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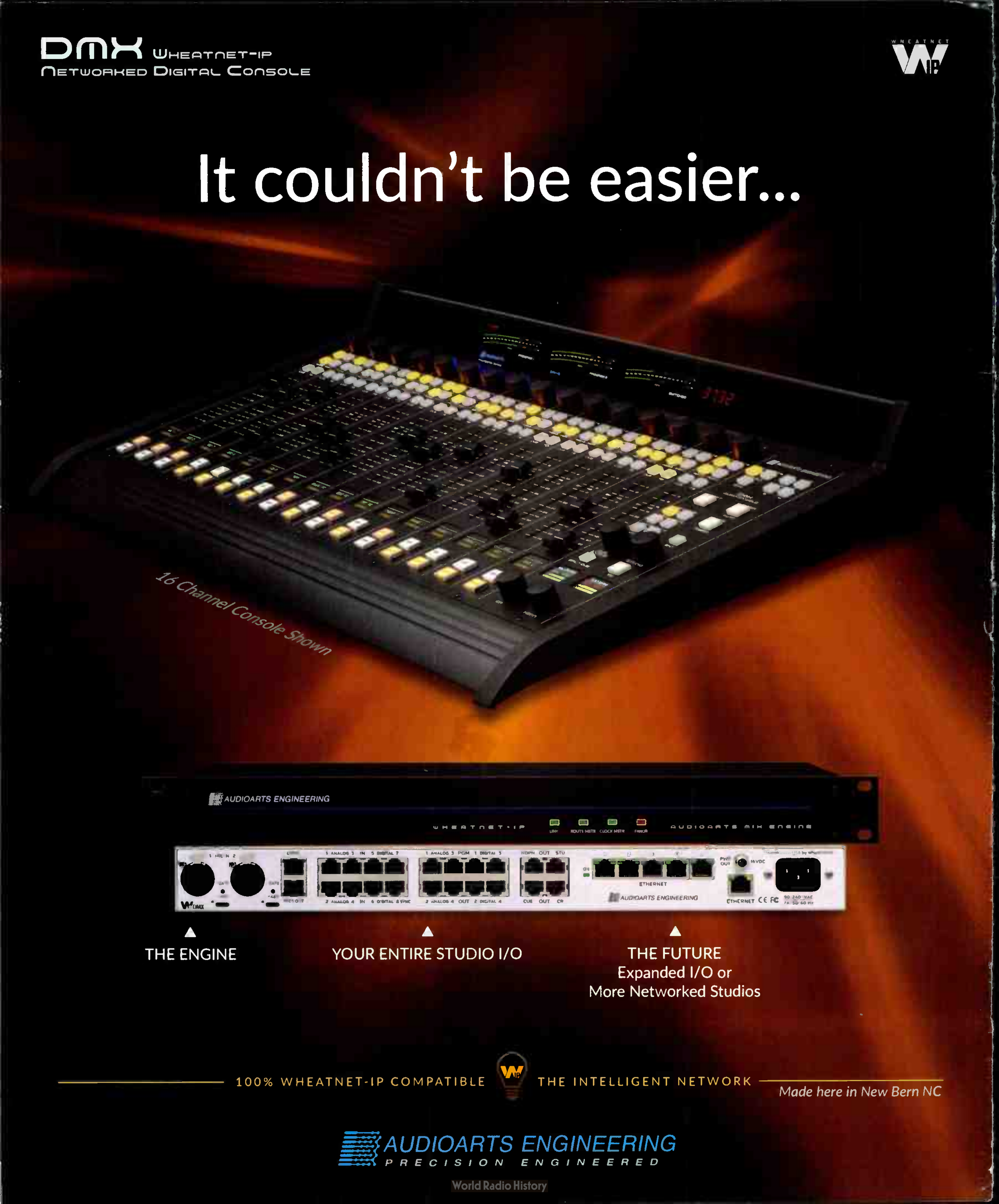
Add some flare to that skirt!

Ben Dawson and Bobby Cox write that the simple skirt feed has shortcomings that can be eliminated by use of different geometries.

FUTURE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Get around the NIMBY challenge

Building a new tower today can be just BANANAs

Cris Alexander
CPBE, AMD, DRB
Technical Editor

Putting up a tower was no big deal in the early days of my broadcast engineering career, once you had your FAA "No Hazard" determination. Just order the tower, dig a few holes, pour some concrete and stack up the sections.

From "let's do this" to "done" could be 90 or 120 days.

I was involved in several projects like that back in the good old days. We took for granted the ease with which we could get steel in the air.

But times change, and boy have they changed. The last major tower project I undertook required a full five years from property acquisition to completion. The FAA's part of that was about 60 days, as I recall, but the rest ... the rest took years.

Alphabet soup

We started off on that project by talking to the county, which had jurisdiction over the unincorporated area in which our site was located.

They told us on Day One that no, we couldn't build any towers higher than 30 feet — county ordinance. And indeed, looking around Orange County, Calif., you will see very few towers or monopoles higher than 30 feet, and most of those are grandfathered.

But we pressed on. We really had no choice. We got past the 30-foot cap by going the political route. It wasn't cheap and it wasn't easy.

Of course we then had to do the NEPA screening — the National Environmental Policy Act requires a lot of boxes to be checked. It consumed months of study and produced volumes of paper.

And then there was NPA — the Nationwide Programmatic Agreement. That required us to contact any and all Native American tribes that may have ever had a presence anywhere in the vicinity of the tower site.

Then we had to comply with the state environmental laws, which in California are like NEPA on steroids. We

THIS ISSUE

were required to have a biologist and an anthropologist present at various stages of the project. We had to do biological surveys of the property to ensure that there were no nests of certain endangered species present.

All of that, however, was fairly straightforward: rules, policies and procedures with which we had to comply.

Certainly there were variables; I hate to think what might have happened had the biological survey turned up a nest of an endangered species or had the pier auger brought up some bone fragments. At the very least that would have meant significant delays and added expenses.

Wild card

But the wild card in all this process had little to do with statutes, codes, policies and procedures. It was something that we have come to know as NIMBY — "Not In My Back Yard."

Although the site was remote and not adjacent to anyone's back yard, it was on a private inholding within a national forest, a place used for recreation by a lot of people, and those folks came out of the woodwork when word got out that we were proposing to build not one but four radio towers on top of the mountain.

At that point, the process became even more political, with county commissioners and other politicians involved. We did our best to get ahead of it, hiring a land use expert to advise us and help us through the neighborhood association meetings.

For some, instead of NIMBY, BANANA was the acronym of the day — "Build Absolutely Nothing Anywhere Near Anything" — and in some locales that is the attitude. Don't even ask the question because the answer is no.

Thankfully we were able to deal with most of the concerns, everything from worries about the California Gnatcatcher to the possibility of bats flying into the towers to light pollution (yes, folks were worried about light pollution from the tower lights in the ocean of light that is Southern California).

One at a time, we dealt with those issues, and while we still had some vocal detractors, the majority were satisfied that we would have little to no negative impact on their playground, and eventually we got our use permit and later, our building permit.

