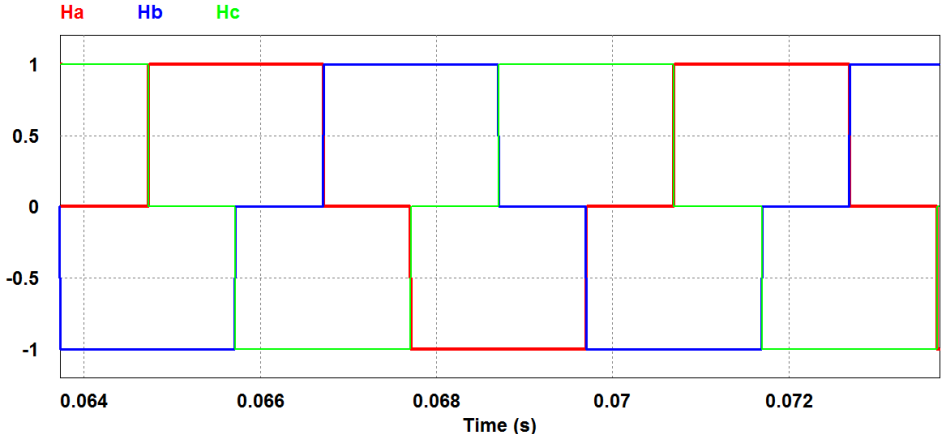
Sudut	Ha	Hb	Hc	S1	S2	S3	S4	S5	S6
0-60	0	-1	1	0	0	0	1	1	0
60-120	1	-1	0	1	0	0	1	0	0
120-180	1	0	-1	1	0	0	0	0	1
180-240	0	1	-1	0	0	1	0	0	1
240-300	-1	1	0	0	1	1	0	0	0
300-360	-1	0	1	0	1	0	0	1	0



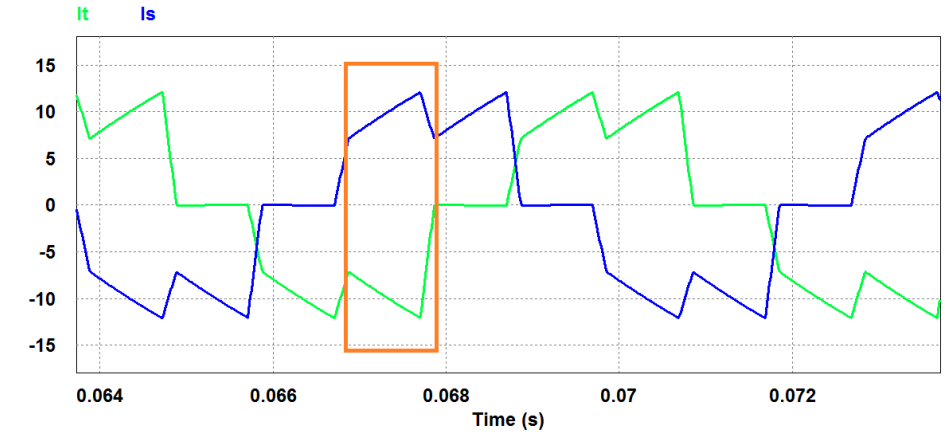


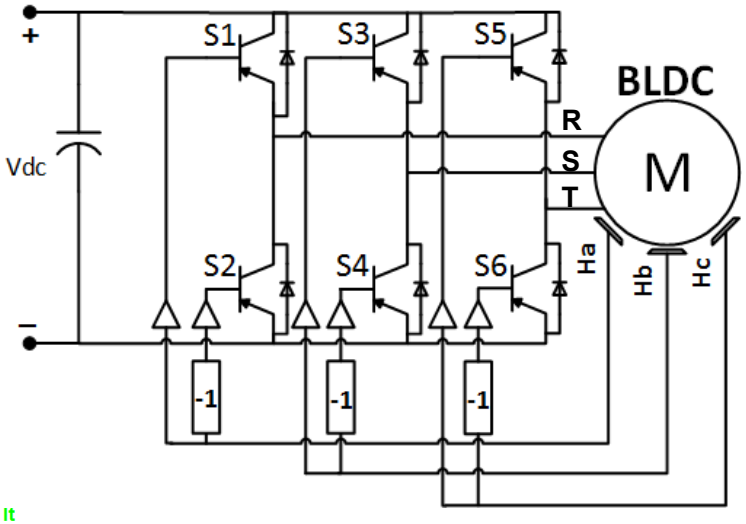


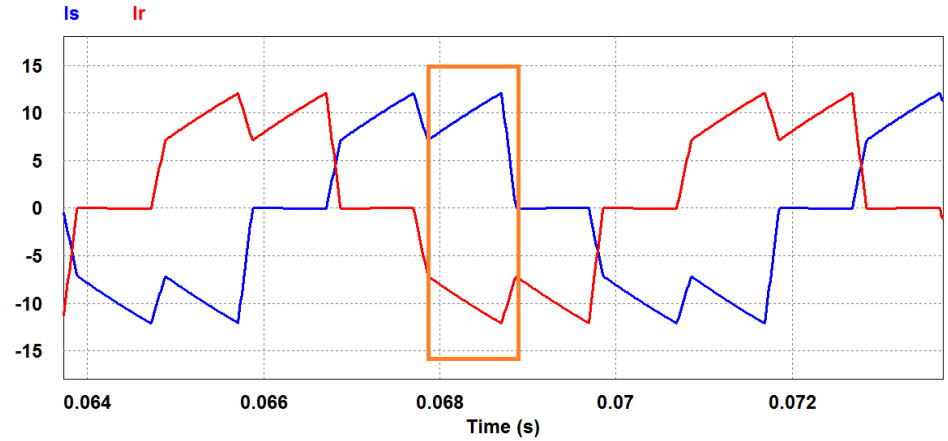


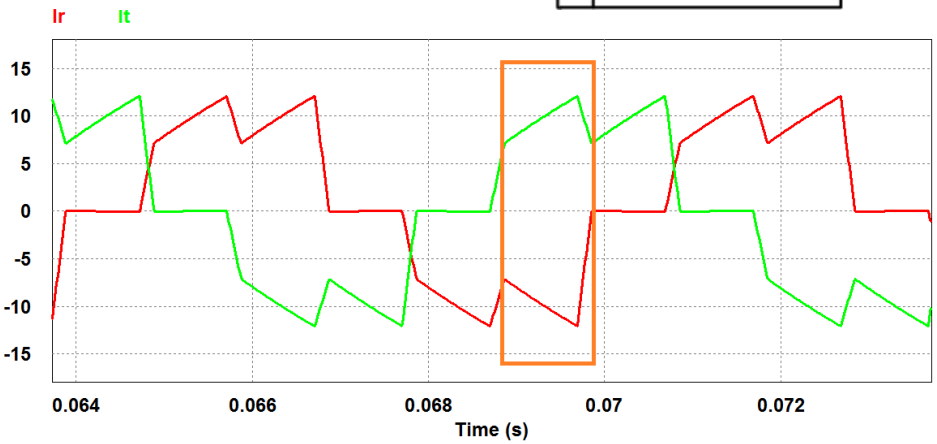


Sudut	Ha	Hb	Hc	S1	S2	S3	S4	S5	S6
0-60	0	-1	1	0	0	0	1	1	0
60-120	1	-1	0	1	0	0	1	0	0
120-180	1	0	-1	1	0	0	0	0	1
180-240	0	1	-1	0	0	1	0	0	1
240-300	-1	1	0	0	1	1	0	0	0
300-360	-1	0	1	0	1	0	0	1	0

