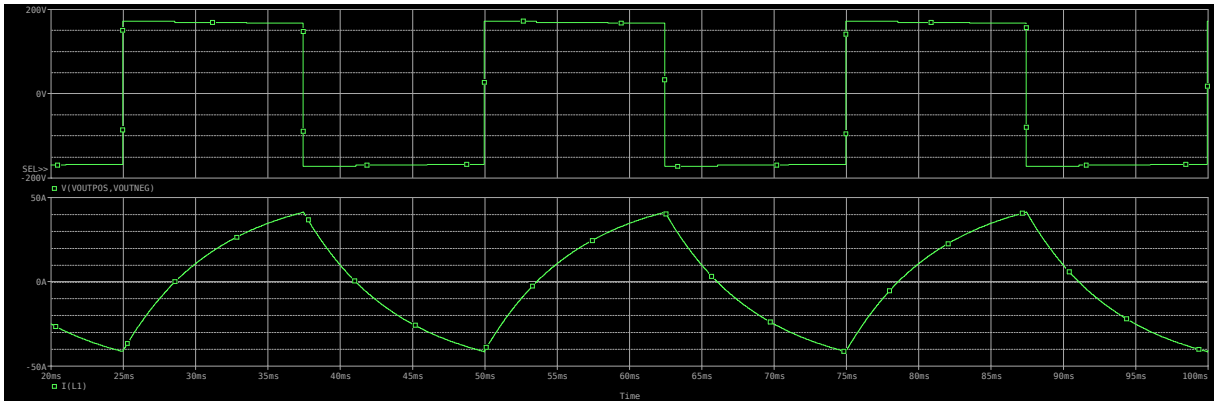
1.

a) Square Wave operation

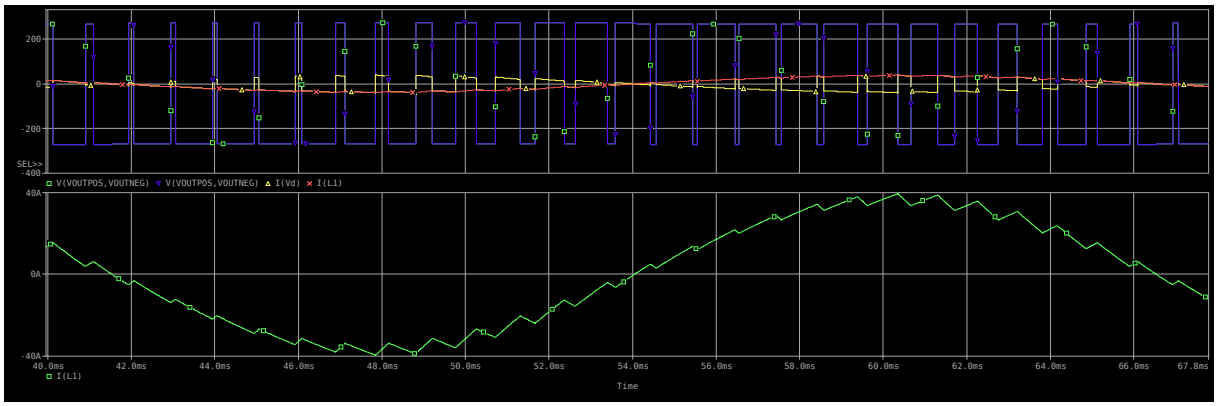


From the plot, we can see that there are four different states in which different devices must conduct in order to accommodate different current paths. This is best illustrated using a table:

Case	Vo	Io	Conducting Device
1	+	-	D1, D2
2	+	+	T1, T2
3	-	+	D3, D4
4	-	-	T3, T4

By simply referring to the schematic and using the information of which direction the current must flow, as well as which (if any) diodes are forward biased, the conducting devices can be determined.

b) PWM operation



Determining which devices are conducting for a bipolar switching scheme is slightly more involved, as it directly synthesizes a sinusoidal signal on the output (after filtering). Since the current will lag the voltage with an inductive load, determining the current paths involves taking into account the bipolar switching in four different cases ([filtered] voltage and current both pos. or both neg., one neg. and one pos.), as well as considering when each switch pair is active. This gives a total of eight current paths, which can be determined in the same manner as for square wave operation.

