by Don Lancaster

Steplocked Magic Sinewaves

I have long been fascinated by long sequences of digital ones and zeros. Those I prefer to call *magic sinewaves* seem especially useful to convert any raw unregulated direct current supply source into high level single or multi phase sinewaves with precisely controlled amplitudes and amazingly low distortions.

Important uses of magic sinwaves include...

- electric or hybrid vehicles
- ac motor speed controls
- solar panel converters
- portable battery inverters
- 400 cycle aerospace power
- uninterruptable power supplies
- power quality pfc management
- robotic motion controls
- 3-phase industrial machinery
- telephone ring generation

The advantages of the all-digital magic sinewave route do include simplicity, efficiency, amazingly low distortion, precise control, and low-end microcontroller compatibility. Far less high frequency energy is involved. There are fewer switching events for significantly reduced switching losses.

Any need for custom magnetics can be minimized or eliminated entirely.

Magic sinewaves also have been a challenging quest and an ongoing venture. Because all of the really good ones are exceedingly beyond one-in-a-trillion rare. Until recently, really worthwhile magic sinewaves did seem excruciatingly hard to pin down.

Secrets of Steplocking

Recently, I have been exploring a new magic sinewave synthesis concept that I call *steplocking*. Steplocked magic sinewaves give you all the jitter-free amplitudes you could possibly need. They also do so while letting you *force any desired number of low frequency harmonics to zero!*

Steplocking is somewhat similar to PWM, or *pulse width modulation*, but with these crucial differences

- Vastly fewer pulses per cycle are needed
- Pulses are locked to the fundamental
- All chosen low harmonics are nearly zero.
- Any number of jitter free steps are possible.
- Low storage needs of 26 bytes per amplitude.
- Often can be made 3-phase delta friendly
- Extreme (0.001 degree) accuracy is required.

The concept here is simple enough: You design a digital binary waveform that is all fundamental and carrier. Make 100% of your energy be one or the other, and there will be nothing left over to create problem harmonics. You'll also shove as much of your error energy as high in frequency as you possibly can. Then you'll get rid of unwanted "sharp corners" energy by using intertia or a motor's inductance as an integrating filter.

Let's look at the nearby "normal" example. Six pulses per quadrant are used, equal to a carrier of 24 times the desired sinewave fundamental frequency.

After being properly optimized, such a carrier might start off giving you *zero* odd and even harmonics up through your 22nd, strong 23rd and 25th carrier "sidebands", and mostly weak additional odd harmonics well up into the hundreds. All even harmonics are typically zero.

Analysis & Synthesis

Steplock analysis is sneaky but straightforward. I have not yet found any closed formula to instantly give you the exact magic sinewave you want. Especially for the fancier options we will look at shortly.

Such obvious tricks as interpolation from earlier results only get you close. Instead, a progressive approximation search seems needed.

You might start off by obeying what I call the *minimum visible pollution theorem*. This principle tells us that the closer you make your pulses "look" like a pure sinewave, the better off you will be.

One good starting point is to pick equally spaced pulse centers, and then proportion your width of each pulse to what a sinewave would need near that angle for the exact amplitude you are now seeking.

Try this, though, and you're likely to get lousy results with unacceptable harmonic distortion. So your next step is to simply "shake the box". Carefully move the start and end of each pulse in 0.000001 degree or tighter increments, seeking a minimum of the rms total of the harmonics you are expecting to force to zero. If a magic sinewave solution exists, such a minimization technique often finds it.

Despite those trillion to one odds.

Now, the only little remaining problem is that you've got your zero harmonics but your amplitude will probably be off. So, you "servo" your amplitude, "lying" about the amplitude you ask for to try and get the value you really want. Ferinstance, if you are after amplitude 0.4000 and get a 0.4006 instead, you ask for a 0.3994 on the next try.