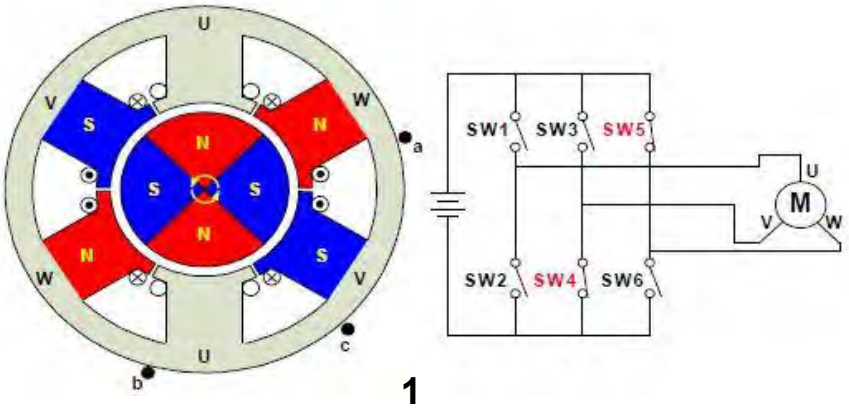




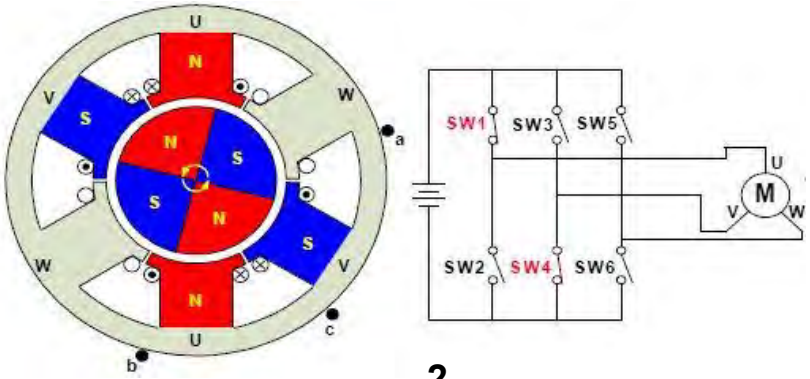




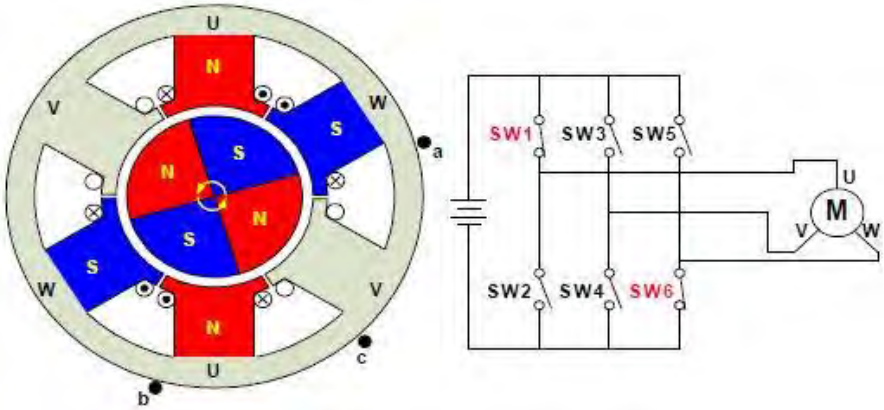
	Sudut	Ha	Hb	Hc	S1	S2	S3	S4	S5	S6
1	0-60	0	-1	1	0	0	0	1	1	0
2	60-120	1	-1	0	1	0	0	1	0	0
3	120-180	1	0	-1	1	0	0	0	0	1
4	180-240	0	1	-1	0	0	1	0	0	1
	240-300	-1	1	0	0	1	1	0	0	0
	300-360	-1	0	1	0	1	0	0	1	0