Above
Stacking the new towers was easy. Getting to that point was anything but.

All of that was before the FCC's ASR rules were revised, requiring public notice and a comment period. Today, those wishing to stack steel have those requirements to deal with on top of everything else.

Save yourself trouble

While Southern California may not be the best example of a typical tower construction location, it's not atypical, not anymore. Tower proponents have to comply with NEPA and NPA no matter the location, and just about anywhere in the nation there will be NIMBY or BANANA sentiments in play, and depending on the local political situation, those can be showstoppers.

Which brings me to my point: If a tower is already in existence somewhere close to the desired location, finding a way to utilize it rather than go the route of new construction can take years off the project and save tons of money.

If there is a nearby tower of a height that will work, chances are that it may not be suited for the application. AM towers can be adapted for use by FM, wireless and other applications, but there are challenges. FM and wireless towers can be used for AM, but that requires skirting, which presents mechanical challenges. But that is often much preferable to jumping through all the regulatory hoops and dealing with the NIMBY crowd.

In this issue

On the following pages, Ben Dawson and Bobby Cox present a proven idea for a different way to skirt a grounded tower that avoids many of the mechanical and electrical issues found with traditional skirts.

While you may not be on the cusp of a site move right now, there may be one in your future, and the ideas that Ben and Bobby bring may well be the game-changer you will be looking for some day.

Also in this issue, we'll wrap up Dennis Sloatman's excellent treatment of three-phase power.

So get out your clamp-on ammeter and plug in your soldering iron. Our aim is to give you, the reader, tools you can use in these pages. When you can, drop us a line and let us know how we're doing at *rweetech@gmail.com*. In the meantime, read on …

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1 = Coming Soon | 2 = Requires an additional internal card

Flared skirts offer options for grounded tower feeds

Dawson and Cox on umbrella-spoke feed for grounded medium-wave antenna towers

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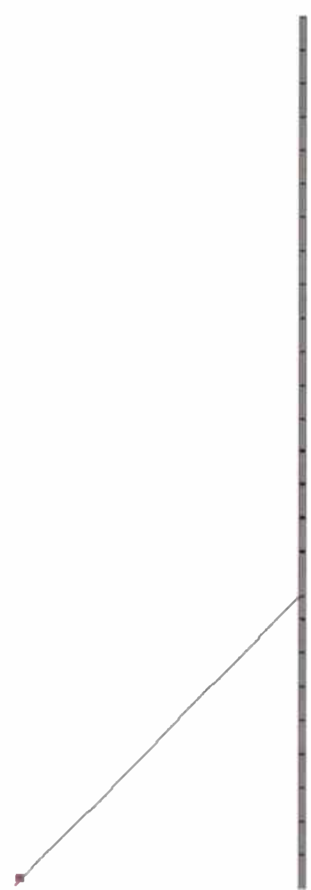
The increasing use of single antenna systems for multiple frequencies and use of medium-wave antenna structures for mounting antennas for other uses has led to the exploration of alternative methods for feeding grounded towers.

While the simple skirt feed with multiple parallel wires insulated from the tower is fairly common, other methods such as slant-wire feeds and skirts with other geometries offer substantial advantages.

The simple skirt feed has shortcomings that can be eliminated by the use of flared skirts, which extend from at or near the tower top to a location near midpoint on a guy wire and then back to a common connection near the tower base. The advantages are that the skirt wires need not add substantial compression load to the tower or be supported by multiple insulators, and that in general their impedance bandwidth is excellent. The flared skirt also has less long-term maintenance concerns and is less obstructive to tower climbers and to installations of other services on the tower.

Flared skirt systems exhibit vertical radiation patterns that are essentially the same as base-fed antennas of the same height, and do not generate excessive horizontally polarized radiation.

Right
Fig. 1: Traditional skirt feed geometry



Far right
Fig. 2: Slant wire feed geometry

Antenna Tower Feed Systems

While the base-fed monopole tower has been the most common medium-wave antenna since the 1930s, antenna towers grounded at the base have also been employed in many installations. Grounded tower antennas have essentially the same electrical behavior (pattern characteristics) as base-fed antennas of the same electrical length.

Straight Wire Skirt Feeds Parallel to Towers

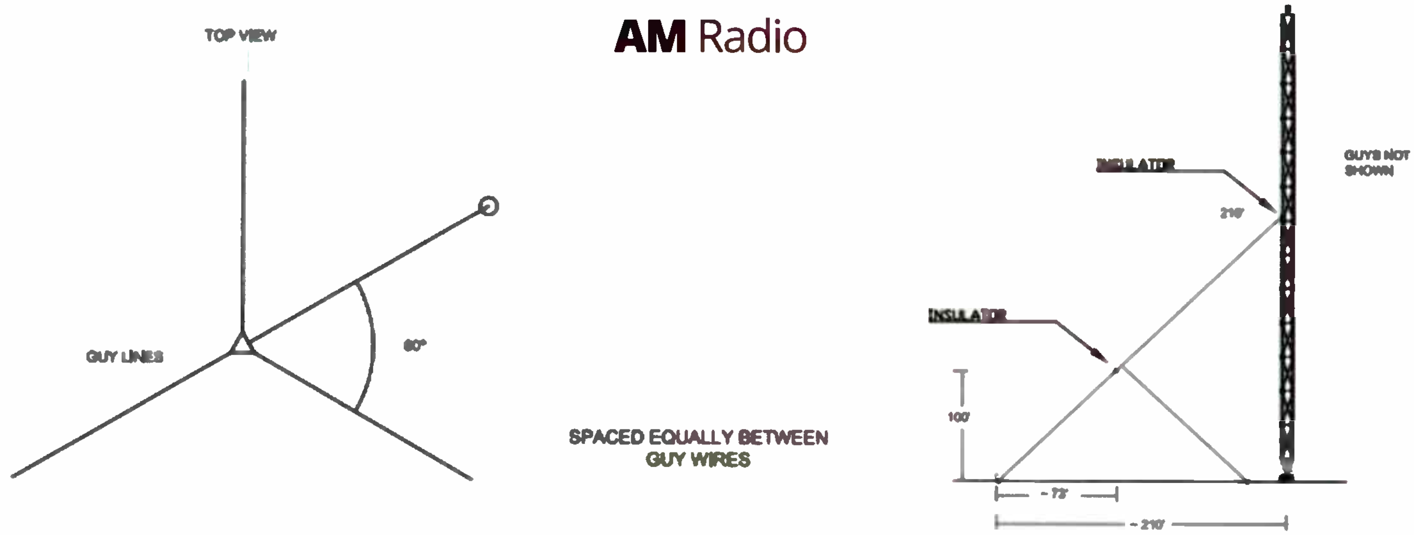
The most common method of feeding the grounded tower employs wires connected to the tower at an elevated location, most commonly a skirt of several wires, roughly parallel to the tower face, as shown in Fig. 1.

Traditional skirt feeds have several unfortunate characteristics. The skirt must be kept at a constant spacing from the tower to avoid impedance changes in windy conditions. This can require the use of numerous insulators between the skirt and the tower, or substantial tension on the skirt wire. The wire tension adds additional compression load on the tower legs. The use of insulators adds weight and wind loading, and can obstruct other installations on the tower.

