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Single Cycle Controller Type CB17

(UK Patent No 2403855B)

Harmonic Analysis with 3-phase Thyristor Controlled Loads

The following is a description of the frequency spectrum of the current drawn by a thyristor controlled 3-phase 3-wire AC resistive load operating in single cycle burst fire mode using the algorithms adopted by Caledon Controls Ltd. and covered by the above patent. Four wire star connected loads, which are essentially 3 single phase loads are not described.

It is important to understand that in this application the thyristor stack itself acts simply as a switch, and is not in itself a source of distortion. At full power, when the thyristor stack is conducting continuously there will be essentially no distortion or harmonics produced as a result of the thyristors. At less than full power harmonics and inter-harmonics are generated due to two actions:-

1 The current is being switched on and off, and the waveform is therefore discontinuous. The fundamental frequency of the switched waveform is no longer 50Hz (or 60Hz), but the inverse of the period over which the waveform repeats, which will always be less than the supply frequency.

2 Although zero-voltage switch on is employed, with a 3-phase 3-wire load, because of the 120 degree displacement of the 3-phases they do not all turn on simultaneously (two will turn on together, followed by the third), and similarly they do not all turn off simultaneously; one will turn off first, followed by the other two.

The line current waveforms may be synthesised by sequences of partial sinewaves of amplitude 1 (the nominal amplitude of the wavetrain), and $\sqrt{3}/2$ (at the start and finish of the conducting period).

Two control types are shown. In both cases the one supply cycle on followed by one cycle off situation (or the nearest attainable to this), which corresponds to approximately half power, is shown. This maximises the switching frequency and therefore the amount of discontinuity:-

Type 1 With thyristor control on all 3 lines, in which case the waveform repeats after every 6 on-off periods.

Type 2 With thyristor control on only 2 of the three lines, in which case the waveforms repeat after every 2 on-off periods, but the waveform on the uncontrolled line is different from that on the controlled line.

Photographs showing oscilloscope traces of actual currents are shown, followed by waveforms synthesised in Microsoft Excel, on which the fast Fourier transform tool in Excel has been run. The frequency spectrum thus derived is then shown. Two graphs of the spectrum are given in each case, the second showing an expanded vertical scale over the range 0-10% so that the levels of the higher order harmonics may be more readily seen. The waveforms are all based on a 50Hz mains frequency, and for 60Hz operation all frequencies shown will be multiplied by 6/5.

Because these are low frequency effects the values obtained in practice should closely match the calculated values. It is standard practice to derive harmonic spectra analytically, and analysis for common firing techniques can be found in standard textbooks.

For comparison a similar analysis for single phase, phase angle control with a firing delay of 90 degrees is also shown. In the case of the single cycle control the frequency spectrum extends below 50Hz, and most of the frequencies present are not multiples of 50Hz. This is because they are harmonics of the fundamental frequency of the composite switched waveform (the lowest frequency component on the graphs). They are often referred to as ‘interharmonics’. By contrast the phase angle control has a 50Hz fundamental, and harmonics of 50Hz. In particular the 3rd harmonic is very high.

Note that the waveforms all show the harmonic current. From the point of view of other users it is the harmonic voltage on the supply at a point of common coupling (ie where another user is connected to the supply) which is of interest. The harmonic voltage results from the harmonic current causing a voltage drop across the impedance of that part of the supply link which is common to both users. The harmonic voltage cannot be calculated without knowing this impedance. It is this harmonic voltage which in turn drives an undesirable harmonic current through the other users' equipment.

In the case of burst fire control, including single cycle burst fire control, the harmonics of the line frequency are low. This means that the effects on other users are generally associated with voltage flicker (eg lighting flicker) rather than adverse effects on 3-phase machinery caused by odd harmonics of the supply frequency.

The sum of the squares of all the harmonics and interharmonics shown in the graphs equals the power being delivered to the load, expressed as a percentage of full power. The square root of this value represents the RMS load current expressed as a percentage of the full load current. The values of the power and current have been independently calculated to verify the accuracy of the Excel calculations.