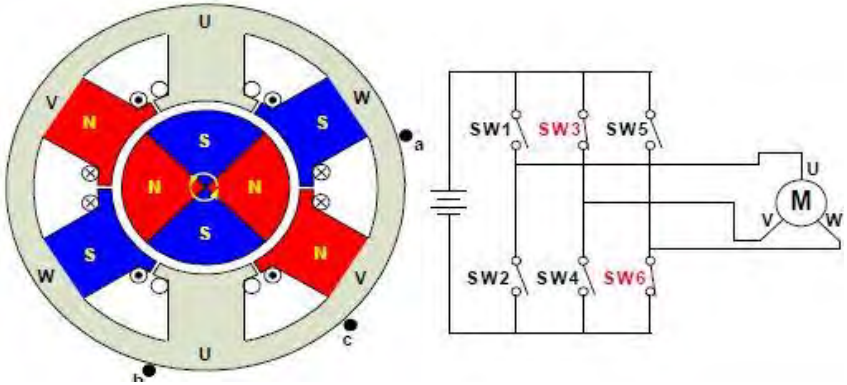
1



2

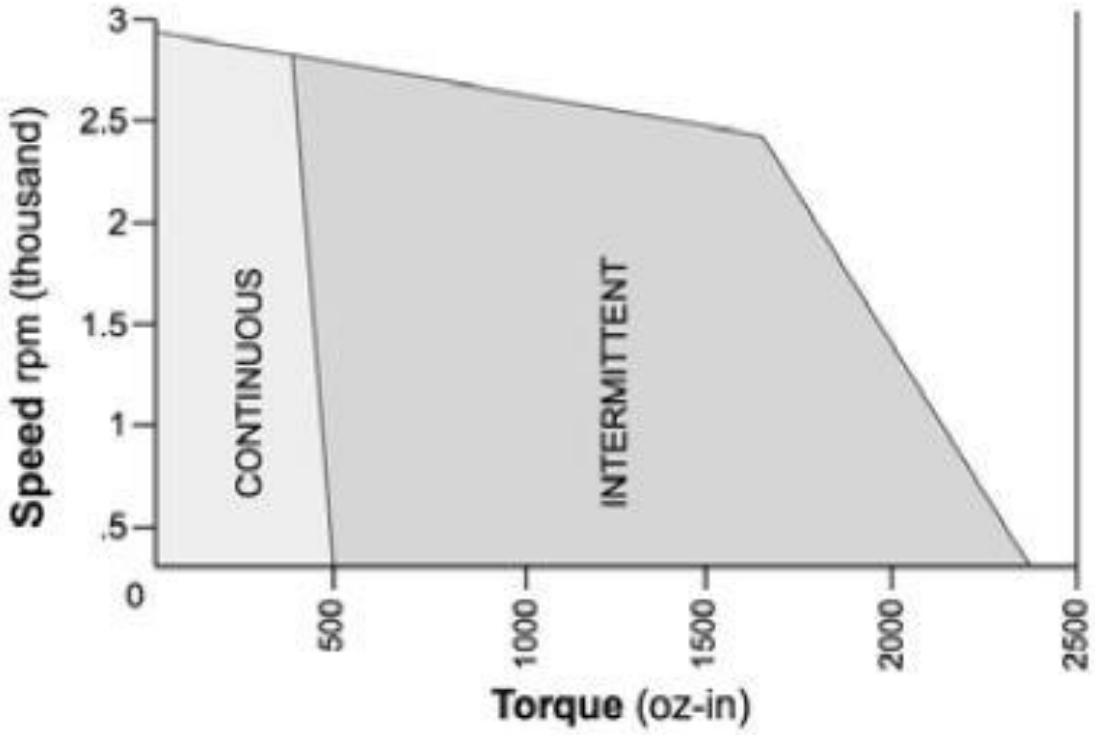


3

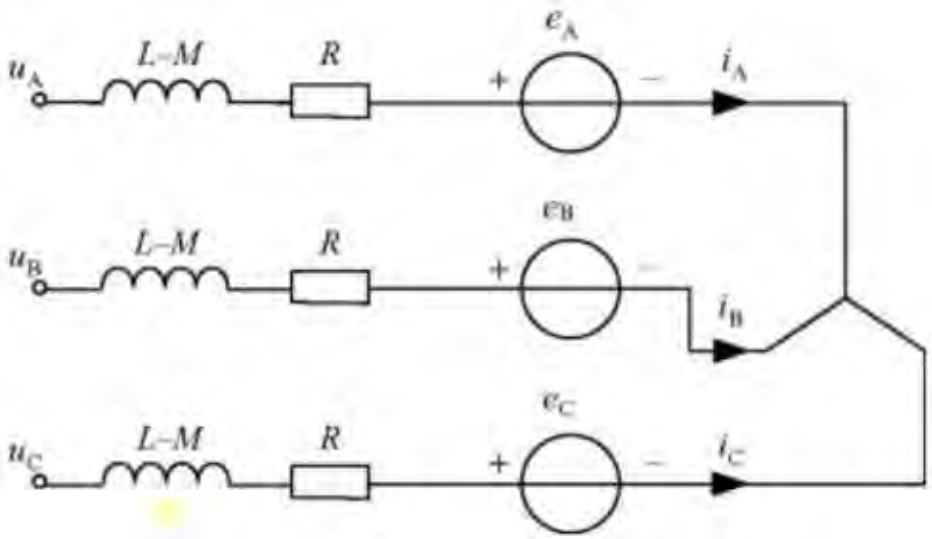


4

Karakteristik Motor *Brushless* DC



Persamaan Motor *Brushless* DC



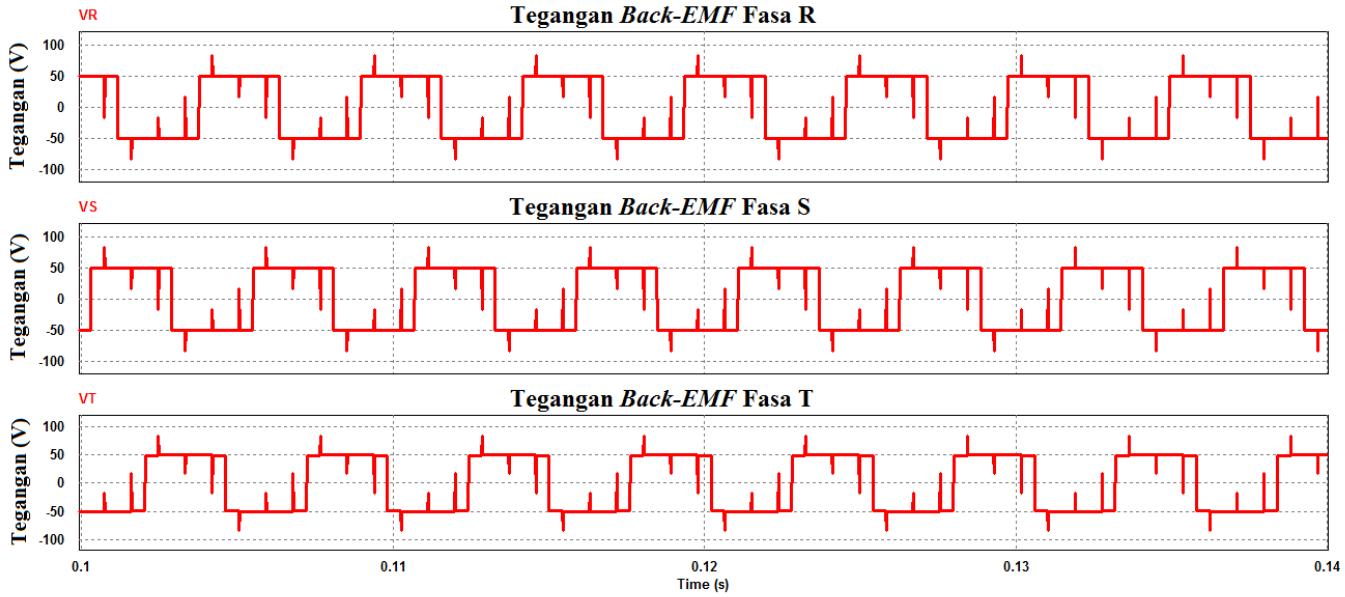
$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\Omega}$$