Case	Vo	Io	Conducting Device	Notes
1	-	-	T3, T4	Vo1 neg, Io neg
2	+	-	D1, D2	
3	+	-	D1, D2	Vo1 pos, Io neg
4	-	-	T3, T4	
5	+	+	T1, T2	Vo1 pos, Io pos
6	-	+	D3, D4	
7	-	+	D3, D4	Vo1 neg, Io pos
8	+	+	T1, T2	

From these two modes of operation, one may conclude that the diodes conduct when the output (filtered) voltage and current have opposing polarity.

2.

Square Wave

Load Voltage

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(VOUTPOS,VOUTNEG)

DC COMPONENT = -3.4908E-07

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	4.0000E+01	2.1533E+02	1.0000E+00	1.1680E+00	0.0000E+00
2	8.0000E+01	6.8044E-07	3.1601E-09	1.6912E+02	1.6678E+02
3	1.2000E+02	7.2945E+01	3.3876E-01	2.1943E+00	-1.3096E+00
4	1.6000E+02	6.5449E-07	3.0395E-09	6.5354E+01	6.0682E+01
5	2.0000E+02	4.3434E+01	2.0171E-01	2.6729E+00	-3.1669E+00
6	2.4000E+02	6.5775E-07	3.0546E-09	-3.9927E+01	-4.6935E+01
7	2.8000E+02	3.0657E+01	1.4237E-01	4.5829E+00	-3.5929E+00
8	3.2000E+02	6.8245E-07	3.1694E-09	-1.4284E+02	-1.5218E+02
9	3.6000E+02	2.4163E+01	1.1222E-01	6.3808E+00	-4.1309E+00
10	4.0000E+02	6.8742E-07	3.1925E-09	1.1611E+02	1.0443E+02
11	4.4000E+02	1.9875E+01	9.2300E-02	6.8318E+00	-6.0158E+00
12	4.8000E+02	6.6806E-07	3.1025E-09	1.4210E+01	1.9420E-01
13	5.2000E+02	1.6558E+01	7.6896E-02	8.0296E+00	-7.1540E+00
14	5.6000E+02	6.5417E-07	3.0380E-09	-8.9787E+01	-1.0614E+02
15	6.0000E+02	1.4382E+01	6.6792E-02	1.0214E+01	-7.3051E+00
16	6.4000E+02	6.5984E-07	3.0644E-09	1.6636E+02	1.4767E+02
17	6.8000E+02	1.2873E+01	5.9785E-02	1.1173E+01	-8.6827E+00
18	7.2000E+02	6.6746E-07	3.0997E-09	6.3866E+01	4.2842E+01
19	7.6000E+02	1.1415E+01	5.3013E-02	1.1754E+01	-1.0438E+01
20	8.0000E+02	6.6327E-07	3.0803E-09	-3.8453E+01	-6.1812E+01
21	8.4000E+02	1.0225E+01	4.7488E-02	1.3726E+01	-1.0801E+01
22	8.8000E+02	6.5912E-07	3.0610E-09	-1.4145E+02	-1.6714E+02
23	9.2000E+02	9.4670E+00	4.3966E-02	1.5405E+01	-1.1458E+01
24	9.6000E+02	6.6134E-07	3.0713E-09	1.1585E+02	8.7823E+01
25	1.0000E+03	8.7374E+00	4.0578E-02	1.5848E+01	-1.3352E+01

TOTAL HARMONIC DISTORTION = 4.6843E+01 PERCENT

Load Current

FOURIER COMPONENTS OF TRANSIENT RESPONSE I(L_L1)