In the 3 line control example the power being delivered to the load is 42% of full power and the RMS load current is 65% of full load current. There are no harmonics of the supply frequency present in the waveform.

In the 2 line control example the values are marginally different for the controlled and uncontrolled lines.

> For the controlled lines the power is 44% of full power, and the RMS load current is 66% of full load current. The RMS sum of the harmonics of the supply frequency (up to the 9th harmonic), expressed as a percentage of the RMS current flowing is 4.5%. As a percentage of full load current it is 3.0%
>
> For the uncontrolled lines the power is 43% of full power, and the RMS load current is 65% of full load current. The RMS sum of the harmonics of the supply frequency (up to the 9th harmonic), expressed as a percentage of the RMS current flowing is 4.5%. As a percentage of full load current it is 3.0%
>
> In both cases the harmonics are odd.

The same algorithms are used in the caledon Controls Load Sequencing Controller, type CU02.

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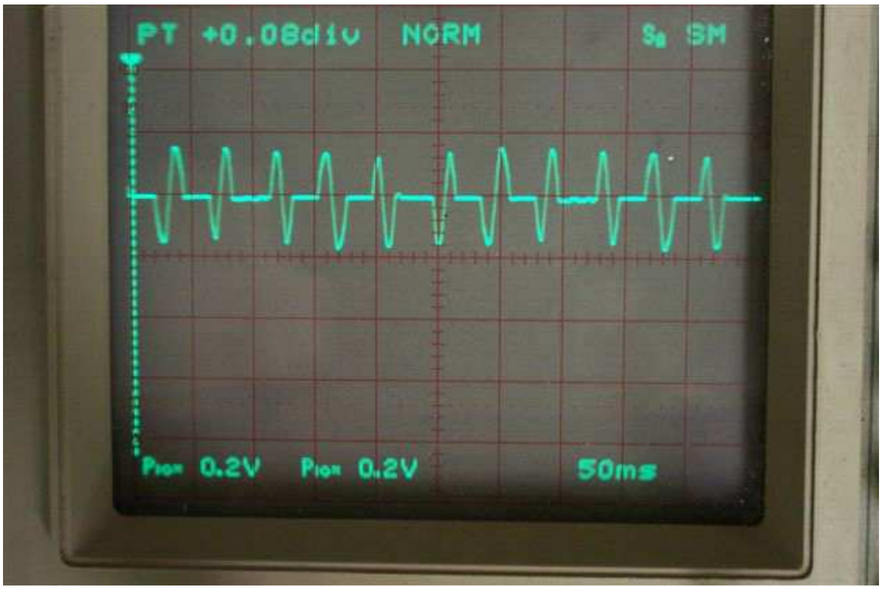
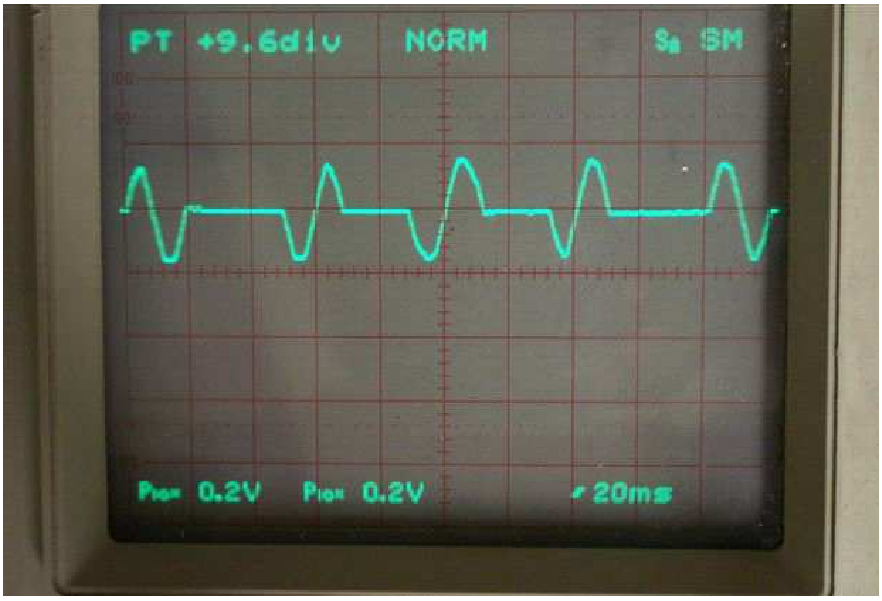
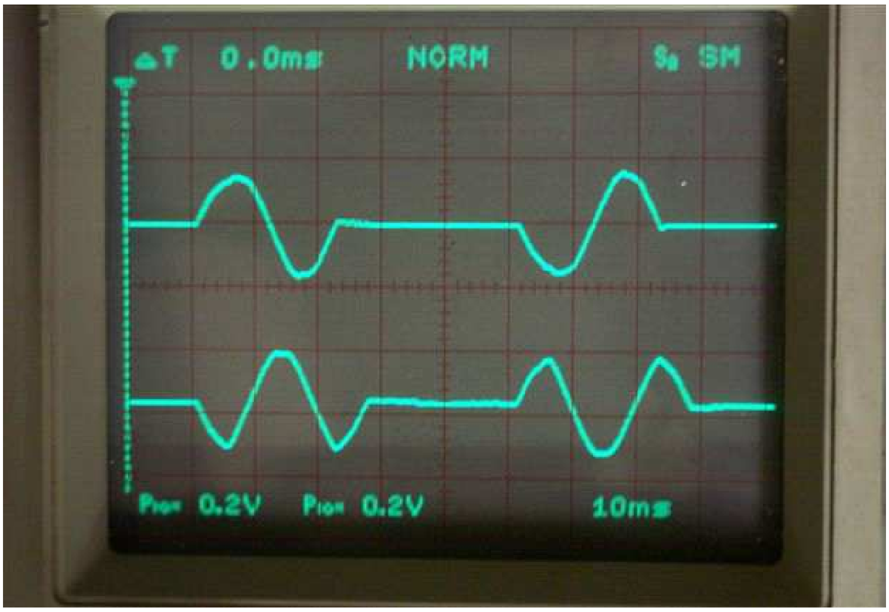