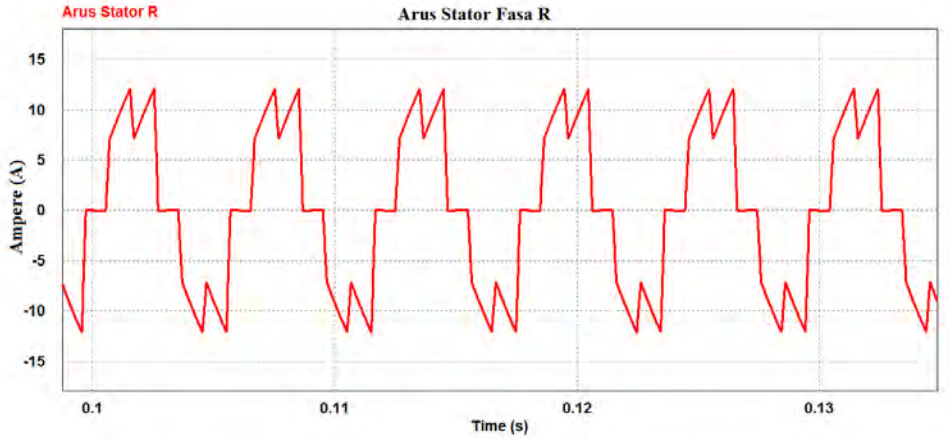
$$e_A = \omega \psi_m f_A(\theta)$$

$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\Omega}$$

$$u_A = R i_A + (L - M)\frac{di_A}{dt} + e_A$$

Tegangan dan Arus Motor





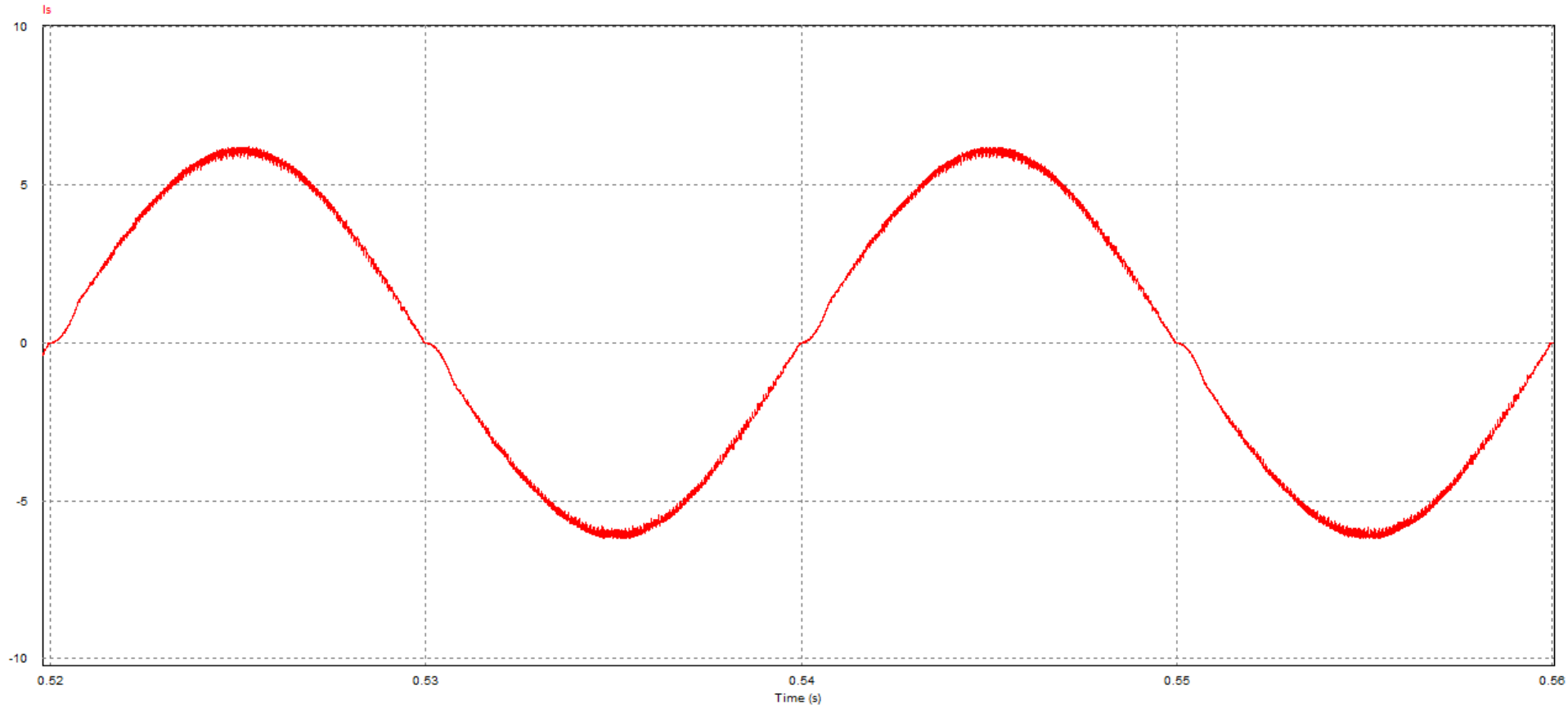
Perbedaan Motor

Motor DC Konvensional	Motor DC *Brushless*
Magnet permanen pada stator	Magnet permanen pada rotor
Komutasi menggunakan brush dan komutator	Komutasi secara elektris
Rugi-rugi mekanis akibat brush	Rugi-rugi mekanis sangat minim
Kecepatan tidak terlalu tinggi	Kecepatan dapat sangat tinggi
Membalikkan putaran dengan membalik tegangan terminal	Membalikkan putaran dengan mengubah urutan sinyal Hall
Maintenance rutin	Sangat kurang memerlukan maintenance
Disipasi panas kurang baik akibat panas pada jangkar rotor	Disipasi panas cukup baik karena panas pada jangkar berada di stator