They can also be a maintenance issue, requiring periodic cleaning, and they can obstruct tower climbing.

The spacing of the skirt from the tower and the number of skirt wires are critical for impedance bandwidth. In some cases the design can result in poor performance because of inappropriate choice of insulator length or tuning stub location.

A particular concern often caused by insufficient spacing between the skirt wires and the tower is impedance changes caused by icing. Even a very small skin of ice can result



Above, left and right
Fig. 3: STA antenna using single umbrella-spoke skirt wire

Below
Fig. 4: The flared skirt feed

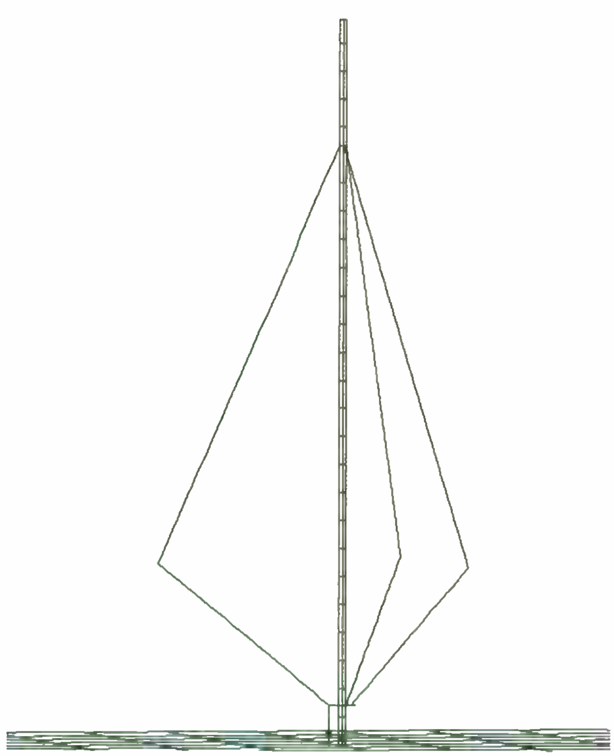
in considerable impedance change under some conditions.

Slant Wire Feeds

Slant wire feeds, which have been used since the 1930s, are a simple feed system solution for grounded towers in the quarter wavelength range.

They are simple to install, and structurally minimal. However, for towers much over 120 degrees in height they result in high angle radiation pattern distortion. They also have a ground level high voltage point, at their feed location, distant from the tower base area, as shown in Fig. 2 on page 6.

They are the most economical method of feeding a grounded tower. Their only complexity is in high-power installations where the slant wire needs to be a ribbon or bundle to reduce surface voltage gradients well below corona levels.



Single Parallel Wire Feeds

A single wire, extending along the tower structure, connected at the top and insulated from the tower as it descends (like one wire of a conventional skirt), can also be used to drive a grounded tower. It can be visualized as one half of a folded dipole, with unequal diameters.

This design can be a good emergency antenna but generally will have relatively narrow bandwidth impedance characteristics.

Single Wire Umbrella-Spoke Feeds

The single wire "umbrella spoke" feed is sometimes used as an emergency or Special Temporary Authority ("STA") antenna and is a good solution for that purpose, such as shown in Fig. 3.

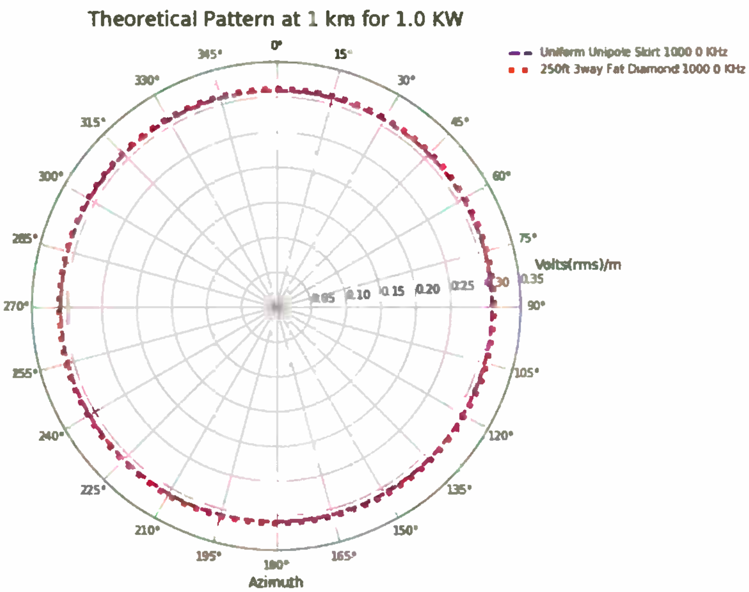
Examples have also been constructed with the geometry carefully modeled so as to have a purely resistive input impedance. Others have used guy wires on HF curtain antennas or have been supported by grounded FM towers. But this feed arrangement suffers from high angle radiation pattern distortion if used with taller towers, and can produce non-circular horizontal radiation patterns.

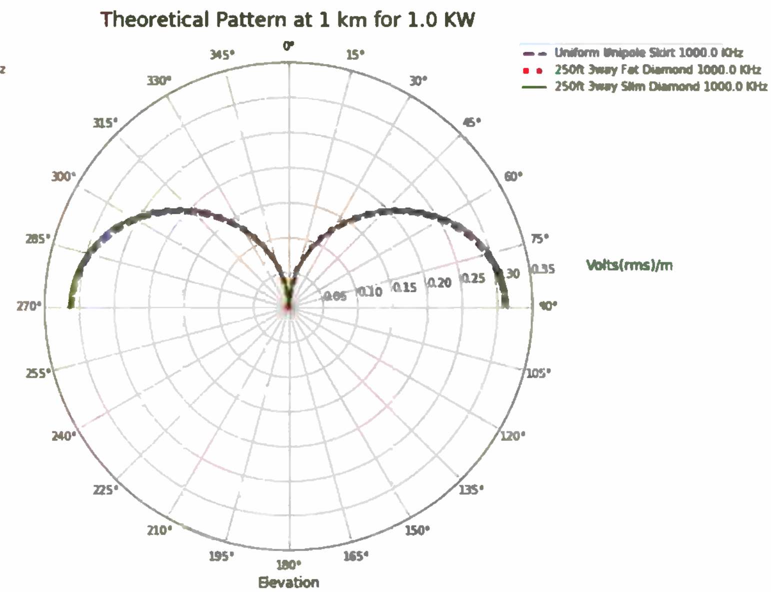
Flared Skirt or Umbrella-Spoke Feeds

The flared skirt with multiple wires, usually three for triangular towers and four for square ones, has significant advantages over all other methods of feeding a grounded tower as an efficient wide-bandwidth radiator.

The flared skirt, as shown in Fig. 4, does not require tower attachment except at its top and (if mechanically convenient) bottom ends. It can be configured so that it's used as part of one of the uppermost guy levels. Its additional structural load is largely just the weight of the necessary cables, with no extra compression load on the tower legs. Because there is no requirement for intermediate support insulators, there is easier access to other antennas and hardware on the tower, and maintenance is reduced.