Line current waveform: 3-phase 3-wire load with 3 line control. The pattern repeats after 6 on-off cycles.



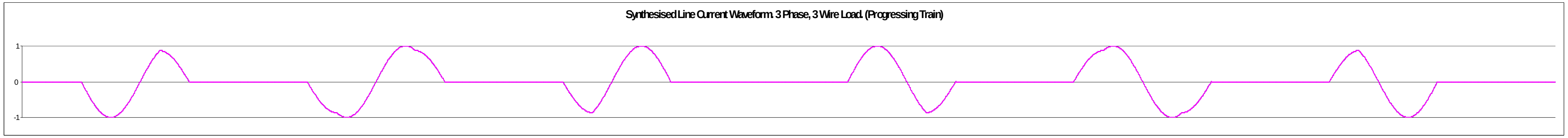
As above, but expanded view to show the shape of the waveforms more clearly

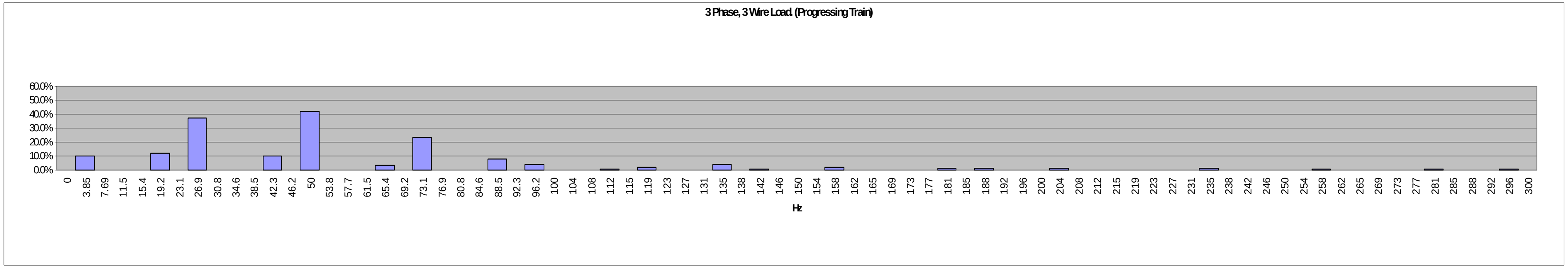


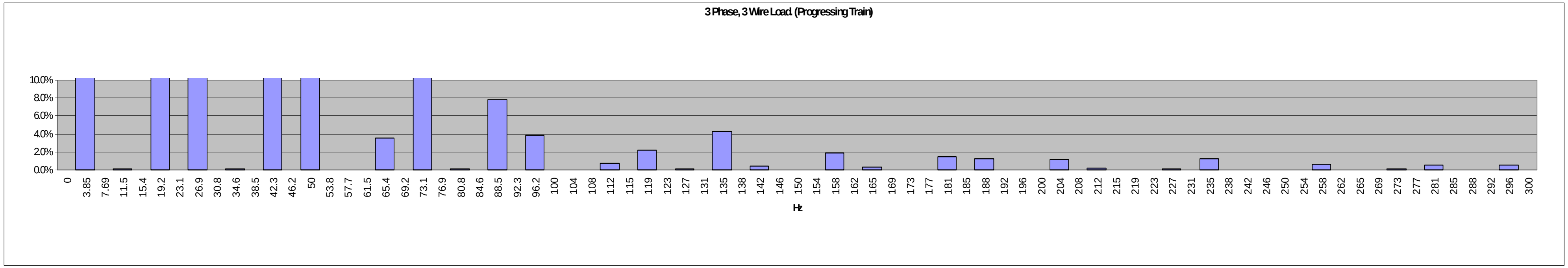
Line current waveform: 3-phase 3-wire load with 2-line control.

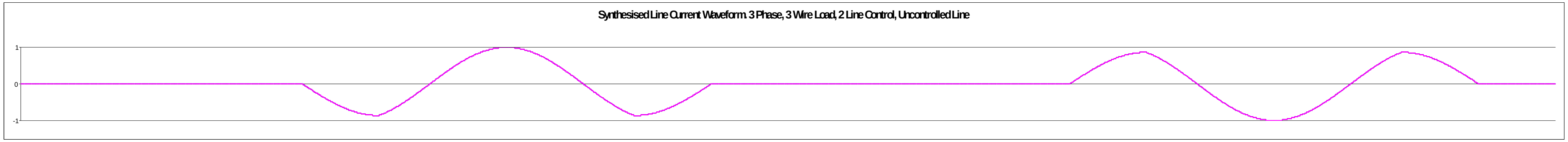
Upper waveform: Controlled lines.

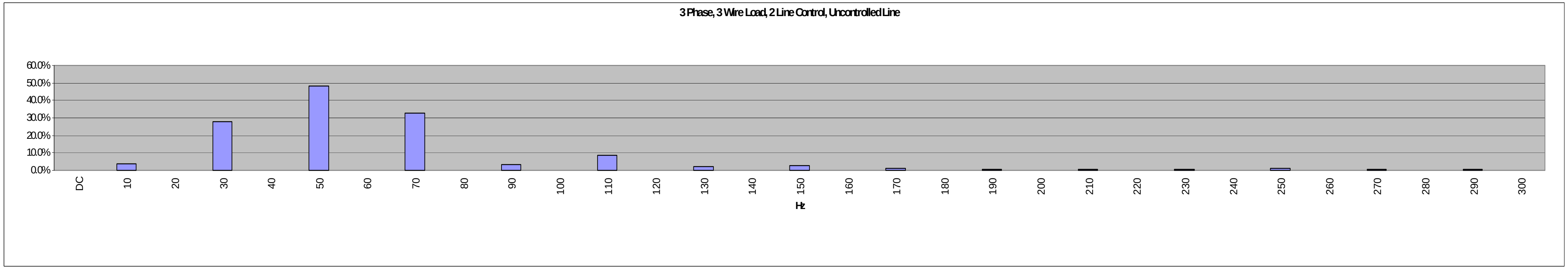
Lower waveform: Uncontrolled line.


Synthesised Line Current Waveform 3 Phase, 3 Wire Load (Progressing Train)


3 Phase, 3 Wire Load (Progressing Train)
Hz


3 Phase, 3 Wire Load (Progressing Train)
Hz


Synthesised Line Current Waveform 3 Phase, 3 Wire Load, 2 Line Control, Uncontrolled Line
1
0
-1


3 Phase, 3 Wire Load, 2 Line Control, Uncontrolled Line
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
DC
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
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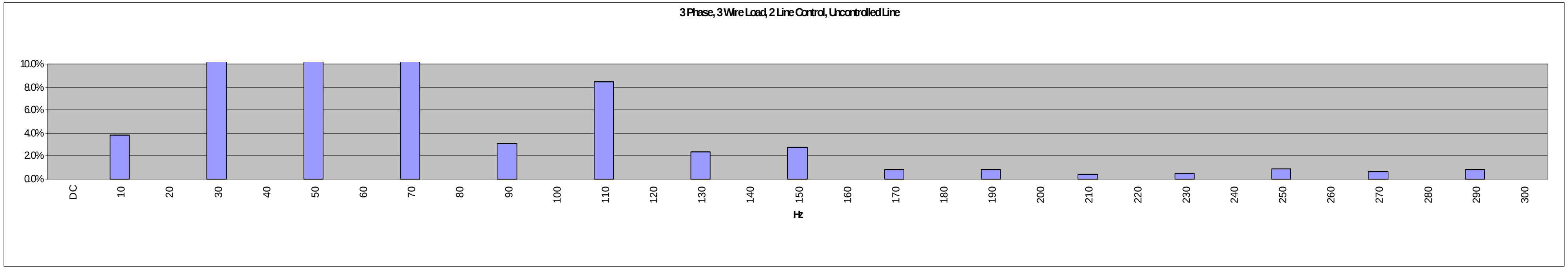
250
260
270
280
290
300
Hz