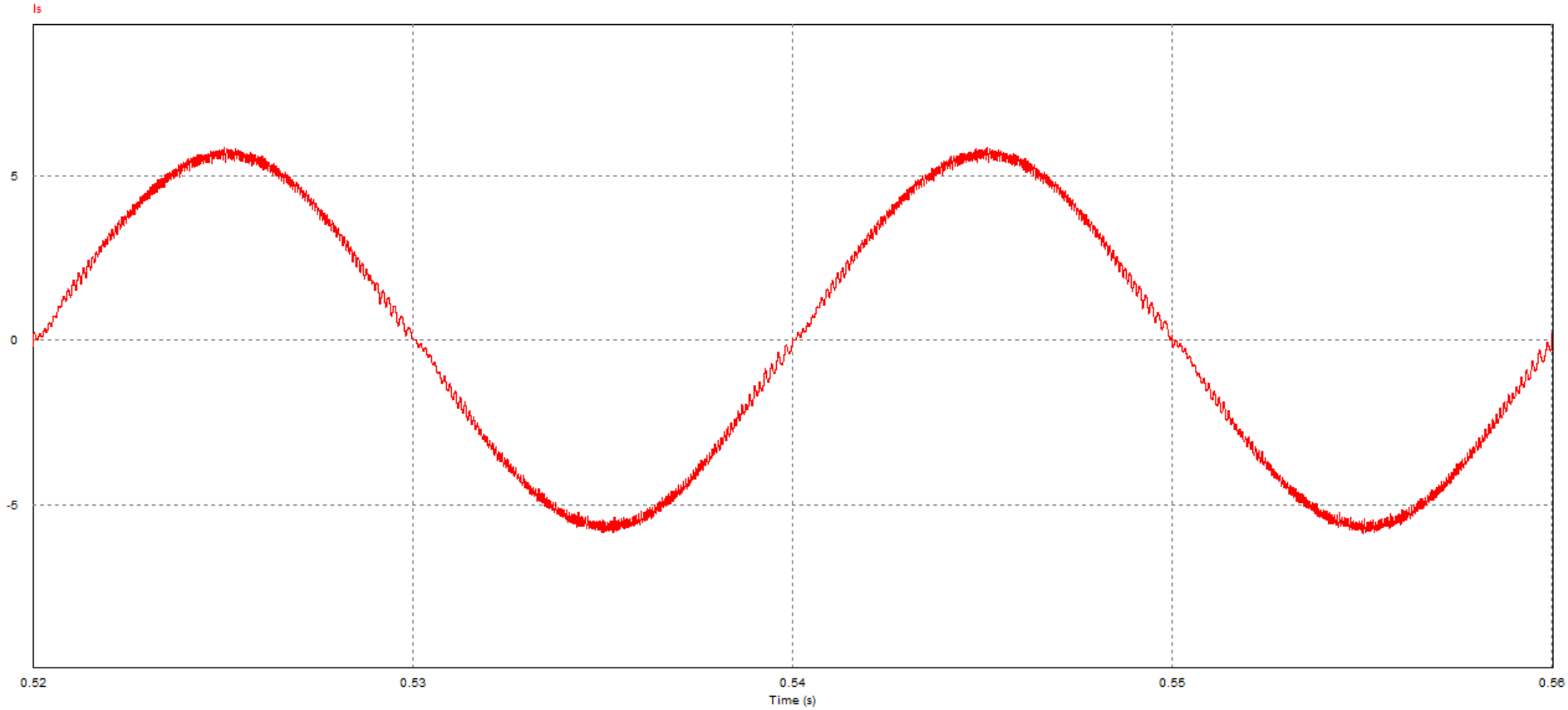
Perbedaan Motor

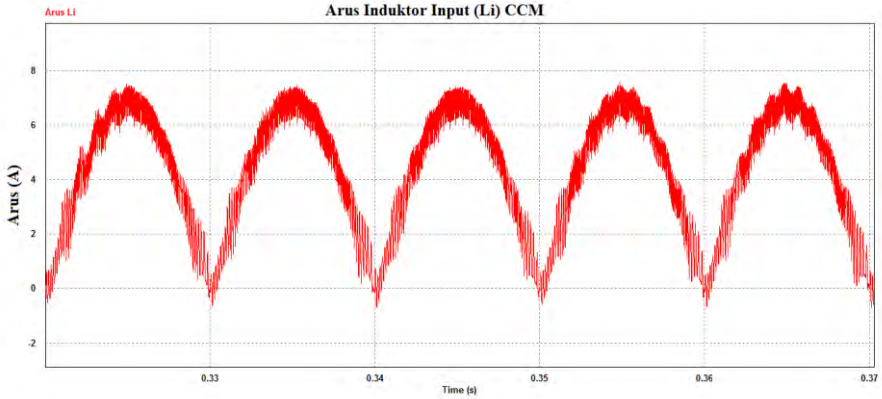
PMSM	Motor DC *Brushless*
Input Sinusoidal	Input Trapezoidal
Tidak ada Feedback sensor	Feedback sensor Hall
Kontrol lebih sulit pada penggunaan inverter	Kontrol lebih mudah
Daya besar	Daya rendah-menengah
Kebanyakan kecepatan menengah kebawah	Kecepatan dapat sampai tinggi

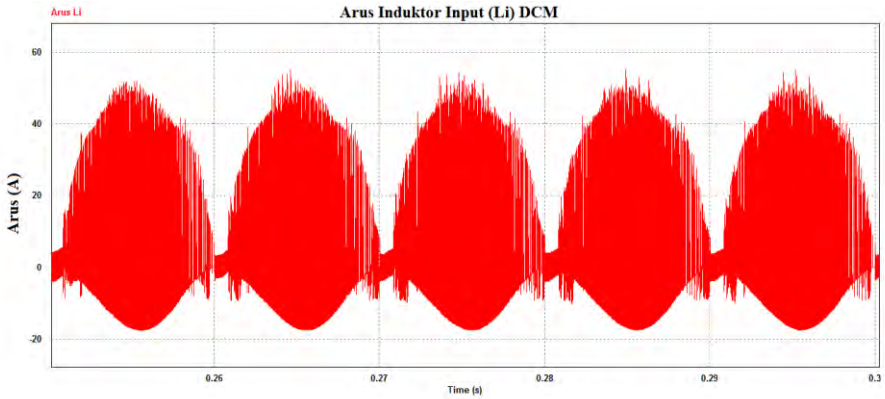
Mode DCM

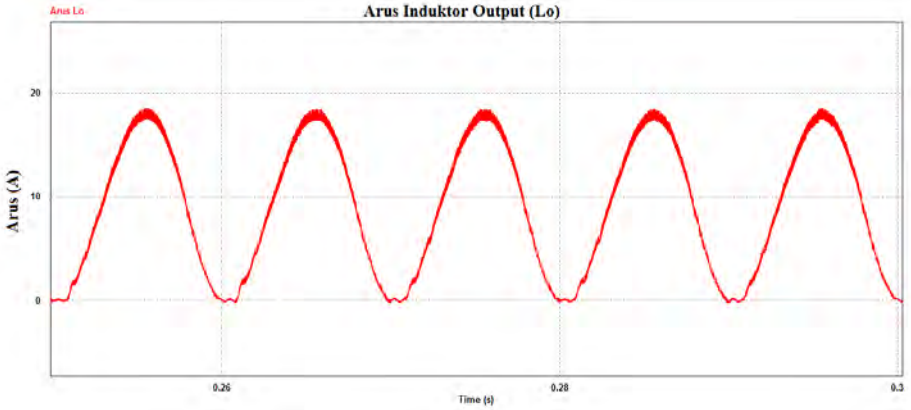


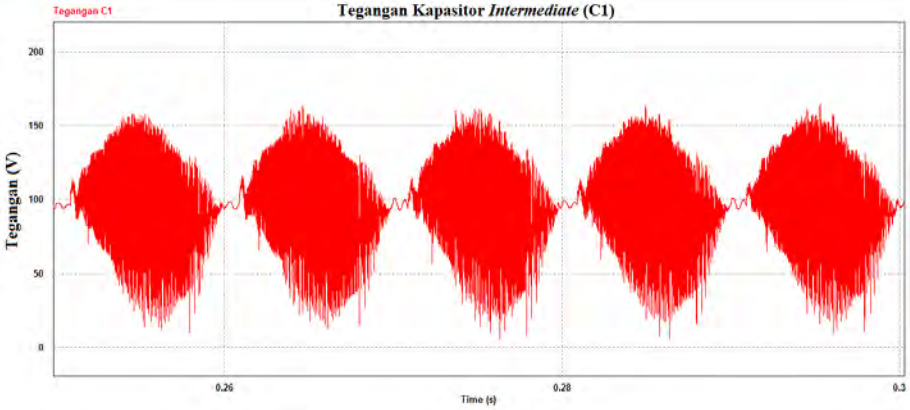
Mode CCM

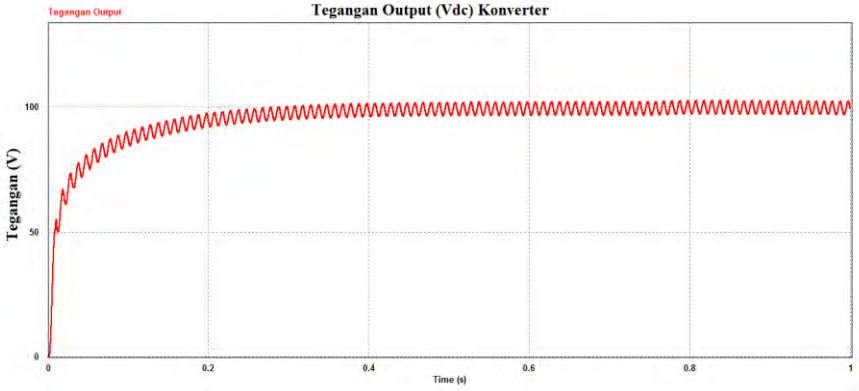



Arus Li
Arus Induktor Input (Li) CCM
Arus (A)
Time (s)