DC COMPONENT = 4.9189E-06

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	4.0000E+01	3.6785E+01	1.0000E+00	-5.7930E+01	0.0000E+00
2	8.0000E+01	2.8583E-06	7.7703E-08	1.6418E+01	1.3228E+02
3	1.2000E+02	4.7444E+00	1.2898E-01	-7.6340E+01	9.7448E+01
4	1.6000E+02	1.4579E-06	3.9634E-08	-3.1219E+00	2.2860E+02
5	2.0000E+02	1.7159E+00	4.6647E-02	-8.0161E+01	2.0949E+02
6	2.4000E+02	7.9817E-07	2.1698E-08	8.1471E+00	3.5572E+02
7	2.8000E+02	8.6815E-01	2.3601E-02	-8.0035E+01	3.2547E+02
8	3.2000E+02	7.2274E-07	1.9648E-08	2.9439E+01	4.9288E+02
9	3.6000E+02	5.3302E-01	1.4490E-02	-7.9180E+01	4.4219E+02
10	4.0000E+02	6.6799E-07	1.8159E-08	1.0137E+01	5.8943E+02
11	4.4000E+02	3.5891E-01	9.7569E-03	-7.9278E+01	5.5795E+02
12	4.8000E+02	5.5971E-07	1.5216E-08	-1.0610E+01	6.8454E+02
13	5.2000E+02	2.5310E-01	6.8807E-03	-7.8400E+01	6.7468E+02
14	5.6000E+02	3.5583E-07	9.6734E-09	3.0146E+00	8.1403E+02
15	6.0000E+02	1.9064E-01	5.1825E-03	-7.6423E+01	7.9252E+02
16	6.4000E+02	3.4079E-07	9.2645E-09	2.2217E+01	9.4909E+02
17	6.8000E+02	1.5058E-01	4.0934E-03	-7.5605E+01	9.0920E+02
18	7.2000E+02	3.3329E-07	9.0605E-09	8.4828E+00	1.0512E+03
19	7.6000E+02	1.1945E-01	3.2472E-03	-7.5080E+01	1.0256E+03
20	8.0000E+02	3.1625E-07	8.5973E-09	8.0113E+00	1.1666E+03
21	8.4000E+02	9.6849E-02	2.6329E-03	-7.3120E+01	1.1434E+03
22	8.8000E+02	2.9823E-07	8.1073E-09	1.2905E+01	1.2874E+03
23	9.2000E+02	8.1891E-02	2.2262E-03	-7.1461E+01	1.2609E+03
24	9.6000E+02	2.6394E-07	7.1752E-09	8.8240E+00	1.3991E+03
25	1.0000E+03	6.9508E-02	1.8896E-03	-7.0999E+01	1.3772E+03

TOTAL HARMONIC DISTORTION = 1.4068E+01 PERCENT

In square wave operation the harmonic components are odd and decrease linearly. The THD values for the output voltage and current are 46,8% and 14,1% respectively.

PWM

Load Voltage

FOURIER COMPONENTS OF TRANSIENT RESPONSE V(VOUTPOS,VOUTNEG)

DC COMPONENT = 2.6328E-05

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	4.0000E+01	2.1520E+02	1.0000E+00	8.0182E-01	0.0000E+00
2	8.0000E+01	2.9107E-05	1.3525E-07	-2.8409E+01	-3.0013E+01
3	1.2000E+02	2.6427E+00	1.2280E-02	2.2666E+01	2.0261E+01
4	1.6000E+02	2.6521E-05	1.2324E-07	-1.4399E+02	-1.4720E+02
5	2.0000E+02	2.1990E+00	1.0218E-02	-1.5833E+02	-1.6234E+02
6	2.4000E+02	2.5058E-05	1.1644E-07	9.9056E+01	9.4245E+01
7	2.8000E+02	1.4957E+00	6.9499E-03	-1.3401E+02	-1.3963E+02
8	3.2000E+02	2.3903E-05	1.1107E-07	-1.7436E+01	-2.3850E+01
9	3.6000E+02	7.0034E-01	3.2543E-03	-1.4334E+02	-1.5056E+02
10	4.0000E+02	2.3257E-05	1.0807E-07	-1.3354E+02	-1.4155E+02
11	4.4000E+02	1.4288E+00	6.6394E-03	-3.8445E+01	-4.7265E+01
12	4.8000E+02	2.2089E-05	1.0264E-07	1.1077E+02	1.0115E+02
13	5.2000E+02	4.8170E-01	2.2384E-03	1.3599E+02	1.2556E+02
14	5.6000E+02	2.1611E-05	1.0042E-07	-5.1346E+00	-1.6360E+01
15	6.0000E+02	6.9791E-01	3.2430E-03	-1.6995E+01	-2.9022E+01
16	6.4000E+02	2.0751E-05	9.6425E-08	-1.2237E+02	-1.3520E+02
17	6.8000E+02	3.8220E-01	1.7760E-03	-2.6444E+01	-4.0075E+01
18	7.2000E+02	2.0005E-05	9.2957E-08	1.2210E+02	1.0766E+02
19	7.6000E+02	1.4629E+00	6.7977E-03	-4.7695E+01	-6.2930E+01
20	8.0000E+02	2.0747E-05	9.6406E-08	5.3544E+00	-1.0682E+01
21	8.4000E+02	4.1358E+00	1.9218E-02	7.7151E+01	6.0313E+01
22	8.8000E+02	2.0014E-05	9.3000E-08	-1.1108E+02	-1.2872E+02
23	9.2000E+02	5.7709E+01	2.6816E-01	8.9524E+01	7.1082E+01
24	9.6000E+02	1.9150E-05	8.8988E-08	1.3578E+02	1.1653E+02
25	1.0000E+03	2.2189E+02	1.0311E+00	8.9655E+01	6.9609E+01