One minor disadvantage is that the skirt wires need to be "clocked" from the primary guy wire directions to avoid contact with the lower guy levels. Intermediate azimuths 60 degrees from the adjacent guy orientations can be used, but much smaller offsets of just a few degrees are also possible. This requires additional anchors, but unless the skirt support is also used as a primary upper-level guy, this anchor is far less substantial than the anchors for the main guy cables.





Above left
Fig. 5: Horizontal plane pattern

Above right
Fig. 6: Vertical patterns

Frequency Allocation Considerations

While the RMS efficiency of an MF or LF antenna (directional or non-directional) is a significant characteristic in determining the value of the antenna, the radiation pattern, both vertical and horizontal, is of critical importance in its fit to the allocation requirements for operation.

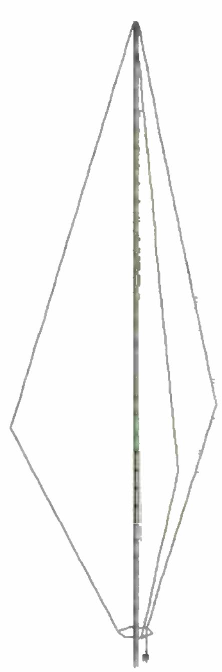
The horizontal plane circularity of flared skirt antennas is generally well within ±1 dB or less, which is within the accepted definition of omni-directional operation [see 47CFR1.30002(a)]. Vertical pattern characteristics of a flared skirt antenna or of multiple tower directional antennas employing flared skirts are nearly indistinguishable from the patterns of base fed antennas of the same electrical height.

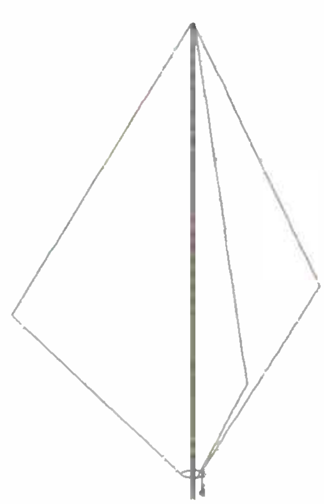
Impedance and Bandwidth Characteristics

Electrically, the significant advantage of the flared skirt is superior impedance bandwidth characteristics. This is of substantial value for very short (45 to 60 degree) towers, or for use with multiple frequencies. The flared skirt generally has the best bandwidth performance of any feed system for short towers and has significantly better impedance characteristics than conventional vertical wire skirts.

Two examples of flared skirt antennas are shown in Fig. 7. The example on the left is a "Slim" flared skirt and the one on the right is a "fat" flared skirt. The enhanced bandwidth qualities are more pronounced with the wider flared skirt.

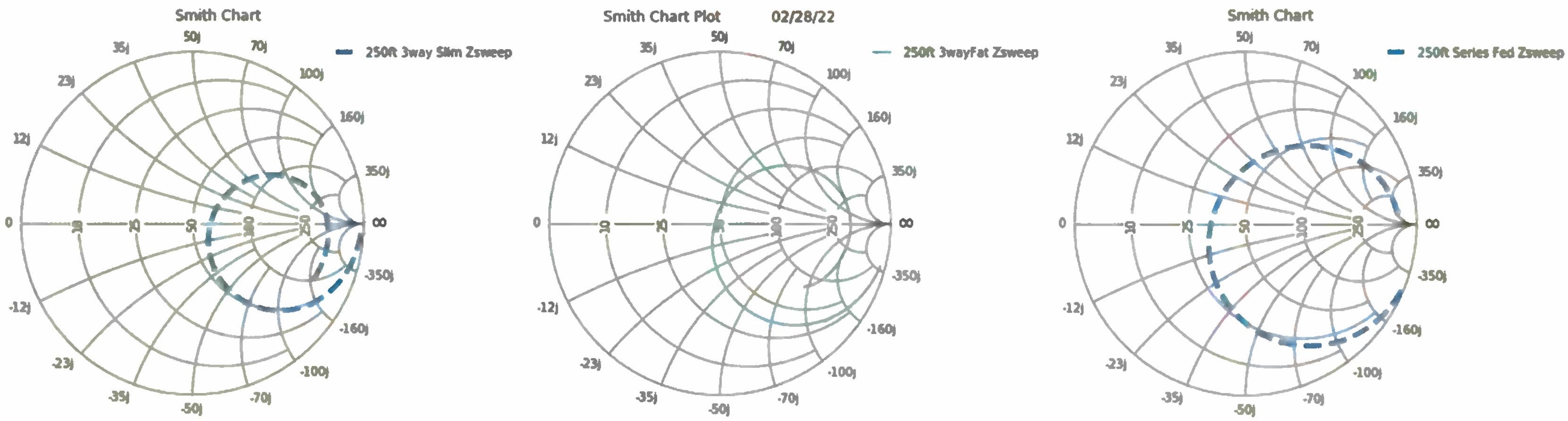
Note that as the skirt is made more and more slim, the design





Below left
Fig. 7: Small and large angle of skirt and tower

> "The flared skirt with multiple wires has significant advantages over all other methods of feeding a grounded tower as an efficient wide-bandwidth radiator."



approaches the case of the traditional straight skirt fed "folded unipole" antenna, and the wideband characteristics diminish significantly. A good proportion for a wide flared skirt antenna is to have the individual folds of the antenna form roughly a 3-4-5 triangle with the tower being the longest length of the triangle, the upper half of the skirt being the "4" and the lower half of the skirt being the "3" of the triangle. This wide flare can be achieved using anchors for the cables that tension the skirt elements placed no further from the tower than the uppermost guy anchors. If this wide flare is not achievable, then the more narrow flare is still a significant improvement in bandwidth characteristics over the traditional skirt fed system.

The midband VSWR values for the flared skirt are several percent better at ±10 and 15 kHz than that of the conventional unipole.

Examples of typical impedances for several feed arrangements are shown in Figs. 8 and 9. The fat skirt definitely works well over the full band for the 250-foot tower height used as the example. The example tower's electrical height ranges from 49° to 147.7° over the frequency range. The series fed tower is too short to be desirable at the lower end of the band for that tower height. The slender skirt is a bit in between, but still quite a bit better than the series fed.

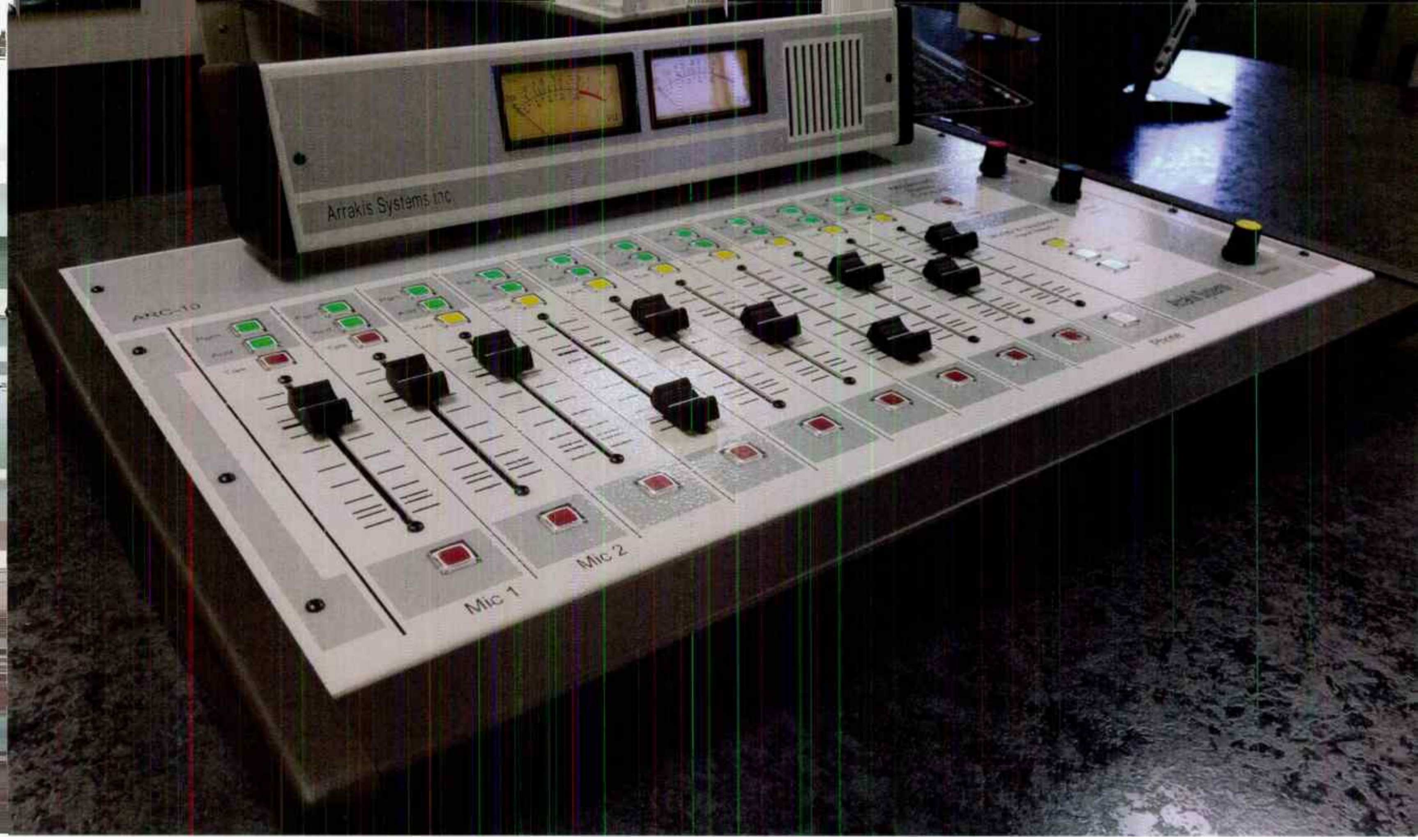
Above
Fig. 8: 530–1695 kHz impedance plots for small and large angle of skirt and tower as well as base-insulated and series-fed tower, all at 250-foot height

Right
Fig. 9: Comparison of normalized impedance characteristics for 250-ft. tower fed with three methods for example frequencies across the AM band

Below
Fig. 10: Calculated vs. measured impedance for a typical flared skirt antenna

Freq. (kHz)	Series Fed Impedance	VSWR	Slim Flared Skirt Impedance	VSWR	Fat Flared Skirt Impedance	VSWR
535	7.7 – j 244.4	4.243	350.9 – j 1403	4.600	43.2 – j 359 .0	3.066
540	7.9 – j 240.2	2.694	283.6 – j 1230	2.838	41.8 – j 341.6	2.121
545	8.0 – j 236.1	1.671	236.3 – j 1093	1.693	40.6 – j 325.4	1.453
550	8.2 – j 231.9	1.000	201.6 – j 982.2	1.000	39.5 – j 310.4	1.000
555	8.4 – j 227.9	1.613	175.3 – j 890.6	1.651	38.6 – j 296.4	1.430
560	8.5 – j 223.9	2.523	154.9 – j 813.6	2.595	37.8 – j 283.3	1.992
565	8.7 – j 219.9	3.756	138.7 – j748.0	3.843	37.0 – j 270.9	2.702
885	28.6 – j 22.9	1.319	58.7 – j 12.2	1.181	57.8 + j 34.4	1.159
890	29.1 – j 20.2	1.200	59.5 – j 8.9	1.115	58.9 + j 37.1	1.103
895	29.6 – j 17.6	1.096	60.2 – j 5.7	1.056	60.0 + j 39.8	1.050
900	30.1 – j 14.9	1.000	61.0 – j 2.5	1.000	61.2 + j 42.5	1.000
905	30.6 – j 12.3	1.091	61.8 + j 0.7	1.055	62.3 + j 45.2	1.048
910	31.1 – j 9.7	1.189	62.7 + j 3.8	1.111	63.6 + j 47.9	1.099
915	31.7 – j 7.0	1.297	63.5 + j 6.9	1.169	64.8 + j 50.6	1.151
1235	98.9 + j173.0	1.118	245.3 + j 157.4	1.080	300.3 + j 130.6	1.076
1240	100.8 + j176.2	1.077	251.7 + j 157.3	1.053	306.6 + j 126.6	1.050
1245	102.8 + j179.5	1.037	258.3 + j 156.9	1.026	312.7 + j 122.2	1.025
1250	104.8 + j182.7	1.000	265.0 + j156.4	1.000	318.7 + j117.4	1.000
1255	106.9 + j186.0	1.038	271.8 + j 155.5	1.026	324.6 + j 112.3	1.025
1260	109.0 + j189.3	1.076	278.7 + j 154.4	1.052	330.3 + j 106.7	1.050
1265	111.1 + j192.6	1.115	285.8 + j 152.9	1.080	335.8 + j 100.8	1.076
1585	484.8 + j404.0	1.080	187.4 – j 211.8	1.107	128.4 – j 141.3	1.102
1590	497.5 + j404.2	1.053	181.4 – j 210.3	.071	124.9 – j 139.3	1.067
1595	510.4 + j404.0	1.026	175.6 – j 208.6	1.035	121.5 – j 137.2	1.033
1600	523.7 + j403.6	1.000	169.9 – j 206.8	1.000	118.2 – j 135.1	1.000
1605	537.3 + j402.7	1.026	164.5 – j 205.0	1.035	115.0 – j 132.9	1.034
1610	551.1 + j401.3	1.053	159.2 – j 203.0	1.071	112.0 – j 130.7	1.068
1615	565.3 + j399.5	1.080	154.1 – j 200.9	1.110	109.0 – j 128.4	1.105

Frequency	Calculated Impedance	Measured Impedance
540 kHz	39.3 + J 41.8	43.8 + J 40.8
702 kHz	116.4 + J 83.9	139.8 + J 78.2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Below
Fig. 12: Base region geometry of a six-wire flared skirt, upper image, and a flared skirt replacing conventional skirt due to instability in icing conditions, bottom image.

Above
Fig. 11: Temporary installation, left, and high-power installation, above.

The example shows that the usable portion of the band is widest with the fat skirt, and that it has noticeably wider bandwidth than a series fed configuration.

The low resistances of the series fed case on the low end of the band are especially troublesome for multiplexing.

Comparisons with measured data show that the NEC impedance calculations for the flared skirt antenna are quite accurate. As an example, see Fig. 10 at the bottom of page 10.

Examples of some real-world flared-skirt installations are shown on this page. Umbrella-spoke towers perform equally well in directional arrays.

Conclusions

The flared or "umbrella-spoke" feed arrangement for grounded towers employed as radiators in medium- and long-wave antennas is both physically practical and electrically advantageous. Numerous examples of both temporary and permanent installations shown in this discussion have performed reliably.

The vertical and horizontal radiation patterns are essentially the same as conventional parallel skirt fed antennas or base driven antennas. They exhibit drive impedance characteristics that make them very desirable for multiple-frequency installations, particularly when the frequency spacing is large.

The flared skirt has proven to be a valuable tool to make multiplexed scenarios practical when no other tower feed method would do so. They are no more mechanically complex than conventional skirt feed arrangements and exhibit fewer undesirable effects from adverse weather conditions.

Dennis Sloatman
CSRE, AMD, CBNT, BSEET

A three-phase power tutorial — Part 2

Engineers must have a good understanding of three-phase power

In Part I of this series in June, I hit the high points of three-phase power and briefly discussed closed and open delta and wye connections. In this part, we'll take a look at the wye connection, then review the delta and look at some three-phase math. Let's get right to it.

Ask Wye!

Three-phase wye connections are also known as "Y" and "star" connections. In our use, they generally provide a three-phase 208 VAC service.

The wye has advantages in that it offers better power distribution. It provides a neutral and each phase to neutral can provide a source for a single-phase load. The phase to neutral is 120 VAC and the phase-to-phase voltage is 120 x √3 VAC or 208 VAC. Let's discuss the schematic of a three-phase wye connection shown in Fig. 1.

To be clear, this circuit may be constructed using a single "package" transformer or by using three separate transformers with the same ratings. Also with this arrangement, the neutral is connected to ground (or "earth") at the distribution panel.

Unlike the delta connection in which the line current is the vector sum of the winding currents at the line-to-windings node (see Part I in the June 15 issue at *radioworld.com/digital-editions*), in the wye the line current is also the phase current.

One important aspect of a wye service is the opportunity for the electrician to analyze your three-phase loads and balance these between the three phases (something that is more difficult with the delta system described in the first article).

Wye service can also be supplied as a 480 VAC service with a phase-to-neutral voltage of 480/√3 VAC, or 277 VAC. The 277 VAC service is often used for lighting circuits.

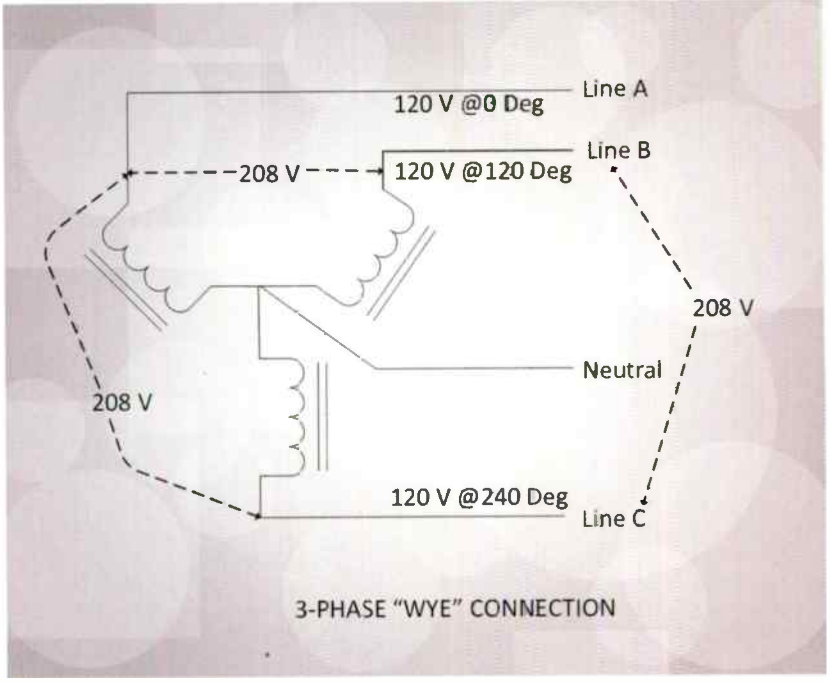
Another possible use of 480 VAC vs. a 208 VAC service can be illustrated with a real-world example from a project where I was the CE.

The facility was expanded to add more stations in the same building. The original generator was undersized and wasn't of sufficient capacity to support offices, AC and the studios. So the decision was made to double the generator capacity.

The problem facing us was that the existing wiring, sized for the ampacity of the smaller generator, was buried beneath the concrete parking lot, and could not economically or practically be upgraded.

The solution was to wire the generator for 480 VAC delta, and by doubling the voltage, the ampacity of the existing wiring was not exceeded (but twice the power delivered — same current, double the voltage).

Below
Fig. 1: Three-phase wye connection



> **The problem facing us was that the existing wiring, sized for the ampacity of the smaller generator, was buried beneath the concrete parking lot.**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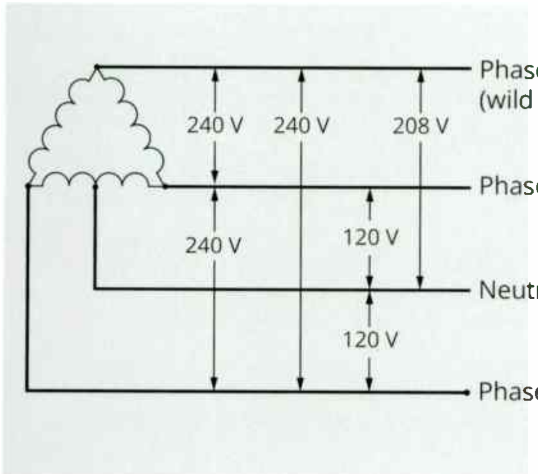


Step-down transformers in a wye configuration were then installed in the building between the generator and the generator-supplied loads to provide 120 and 208 single-phase current. The automatic transfer switch (ATS) switches between standard 208 VAC wye from Dominion Power and the stepped-down generator voltage.

Delta Revisited

Here are the key points of a Delta connection to take away. Refer to Fig. 2.

- The line and phase voltage are equal due to the phase connections being in parallel with the windings. So if you measure a voltage between phase A and phase B, you are directly measuring the voltage across winding A-B. In a similar manner, phase C to phase A is directly in parallel with winding A-C. Typical voltage in our use at transmitter plants is 240 VAC (although this can be 480 VAC in some cases).
- Line current and winding currents are related in the following manner: Phase Current = winding current / √3. Note that at any winding junction current to a phase is the current contributed to by two windings, which cannot be added to algebraically because these voltages are out phase by 120 degrees with respect to each other.

The above can best be illustrated with some examples:

- You put your clamp-on ammeter on phase A of your HT35 transmitter inside the wall disconnect and measure 118 amps. This means winding A-B contributes (118A / √3) = 68.13 amps and similarly, winding A-C contributes 68.13 amps to the phase or "line" A current of 118 amps. Again, were you to add 68.13 amps from A-B and 68.13 amps from A-C, you'd obtain 136 amps, which would be incorrect.
- You measure the phase B current as 100 amps. The winding A-B and B-C each contribute (100A / 1.732) — notice here I'm using the approximation value of √3 or 57.73 amps. (There's always a caveat. Due to imbalanced loads, IR [or resistance] losses in the transformer windings and terminals, minor variances in transformer construction, etc., your observations may vary slightly from the theoretical calculations. Also, it's often very difficult to measure the phase currents as these are often accessible only if you have access to the pole-mount transformers).

Above Left
Fig. 2: Closed delta secondary feed

Above
Fig. 3: WKHK utility pole-mounted transformers

Finally, if one of the windings has a center-tap, this can be grounded to provide a grounded neutral in order to supply current to single-phase 240/120 VAC loads (as shown in winding A-C in Fig. 2). When using this arrangement, be very cautious not to connect single-phase loads from N (neutral) to the "high" or "wild" leg which would provide a voltage of 208 VAC and destroy 120 VAC loads.

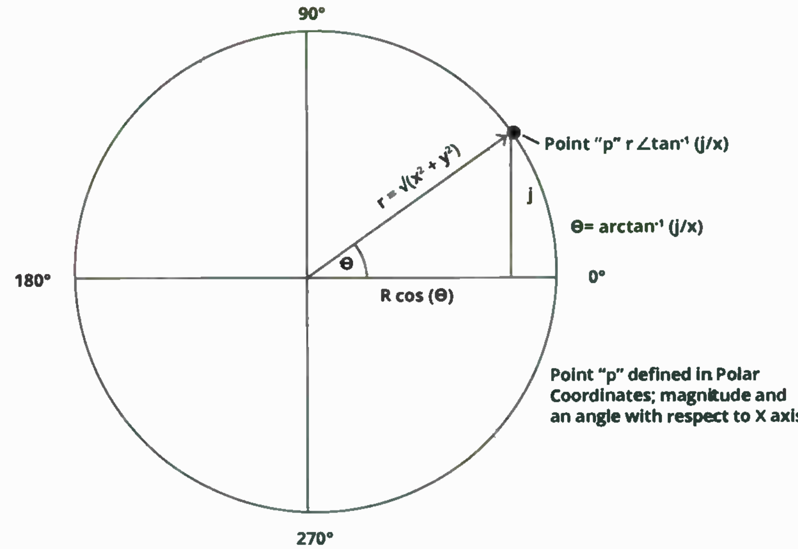
Refuse an Open Delta supply from your utility; that's "bad juju" and will introduce harmonics into your load, which is potentially damaging. GatesAir has often included a very good paper explaining this in an addendum to their transmitter manuals — highly-recommended reading.

Wye review

Now let's review wye, star or "Y" connections.

In a wye connection the center is often used a neutral connection, which is generally grounded at the main distribution panel. Let's review the wye connection as shown in Fig. 1 on page 15.

- In a wye, the line voltage is the phase voltage multiplied by the square root of 3 (√3) so, if the phase to neutral voltage is measured as 277 VAC, then the line voltage is 277 VAC * √3, or 480 VAC.
- In a wye, the line current is equal to the phase current.
- A wye has a benefit of balancing currents in the neutral, and in fact, if the load is balanced (not really a real-world situation), then no current flows in the neutral.
- Often, we will see a delta/wye HV transformer configuration in transmitters. One troubleshooting benefit in these transmitters is a wye common switch such as is available in the GatesAir (Harris) HT series transmitters, which can ground the common in the wye secondary. This will provide a high-voltage value of about 58% of the full HV value in order to run the transmitter at approximately half-power. This may allow your transmitter to remain on the air until parts arrive.



Above
Fig. 4: Polar coordinates

[An aside: There exist some transmitters such as the CSI/CCA series in which grounding the common of the wye secondary is employed as a step-start so that the center of the wye is grounded briefly at HV on and then reverts to an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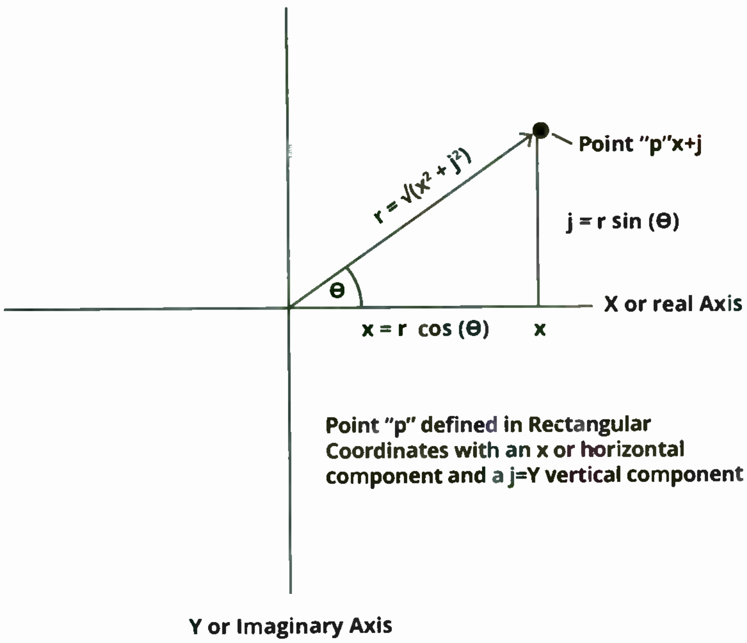

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Fig. 5: Rectangular coordinates

ungrounded wye after a fraction of a second. This reduces the high-current surge as a result of the instantaneous change of voltage across the HV supply filter capacitor (recall that Ic = C ΔE/Δt, which means the current across a capacitor Ic is the capacitance times the change in voltage per unit time. So, if the time is "instantaneous" or near zero, then the current "I" approaches infinity). The step start system used in a transmitter serves to reduce this effect.]

With what you have learned from this series, you should become familiar with your facility utility power feed and look at your pole-mounted transformers (known colloquially as "pole pigs"). Fig. 3 on page 18 shows utility pole-mounted transformers. Note at the very center of the photo the large connection plate that has six wires connected. The other three wires (one from each transformer) run down the pole through a wire chase.

> "With what you have learned from this series, you should become familiar with your facility utility power feed and look at your pole-mounted transformers."

So, what type of service is this? If you answered a "wye," you are correct! The three transformers are bonded together at a common point for neutral (there are six wires to provide two per phase for current handling and redundancy).

You should venture to be at least conversational about your electrical service as a broadcast engineer. Sincerely, if you want to discuss the topic with me or have some questions, please reach out. It's a complex topic for sure.

The √3 Mystery

So where does the √3 factor comes from in calculating phase to phase voltage when the phase to neutral voltage is known? Let me take you through the steps to show how that number is derived. First, let's look again at Fig. 1, a three-phase wye circuit.

Each phase is 120 degrees out of phase with respect to the other two phases. Note the + and – signs on each winding. These indicate phase and not polarity in the sense you would for DC.

We have the following voltages to consider in our calculations:

V_{AN} (Phase A to Neutral)
V_{BN} (Phase B to Neutral)
V_{CN} (Phase C to Neutral)

We arbitrarily choose for our zero degree reference the VAN winding, but you can choose any phase to neutral winding you wish.

Before we start, let's make our work a bit easier by doing some "pre-calculations."

In rectangular mode, we know that we have X and Y components with X being the "real" component and Y being the "imaginary" part referred to in engineering as "j" (used to indicate reactance, for example).

So for our convenience, let's pre-calculate some quantities and review coordinates.

Note: there are two expressions to locate a point on Cartesian coordinates. In polar form a point is defined in space by a magnitude "r" and an angle Θ as shown in Fig. 4. In rectangular form, a point in space is defined by cartesian coordinates of x and j as shown in Fig. 5.

Rect = r (cosΘ) + jr (sinΘ) (in rectangular form, where R equals an x value and j value with rectangular coordinates)

Polar = √(x²+y2) ∠tan-1 (y/x) (in polar form, where P equals a magnitude and phase angle)

√3 ≈ 1.732 Van = Phase Voltage; V_{AB}, V_{AC}, V_{BC} = Line-to-line voltages

cos (0) = 1; sin (0) = 0

cos (-120) = -1/2; sin (-120) = ((-√3)/2) (verify this with your calculator; be certain it's in "degree" mode)

Note: Your scientific calculator can perform polar to rectangular **P → R** and rectangular to polar **R → P** conversions, but I prefer to run the calculations manually as above; use whichever approach works best for you.
Now, we begin our calculations:

V_{AB} (the voltage **between** phase A and B (not to neutral) is:

$V_{AB} = V_{AN} - V_{BN}$ (because if you look at Fig. 1 and move from phase A down through neutral to phase B, you see that at the neutral node "N," phase B comes in negative and comes out positive). Also, we know that with respect to phase A, phase B is –120° or +240° (same thing).
So, we write:

$$V_{AB} = V_{AN} - V_{BN}$$

$$V_{AB} = V \angle 0° - V \angle -120°$$

$$= [V\cos(0°) + j\,V\sin(0°)] - [V\cos(-120°) + j\,V\sin(-120°)]$$

Now, using what we already have calculated above:

$$= [V(1)+j(0)] - [V\frac{-1}{2} + jV\left(\frac{-\sqrt{3}}{2}\right)]$$

Simplifying and collecting terms:

$$= V - \left(\frac{-V}{2}\right) - j\left(\frac{-\sqrt{3}}{2}\right)$$ (Remember that minus a minus = plus here!)

$$= V + \frac{V}{2} + j\left(\frac{\sqrt{3}}{2}\right)V$$

$$= \frac{3V}{2} + j\left(\frac{\sqrt{3}}{2}\right)V = V_{AB}$$ (Rectangular form of V_{AB})

We convert the VAB (rectangular) to polar form (using $P = \sqrt{(x^2+y^2)}\ \angle\tan^{-1}(y/x)$) from above:

$$V_{AB} = \left(\left(\frac{3V}{2}\right)^2 + \left(\frac{\sqrt{3}}{2}V\right)^2\right)^{1/2} \angle\tan^{-1}\left(\frac{\sqrt{3}}{2}V / \frac{3V}{2}\right)$$ ($\tan^{-1}$ is also known as "arctangent")

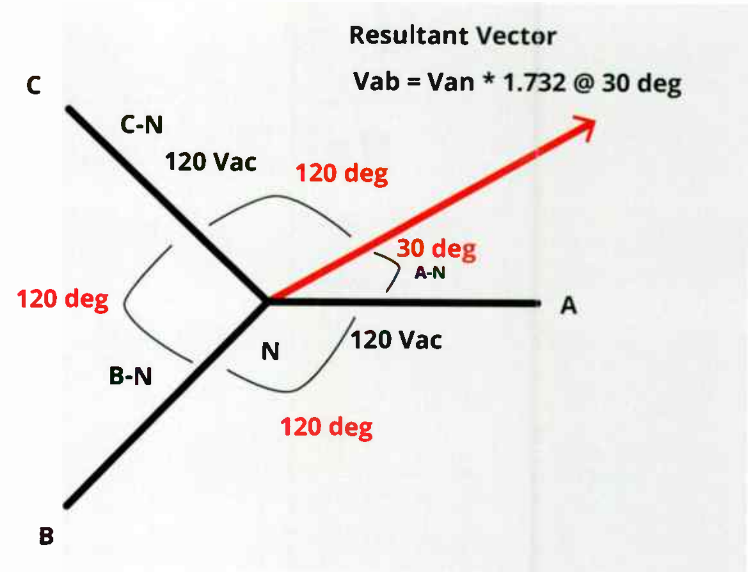
$$V_{AB} = \left(\frac{9V^2}{4} + \frac{3V^2}{4}\right)^{1/2} \angle\tan^{-1}\left(\frac{\sqrt{3}}{2}\right)$$ Note: The 2s and Vs cancel out in the $\tan^{-1}$ portion.

Now, simplifying and collecting terms:

$$V_{AB} = \left[\frac{12V^2}{4}\right]^{1/2} \angle\tan^{-1}\left(\frac{\sqrt{3}}{2}\right)$$

$$V_{AB} = [3V^2]^{1/2} \angle\tan^{-1}\left(\frac{\sqrt{3}}{2}\right)$$ clearing the fraction $\left[\frac{12V^2}{4}\right]$;

$$\tan^{-1}\left(\frac{\sqrt{3}}{2}\right) = 30°$$



Above
Fig. 6: Resultant vector

Therefore:

$V_{AB} = \sqrt{3}\,V \angle 30°$ noting that the square root of 3V2 is just √3 V

(QED - Quo Erat Demonstratum - We have shown that which was to be shown!)
See Fig. 6 for the resultant vector diagram.

Wrapping it up

So, what we have determined here is that the resultant voltage with phase A as the reference with angle 0° is √3 times the phase A-to-N voltage at an angle of +30°. The phase-to-phase angles are as noted earlier 120° apart, and if you were to analyze each phase to phase, you would obtain $\sqrt{3}V_{AN}$, $\sqrt{3}V_{BN}$ and $\sqrt{3}V_{CN}$ – but 120° apart.

As such, the "mystery" of the √3 should now be resolved. I hope!

The same concept also applies to three-phase delta circuits, with the exception being the √3 applies to the current, not to the voltage.

We hope that you have learned something and enjoyed this in-depth look at three-phase power.

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