3 Phase, 3 Wire Load, 2 Line Control, Uncontrolled Line
10.0%
8.0%
6.0%
4.0%
2.0%
0.0%
DC
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
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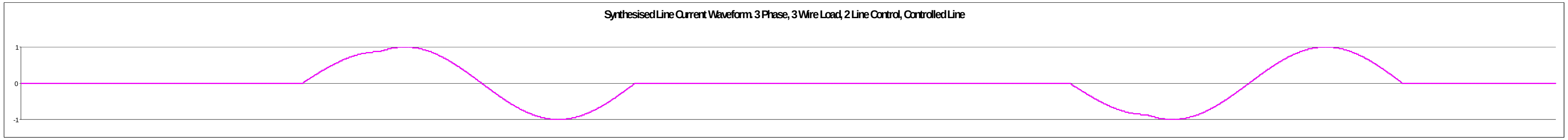
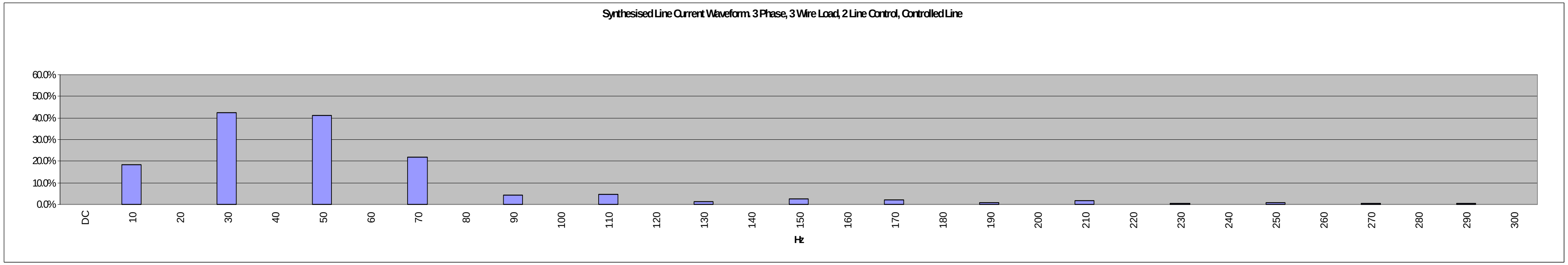
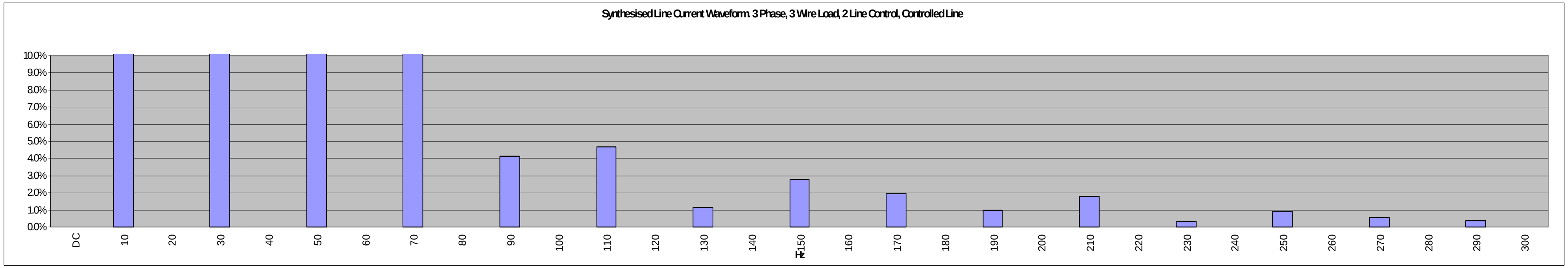
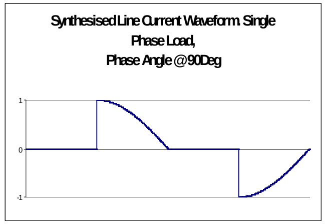
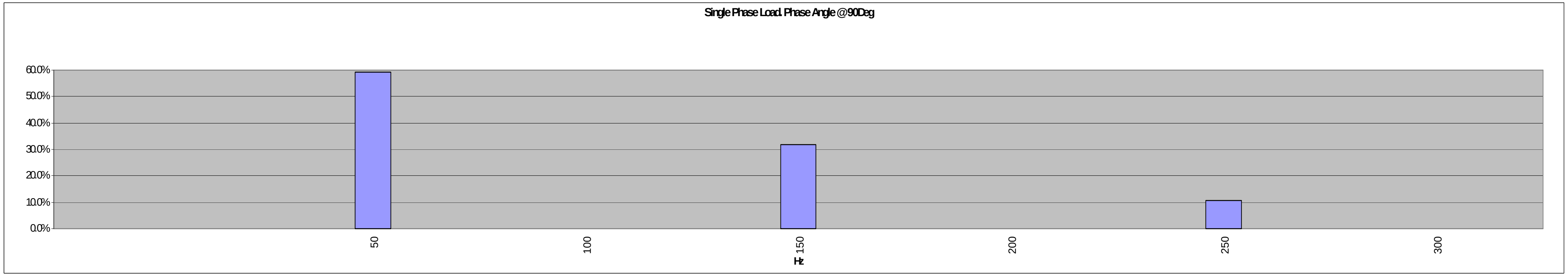
270
280
290
300
Hz


Synthesised Line Current Waveform. 3 Phase, 3 Wire Load, 2 Line Control, Controlled Line
1
0
-1


Synthesised Line Current Waveform. 3 Phase, 3 Wire Load, 2 Line Control, Controlled Line
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
DC
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
Hz


Synthesised Line Current Waveform. 3 Phase, 3 Wire Load, 2 Line Control, Controlled Line
10.0%
9.0%
8.0%
7.0%
6.0%
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
DC
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
Hz


Synthesised Line Current Waveform Single
Phase Load,
Phase Angle @90Deg
1
0
-1


Single Phase Load. Phase Angle @90Deg
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
50
100
150
200
250
300
Hz