TOTAL HARMONIC DISTORTION = 1.0658E+02 PERCENT

Load Current

FOURIER COMPONENTS OF TRANSIENT RESPONSE I(L_L1)

DC COMPONENT = -2.3069E-03

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	4.0000E+01	3.6814E+01	1.0000E+00	-5.8614E+01	0.0000E+00
2	8.0000E+01	2.1565E-05	5.8577E-07	-1.2671E+02	-9.4844E+00
3	1.2000E+02	4.8763E-02	1.3246E-03	-7.4043E+01	1.0180E+02
4	1.6000E+02	8.6348E-06	2.3455E-07	1.0901E+02	3.4346E+02
5	2.0000E+02	1.7653E-02	4.7953E-04	1.6545E+02	4.5852E+02
6	2.4000E+02	1.1767E-05	3.1962E-07	-1.5737E+02	1.9432E+02
7	2.8000E+02	8.9241E-03	2.4241E-04	4.7103E+01	4.5740E+02
8	3.2000E+02	4.6026E-06	1.2502E-07	-1.5521E+02	3.1370E+02
9	3.6000E+02	5.4180E-03	1.4717E-04	-7.0277E+01	4.5725E+02
10	4.0000E+02	3.7736E-06	1.0250E-07	-1.6941E+02	4.1673E+02
11	4.4000E+02	3.6650E-03	9.9555E-05	1.7026E+02	8.1501E+02
12	4.8000E+02	5.8149E-06	1.5795E-07	1.5395E+02	8.5732E+02
13	5.2000E+02	2.5610E-03	6.9567E-05	5.2936E+01	8.1492E+02
14	5.6000E+02	4.6358E-06	1.2593E-07	-1.1170E+02	7.0890E+02
15	6.0000E+02	1.8498E-03	5.0247E-05	-6.6040E+01	8.1317E+02
16	6.4000E+02	3.6644E-06	9.9538E-08	1.4579E+02	1.0836E+03
17	6.8000E+02	1.4794E-03	4.0185E-05	-1.7754E+02	8.1890E+02
18	7.2000E+02	2.8296E-06	7.6862E-08	-1.5107E+02	9.0398E+02
19	7.6000E+02	1.2287E-03	3.3374E-05	4.9161E+01	1.1628E+03
20	8.0000E+02	3.8285E-06	1.0399E-07	-1.4453E+02	1.0277E+03
21	8.4000E+02	2.0104E-02	5.4608E-04	-5.9940E-01	1.2303E+03
22	8.8000E+02	7.3898E-06	2.0073E-07	1.0948E+02	1.3990E+03
23	9.2000E+02	5.1433E-01	1.3971E-02	1.4880E+00	1.3496E+03
24	9.6000E+02	5.8138E-05	1.5792E-06	9.2136E+01	1.4989E+03
25	1.0000E+03	1.7639E+00	4.7913E-02	1.3872E+00	1.4667E+03

TOTAL HARMONIC DISTORTION = 4.9932E+00 PERCENT

In PWM operation the significant harmonic components appear at the fundamental frequency (ie. 40Hz) and at multiples of the *frequency modulation ratio*(ie. *mf = fs/f1 = 1000Hz/40Hz = 25*) and its sidebands. The sidebands are at ±even components for odd multiples for *mf* and ±odd components for even multiples of *mf*.