"NORMAL" MAGIC SINEWAVE

ANXC24 - 57/100

SUMMARY: This steplock-24 "constant amplitude increments" magic sinewave is not delta friendly. Harmonics 2 through 22 are virtually zero. The first major harmonics are the 23rd and 25th. Harmonic amplitudes are relative to the fundamental. Filtered "f" harmonics assume a filter of an "integrating" or 1/H or 1/f response. An 0.001 degree or better timing accuracy is required.

```
Desired Amplitude:         0.57
Actual Amplitude:          0.569999
Actual Power:              0.324899
Distortion 2H-22H:         0.00096016%
First strong harmonics:    23 and 25
Pulses per sine cycle:     24
Total switching events:    48
Delta Friendly:            No
```

```
P1 start: 5.1278      end: 6.2655      delta: 1.1377
P2 start: 20.1049     end: 23.2776     delta: 3.1727
P3 start: 34.1831     end: 39.2932     delta: 5.1101
P4 start: 48.423      end: 55.1945     delta: 6.7715
P5 start: 62.9925     end: 71.0116     delta: 8.0191
P6 start: 77.9668     end: 86.6674     delta: 8.7006
```

```
  H3: -7.10092e-07    H21: -3.80407e-06    H21f: -1.81146e-07
  H5: -3.6481e-06     H23:  0.803194       H23f:  0.0349215
  H7: -5.7061e-08     H25: -0.440767       H25f: -0.0176307
  H9:  4.65998e-06    H27: -0.169326       H27f: -0.00627134
 H11:  4.11531e-07    H29: -0.0100077      H29f: -0.000345094
 H13:  5.11062e-06    H31:  0.0125276      H31f:  0.000404115
 H15: -2.63622e-06    H33:  0.0149846      H33f:  0.00045408
 H17:  2.2086e-06     H35:  0.0162002      H35f:  0.000462862
 H19:  2.01816e-06    H37:  0.0174321      H37f:  0.000471138
```

```
c1sd =  0.0
c1ed =  0.0
c2sd =  0.0
c2ed =  0.0
c3sd =  0.0
c3ed =  0.0
c4sd =  0.0
c4ed =  0.0
varx = 2.2243%.
```

The process sounds ugly and, yes, the convergence ends up rather slow for certain values. Needless to say, if the magic sinewave you are seeking does not exist, you are not very likely to find it. But the analysis routines are easily handled by the superb general purpose PostScript computer language. And should be realizable in other languages.

Useful magic sinewave results are frustratingly few and far between, so you often need to use *extremely* tiny search increments. These dudes are lying in deep cover! The zero harmonic nulls are exceptionally narrow and deep. They are easily missed.

Better than one part per million is recommended during analysis and one part in 30,000 for synthesis.

These precisions may seem extreme, but they really are essential for any useful results. Note that a ten thousandth of a degree of a fundamental gets progressively more coarse as your harmonic numbers go up. And that harmonics are specified relative to the fundamental. And that there is yet another factor of one hundred any time you start talking small perceentage values.

A one microsecond timing precision at 60 Hertz is not excessive. Not in the least.

To zero out more harmonics, you simply increase the number of pulses per cycle. Trading off efficiency-robbing switching events for distortion control.

Synthesis is fairly trivial, and easily handled by any PIC microcomputer. You stash some delay values in memory somewhere. Use these to time out the turnon and turnoff of each pulse. You mirror reflect your first quadrant delay values for the second quadrant. Then interchange outputs for the bottom half cycle.

Bells and whistles are easily added.

Because of the extreme positioning accuracy required, frequency control is probably best handled seperately by raising or lowering the clock frequency of the actual magic sinewave synthesizer. Details vary with need.

Getting Fancy

What I have just described is the *normal* steplock magic sinewave sequence. Things get even more interesting when you start exploring these intriguing options...

"ENHANCED" MAGIC SINEWAVE

AEXC24 - 57/100

SUMMARY: This steplock-24 carrier suppressed "constant amplitude increments" magic sinewave is not delta friendly. Harmonics 2 through 24 are virtually zero. The first major harmonics are the 25th and 27th. Harmonic amplitudes are relative to the fundamental. Filtered "f" harmonics assume a filter of an "integrating" or 1/H or 1/f response. An 0.001 degree or better timing accuracy is required.

```
Desired Amplitude:         0.57
Actual Amplitude:          0.569999
Actual Power:              0.324899
Distortion 2H-24H:         0.0016277%
First strong harmonics:    25 and 27
Pulses per sine cycle:     24
Total switching events:    48
Delta Friendly:            No
```

```
P1 start: 12.7084     end: 14.5303     delta: 1.8219
P2 start: 25.4965     end: 29.0625     delta: 3.566
P3 start: 38.4459     end: 43.5967     delta: 5.1508
P4 start: 51.6323     end: 58.1195     delta: 6.4872
P5 start: 65.1187     end: 72.5928     delta: 7.4741
P6 start: 78.9357     end: 86.9411     delta: 8.0054
```

```
  H3: -4.83751e-06    H19: -3.61587e-06    H19f: -1.90309e-07
  H5: -4.52684e-07    H21: -2.90377e-06    H21f: -1.38275e-07
  H7: -3.48072e-06    H23: -1.94504e-06    H23f: -8.45668e-08
  H9: -6.0062e-06     H25: -0.74578        H25f: -0.0298312
 H11: -5.11993e-06    H27:  0.519984       H27f:  0.0192587
 H13: -9.73988e-06    H29:  0.199263       H29f:  0.00687113
 H15: -6.38196e-06    H31:  0.0249853      H31f:  0.000805979
 H17: -2.45922e-06    H33:  0.00155691     H33f:  4.71791e-05
```

```
c2sd =  0.0
c2ed =  0.0
c3sd =  0.0
c3ed =  0.0
c4sd =  0.0
c4ed =  0.0
c5sd =  0.0
c5ed =  0.0
varx = 3.6166%.
```

Carrier Suppression – By delaying and narrowing all the pulses suitably, you might *enhance* your results by forcing one additional odd harmonic to zero. As is shown in our "enhanced" example, the 23rd harmonic is also forced to zero. Much of the needed 23rd energy moves up to the 27th and 29th. Enhancing can be done by zeroing your narrowest pulse.

Constant Power Increments – Steps of constant power are easily gotten simply by asking for the square root of your amplitude. For instance, to get the 0.57 power level in the "power" example series, you really ask for an amplitude of 0.7549. Other compensations, such as for lamp brightness or load nonlinearity are equally easy to handle.

Delta Friendliness – Three phase loads can be exceedingly demanding in that you'll normally want to switch only the *delta* or wye connected ends of an existing motor. By using only three half-bridge drivers. This places *extreme* limits on your digital sequences. A delta friendly magic sinewave has to obey these two wondrously obtuse rules...

> If there is zero energy in a narrow sample in the 60 to 90 degree interval, then there also must be zero energy in 120-n and n-60 degree samples.
>
> If there is one energy in a narrow sample in the 60 to 90 degree interval, then either but not both of narrow samples 120-n and n-60 degrees must also be a digital one.

Our "delta friendly" example rearranges things such that the "early" quadrant pulses and the "middle" pulses *exactly* add up to and occupy those same shifted time widths and positions as the "late" quadrant pulses. This sometimes can get done by splitting and spreading your "early" pulses. In this example, one of the split pulses was forced to a zero width, leaving you with only one extra pulse needed.

Shared Pulses – Since there is no "hole" in the top of any sinewave, it sometimes makes sense to end each quadrant with a "half" pulse that gets continuously shared with its mirror in the adjacent quadrant. This gains you efficiency because of its four less transitions per cycle.

"POWER" MAGIC SINEWAVE — PNXC24 - 57/100

SUMMARY: This steplock-24 "constant power increments" magic sinewave is not delta friendly. Harmonics 2 through 22 are virtually zero. The first major harmonics are the 23rd and 25th. Harmonic amplitudes are relative to the fundamental. Filtered "f" harmonics assume a filter of an "integrating" or 1/H or 1/f response. An 0.001 degree or better timing accuracy is required.

Desired Power:	0.57
Actual Power:	0.570004
Actual Amplitude:	0.754986
Distortion 2H-22H:	0.00280368%
First strong harmonics:	23 and 25
Pulses per sine cycle:	24
Total switching events:	48
Delta Friendly:	No

P1 start: 6.5807	end: 7.9501	delta: 1.3694
P2 start: 19.7636	end: 23.8198	delta: 4.0562
P3 start: 33.1612	end: 39.748	delta: 6.5868
P4 start: 46.9206	end: 55.7708	delta: 8.8502
P5 start: 61.2185	end: 71.9104	delta: 10.6919
P6 start: 76.226	end: 88.0418	delta: 11.8158

H3: 4.12131e-06	H21: 1.2991e-05	H21f: 6.18618e-07
H5: -1.16603e-05	H23: 0.566697	H23f: 0.024639
H7: -3.73359e-07	H25: -0.223865	H25f: -0.0089546
H9: 1.10683e-05	H27: -0.265764	H27f: -0.0098431
H11: -7.84968e-06	H29: -0.0699187	H29f: -0.00241099
H13: -1.2681e-06	H31: -0.00842073	H31f: -0.000271637
H15: 1.40929e-05	H33: -0.000586764	H33f: -1.77807e-05
H17: -3.21663e-06	H35: 5.63657e-05	H35f: 1.61045e-06
H19: -8.33785e-06	H37: -0.000374254	H37f: -1.0115e-05

c1sd = 0.0
c1ed = 0.0
c2sd = 0.0
c2ed = 0.0
c3sd = 0.0
c3ed = 0.0
c4sd = 0.0
c4ed = 0.0
varx = 1.5721%.

"DELTA FRIENDLY" SINEWAVE — ANDC24 - 57/100

SUMMARY: This steplock-24 "constant amplitude increments" magic sinewave is fully delta friendly. Harmonics 2 through 22 are virtually zero. The first major harmonics are the 23rd and 25th. Harmonic amplitudes are relative to the fundamental. Filtered "f" harmonics assume a filter of an "integrating" or 1/H or 1/f response. An 0.001 degree or better timing accuracy is required.

Desired Amplitude:	0.57
Actual Amplitude:	0.569998
Actual Power:	0.324897
Distortion 2H-22H:	0.000823799%
First strong harmonics:	23 and 25
Pulses per sine cycle:	28
Total switching events:	56
Delta Friendly:	Yes

P1 start: 3.2089	end: 4.4724	delta: 1.2635
P2 start: 0.0	end: 0.0	delta: 0.0
P3 start: 18.0554	end: 19.96	delta: 1.9046
P4 start: 24.8653	end: 26.6919	delta: 1.8266
P5 start: 35.1347	end: 40.04	delta: 4.9053
P6 start: 48.8375	end: 55.5276	delta: 6.6901
P7 start: 63.2089	end: 71.1625	delta: 7.9536
P8 start: 78.0554	end: 86.6919	delta: 8.6365

H3: -2.66285e-07	H19: 1.26135e-06	H19f: 6.63869e-08
H5: 5.51211e-06	H21: 3.80408e-08	H21f: 1.81146e-09
H7: 5.19256e-06	H23: 0.69968	H23f: 0.0304209
H9: 2.21904e-07	H25: -0.49741	H25f: -0.0198964
H11: 2.14239e-06	H27: -2.36698e-07	H27f: -8.76659e-09
H13: 4.0967e-08	H29: 0.213105	H29f: 0.00734844
H15: 6.21332e-08	H31: 0.140614	H31f: 0.00453593
H17: -2.05196e-06	H33: 1.69454e-07	H33f: 5.13498e-09

c2sd = 0.0
c2ed = 0.0
c3sd = 0.0
c3ed = 0.0
c4sd = 0.0
c4ed = 0.0
c5sd = 0.0
c5ed = 0.0
varx = 3.635%.

Sharing is possible when the total number of pulses per cycle is divisible by *two but not four*. As in 14, 18, 22, etc... A bunch of new "mix and match" option combinations are possible. For instance, shared pulses can also be enhanced by carrier suppression and/or get used in power or other increments. But I do not yet see any means to force either carrier suppression or certain shared pulses to also end up 3-phase delta friendly. At least not so far.

Building a Demo

A magic sinewave generator might be done with a PIC whose clock frequency is set externally to a high multiple of your desired sinewave fundamental. Pulse delay values are table stored. Two bytes per delay value should be good enough. Giving us a total of thirteen or so double bytes per sinewave amplitude quadrant.

A simple "pick-and-place" command stalls for suitable pulse or interpulse times. Depending on available pins, amplitudes can be selected from a parallel word input or a pair of "up" and "down" lines.

For More Help

An extensive steplocked magic sinewave catalog full of various options, amplitudes, and carrier frequencies can be found at www.tinaja.com/magsn01.html

Sourcecode, development software, analysis tools, and custom design help is also available through the InfoPack service from Synergetics or by emailing don@tinaja.com

Let's hear from you. ✦

Microcomputer pioneer and guru Don Lancaster is the author of 35 books and countless articles. Don maintains a US technical helpline you will find at (520) 428-4073, besides offering all his own books, reprints and consulting services.

Don has catalogs at www.tinaja.com/synlib01.html and at www.tinaja.com/barg01.html

Don is also the webmaster of www.tinaja.com You can also reach Don at Synergetics, Box 809, Thatcher, AZ 85552. Or you can use email via don@tinaja.com