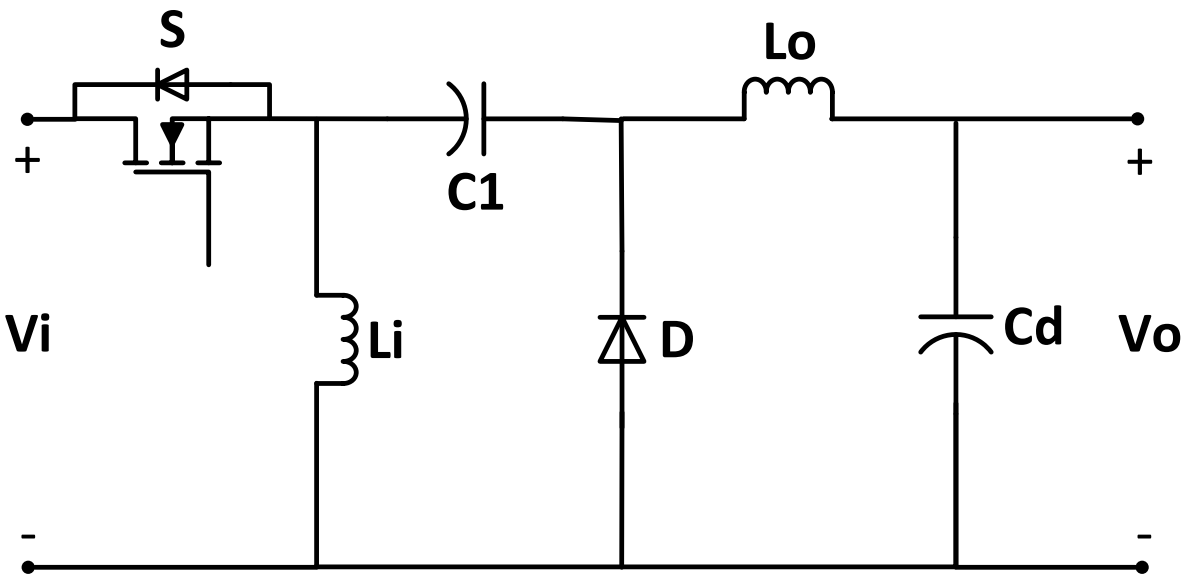

Arus Li
Arus Induktor Input (Li) DCM
Arus (A)
Time (s)


Arus Lo
Arus Induktor Output (Lo)
Arus (A)
Time (s)


Tegangan C1
Tegangan Kapasitor Intermediate (C1)
Tegangan (V)
Time (s)


Tegangan Output
Tegangan Output (Vdc) Konverter
Tegangan (V)
Time (s)

Induktor Input (Li)



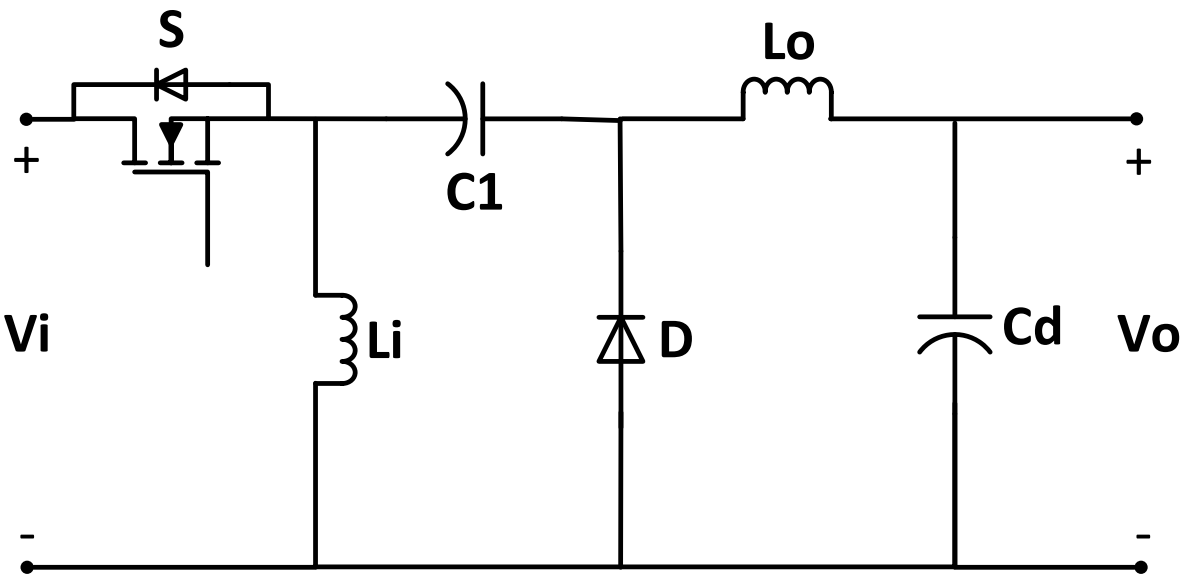
Mode CCM:

$$Li = \frac{Vs^2}{\eta.fs.Pi}\left(\frac{Vdc}{Vdc+Vin}\right)$$

$$Li = \frac{162{,}139^2}{0{,}15.20000.900}\left(\frac{100}{100+162{,}139}\right)$$

Li ccm = 3,7143mH

Induktor Input (Li)



Mode DCM:

$$Li = \frac{Vs^2}{\eta.fs.Pi}\left(\frac{Vdc}{Vdc+Vin}\right)$$

$$Li_{100} = \frac{Vavg_{min}^2}{2.fs.Pmax}\left(\frac{Vdc_{max}}{Vdc_{max}+Vavg_{min}}\right)$$

$$= 0{,}27857mH$$

$$Li_{30} = \frac{Vavg_{min}^2}{2.fs.Pmin}\left(\frac{Vdc_{min}}{Vdc_{min}+Vavg_{min}}\right)$$

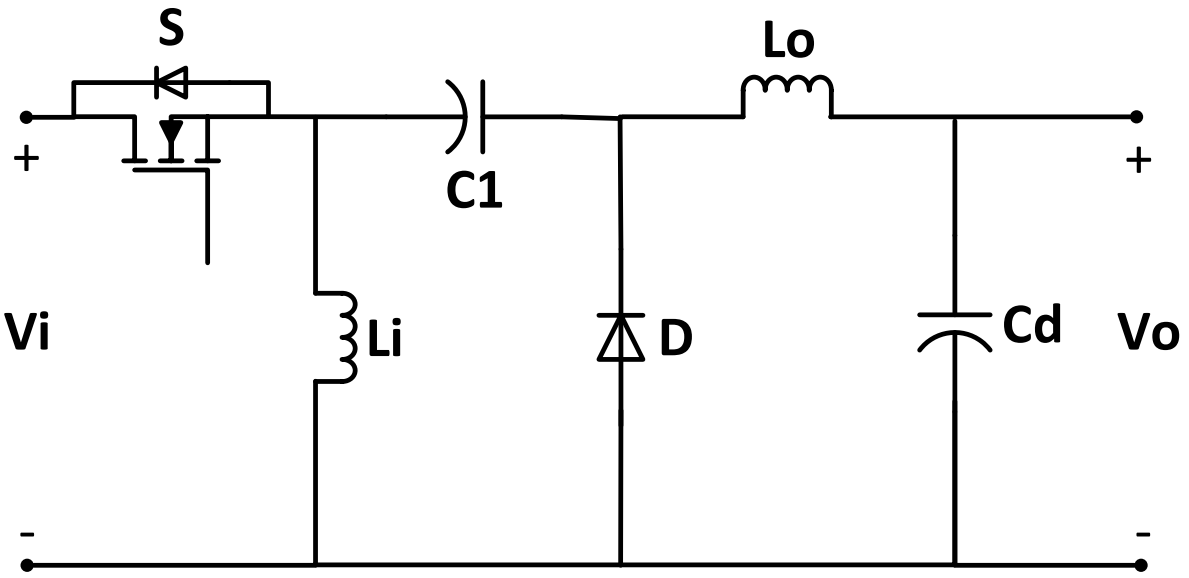
$$= 39{,}787mH$$

$$Li < Li_{100}$$

$$Li < 0{,}27857mH$$

$$Li\ dcm = 40\mu H$$

Induktor Output (Lo)



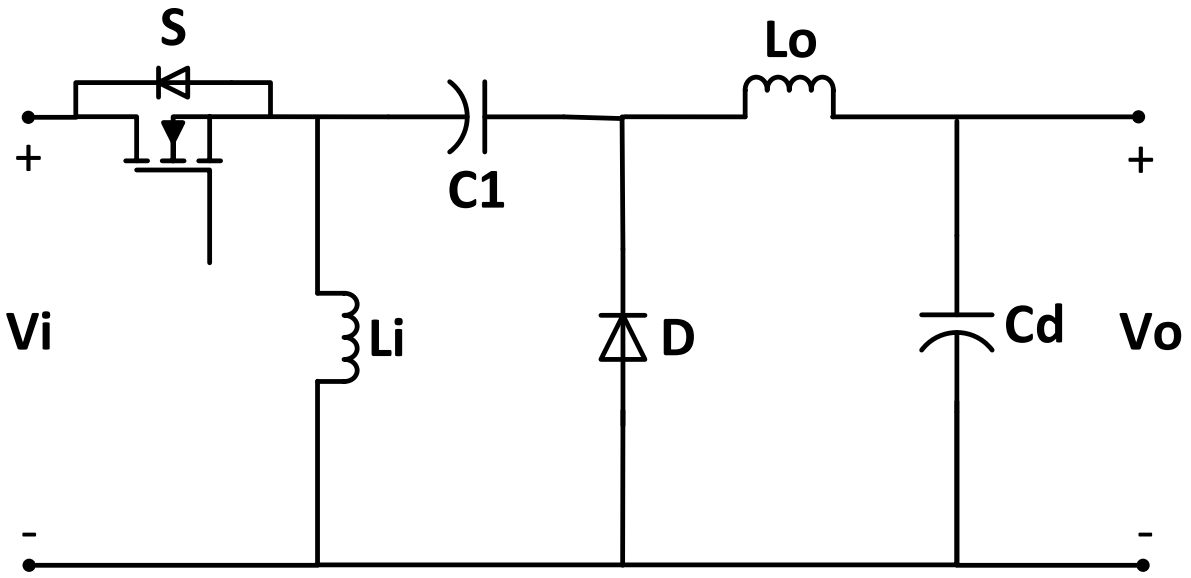
$$Lo = \frac{V_{in}.D}{\Delta I_{Lo}.f_s}$$

$$Lo = \frac{Vdc_{max}}{\eta.Vavg_{min}.fs}\left(\frac{Vavg^2_{min}}{P_{max}}\right)\left(\frac{Vdc_{max}}{Vdc_{max}+Vavg_{min}}\right)$$

$$Lo = \frac{100}{0{,}15.162{,}139.20000}\left(\frac{162{,}139^2}{900}\right)\left(\frac{100}{100+162{,}139}\right)$$

$$Lo = 2.291mH$$

Kapasitor *Intermediate* (C1)

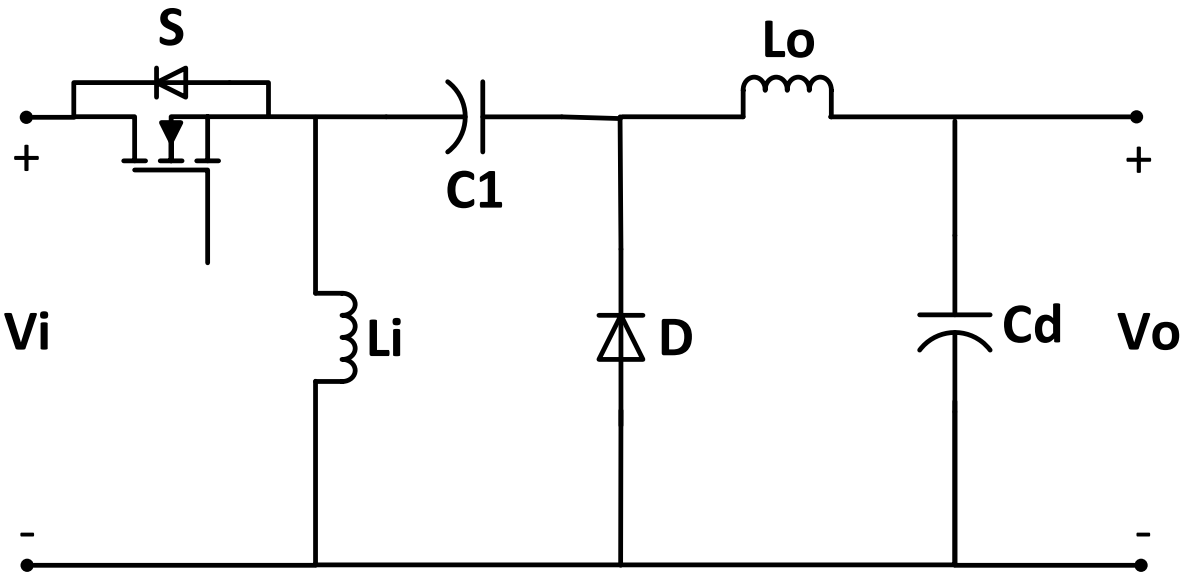


$$C_1 = \frac{Vdc.D}{\Delta V_{C1}.fs.R_L}$$

$$C_1 = \frac{Pmax}{\eta.(Vdc_{max}+Vavg_{max})^2.fs}$$

$$C_1 = 4{,}05\mu F$$

Kapasitor *DC-Link* (Cd)



$$C_d = \frac{Pi}{2.\pi.f.\Delta Vdc.Vdc} = \frac{Pi}{2.\pi.f_{line}.\eta.Vdc^2}$$

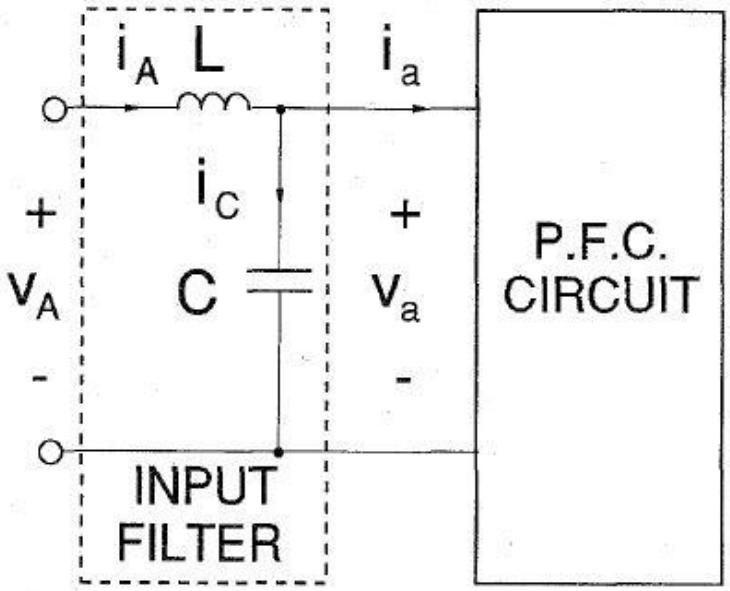
$$C_{d\ min} = \frac{Pmin}{2.\pi.f_{line}.\eta.Vdc^2_{min}} \qquad C_{d\ max} = \frac{Pmax}{2.\pi.f_{line}.\eta.Vdc^2_{max}}$$

$C_{d\ min} = 0{,}4458mF$ $\qquad$ $C_{d\ max} = 5{,}732mF$

Dipilih yang terbesar:

$C_{d\ max} = 5{,}732mF$

Filter DC



$$C_{f\,max} = \frac{I_m}{\omega . V_m} \tan(\theta)$$

$$= \frac{(Pmax/\sqrt{2}.Vs)}{2.\pi.f_{line}.V_m} \tan(\theta)$$

$$C_{f\,max} = 516{,}843nF$$

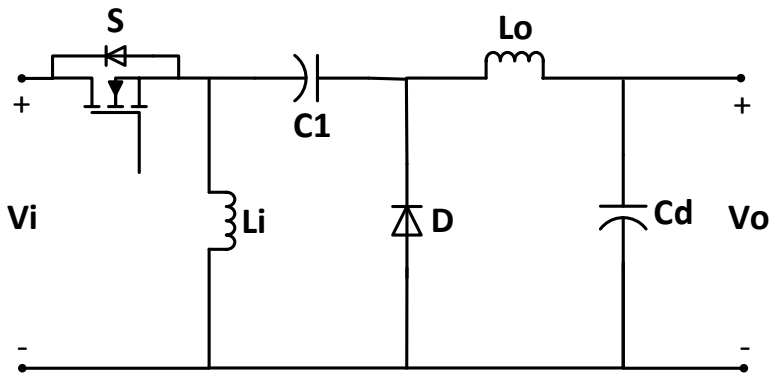
$$L_f = \frac{1}{4.\pi^2.f_C^2.C_f}$$

$$L_f = 21.13mH$$

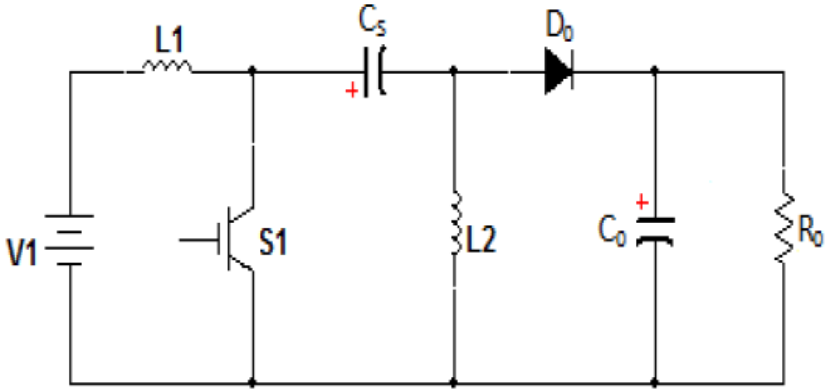
Dipilih nilai dibawah $C_{f\,max}$

$$C_f = 300nF$$

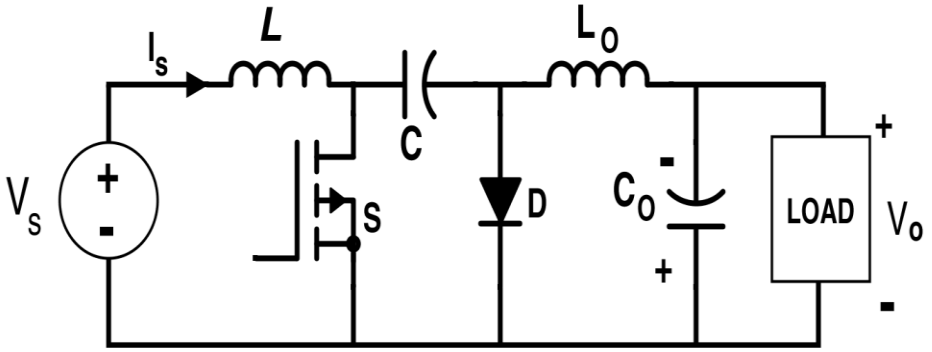
Perbedaan Konverter



Zeta



SEPIC



Cuk

Perbedaan antara metode lain

Filter Pasif	PFC Converter
Tidak Stabil	Cenderung Stabil
Existing System	Fleksibel
Tidak fleksibel	Integrated PFC & Speed Control
Daya tinggi	

THD dan PF

$$THD_I = \frac{\sqrt{\sum_{k=2}^{\infty} I_{krms}^2}}{I_{1rms}} .100\%$$

$$PF_{dist} = \frac{1}{\sqrt{1 + (THD\%)^2}}$$

$$PF_{true} = PF_{disp}.PF_{dist}$$

THD dan TDD

$$I_{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots.}}{I_1} \times 100\%$$

$$I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots.}}{I_L} \times 100\%$$

IEC-61000-3-2

Harmonics [n]	Class A [A]	Class B [A]	Class C [% of fund]	Class D [mA/W]
		Odd harmonics		
3	2.30	3.45	30 x λ	3.4
5	1.14	1.71	10	1.9
7	0.77	1.155	7	1.0
9	0.40	0.60	5	0.5
11	0.33	0.495	3	0.35
13	0.21	0.315	3	3.85/13
15 ≤n ≤39	0.15 x 15/n	0.225 X 15/n	3	3.85/n
		Even harmonics		
2	1.08	1.62	2	-
4	0.43	0.645	-	-
6	0.30	0.45	-	-
8 ≤n ≤40	0.23 x 8/n	0.345 x 8/n	-	-

IEEE-519-1992

Current Distortion Limits for General Distribution Systems (120 V Through 69000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	11≤*h*<17	17≤*h*<23	23≤*h*<35	35≤*h*	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.

* All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

Where

I_{sc} = maximum short-circuit current at PCC.

I_L = maximum demand load current (fundamental frequency component) at PCC.

TDD = Total demand distortion (RSS), harmonic current distortion in % of maximum demand load current (15 or 30 min demand).

PCC = Point of common coupling.