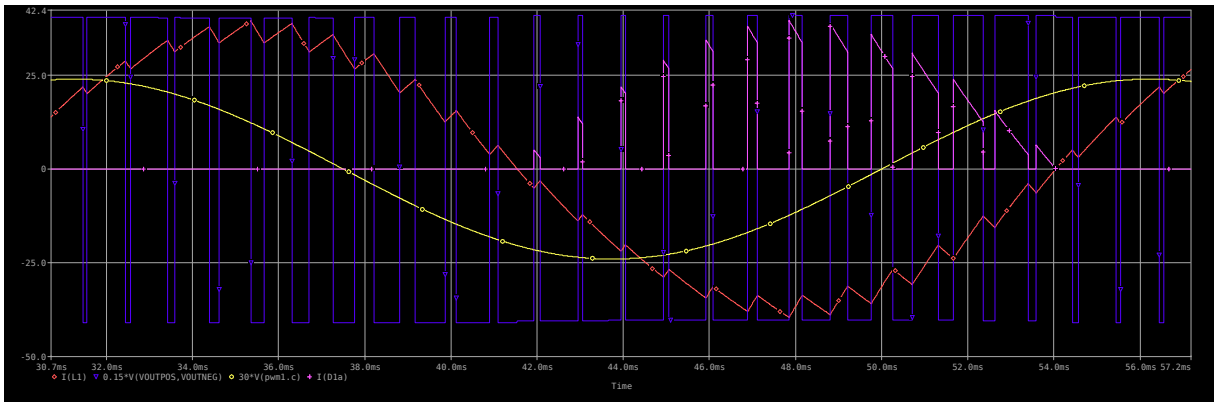
From the fourier analysis above, it is clearly shown that there are significant fourier components at *mf* and *mf*±2 and *mf*±4.

The THD values for the output voltage and current are 106,6% and 5,0% respectively.

In summary, PWM mode has more significant harmonic components at higher frequencies than square wave operation, as well as an exceptionally high THD value on the load voltage. This may be outweighed however by a comparatively clean load current.

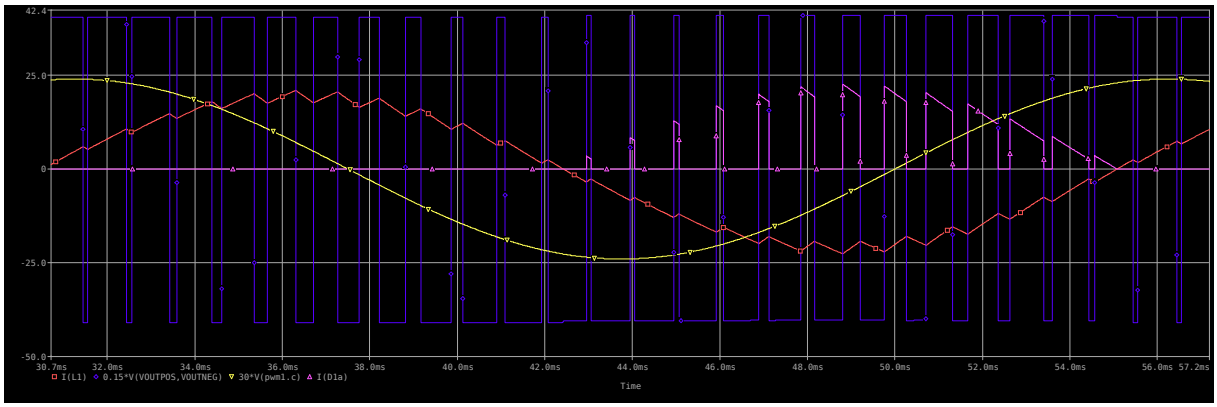
3.

L_out = 20mH



Red=Iout; Yellow=Vref; Purple=Vout; Pink=I_D1

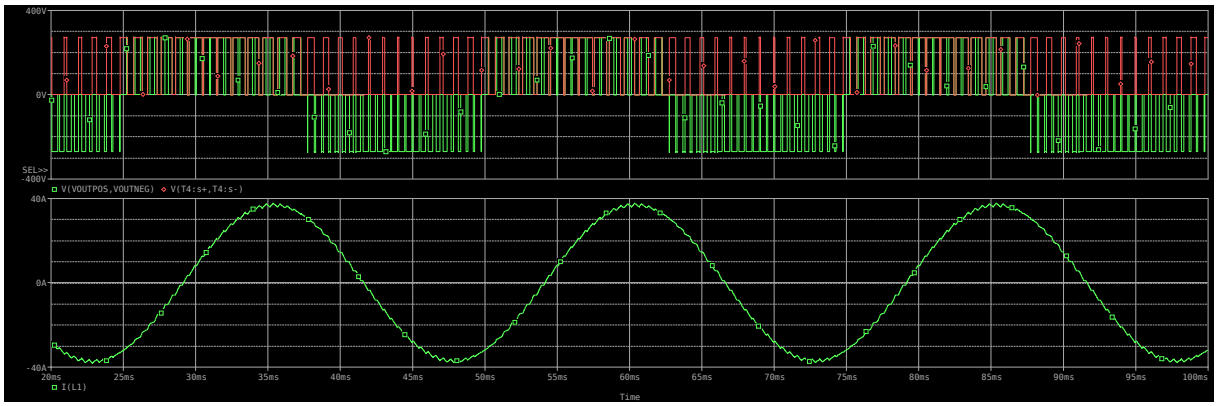
L_out = 40mH



With an increase in load inductance, both the output current and current ripple are lower. The current waveform now has a THD of 4,5%, compared to 5% before.

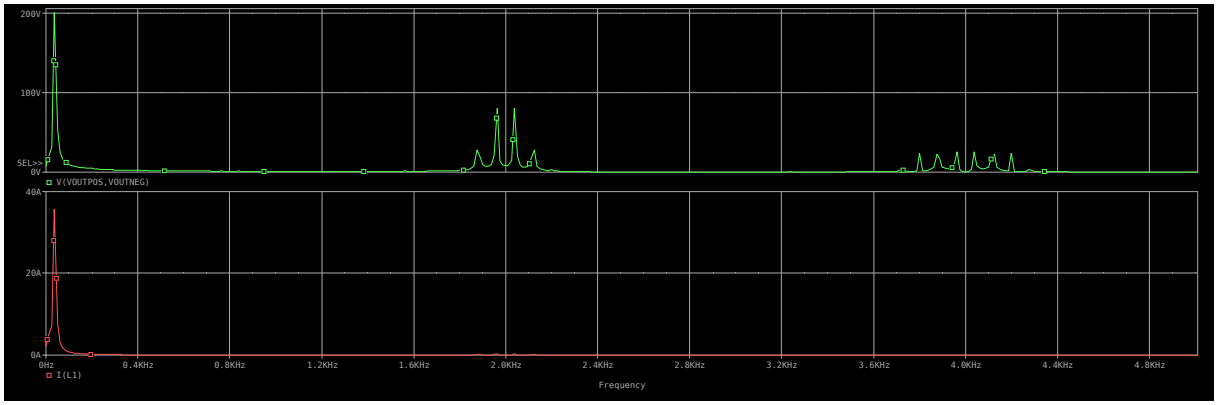
The diode conducting time has not been affected, only phase shifted (1ms to the right).

4.



Unipolar switching is used.

<u>Fourier Analysis</u>



This type of switching effectively “doubles” the frequency of the dominant harmonics and associated sidebands, they now appear only at *2fs*n*, thus reducing the harmonic content of the output signal significantly and resulting in a much cleaner output signal. The THD values for the output voltage and current are 58,5% and 1,4% respectively, indicating very little current ripple.

Another advantage is that the output voltage only has a range of Vd at any one time, lowering voltage handling requirements of peripheral components, such as in filters.

The largest drawback of unipolar switching is the relative control complexity; the two legs of the full-bridge inverter are controlled independently and two control signals are required. Each switch is activated at different times as seen in the waveforms below: