Practical Diplexing

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Abstract

Urban sprawl, increasingly crowded airspace and an often unreasonably restrictive local regulatory climate have made the once fairly easy task of selecting a site for an AM transmitter site a daunting task. In many cases, particularly in urbanized areas, it is virtually impossible to commission a new AM tower site in a location that will provide adequate service to the target areas or communities. Jointly utilizing existing sites is quite often an economical alternative. This paper will explore some of the considerations of such joint use, focusing on combining two or more AM stations into a single antenna system.

1.0 Basic Diplexer Theory

Despite its sometimes mystical reputation, a diplexer is really nothing more than a tuned voltage divider. The on-frequency path for each station consists of a low-impedance series arm to the antenna and a high-impedance shunt arm to ground. The reject path for each station consists of a high-impedance series arm from the antenna and a low-impedance shunt arm to ground. A single series arm is made to be low impedance on the through frequency and high impedance on the reject frequency by means of tuned circuits. By the same means, the shunt arm is made to present a high impedance on the through frequency and a low impedance on the reject frequency.

Depending on transmitter design, in many cases only 35 dB or so of RF isolation is necessary between stations. Modern solid-state transmitters which use power MOSFETs in a switching mode in the output stages have a high degree of immunity to the creation of spurious and intermodulation products. Transmitters that use bipolar or otherwise linear devices in the output stages may require more filtering, as the high gain in the output stages are prone to mix signals and create IM products.

1.1 Design Objectives

The basic task of a diplexer is to combine the power output of two or more transmitters into a single antenna system while achieving the following performance objectives:

- Maintaining spurious and IM products within FCC limits
- Providing adequate bandwidth on each frequency
- Introducing minimal losses

1.2 Practical Indicators

There are several practical indicators of a diplexer's performance that can be observed by the station chief engineer. The first is that the modulation monitor on each station functions and indicates normally. A modulation monitor that indicates overshoots that are not really present or otherwise behaves abnormally is a good indication of inadequate filtering, insufficient bandwidth, spurious emissions or a combination of these factors.

Each station's transmitter should operate normally and have no observable effect on the other station's transmitter. If the operating parameters of one transmitter visibly change when the other station's transmitter is turned on and off, this is a good indicator of inadequate diplexer design or some other problem with the diplexer.

A well-constructed diplexer will have J-plugs installed at strategic points throughout the system. One such point is on each station's side of the diplex point (or the point where all station's signals combine together). With the transmitter turned off, one should be able to remove the shorting bar on this J-plug without affecting any of the other transmitters in the system. No change in the antenna current, VSWR or other observable parameters should take place when this shorting plug is removed.

Finally, all the components in a diplex system should run relatively cool to the touch. Hot components are indicators of excessive loss and that something is wrong with the design, construction or tuning of the system.

2.0 Diplexer Design

While there are a number of ways to design a diplexer from the very simple to the very complex, there is a more-or-less "conventional" scheme that has been well proven. Using this conventional diplexer design scheme, it is hard to go wrong.

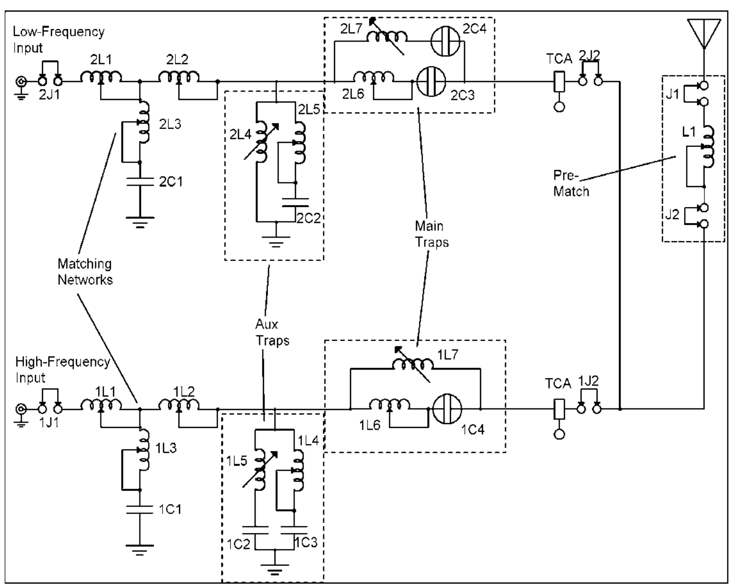

Figure 1

In the field, a number of simpler designs may be encountered. Such designs are usually found in low-power applications and they seldom provide optimal bandwidth and loss. For the purposes of this discussion, we will include only "conventional" designs. Figure 1 shows a typical conventional diplexer design.

2.1 Design Variations

The trap filter is the heart of a diplexer. One such trap, called the "main trap," is installed in series for each frequency. Another, called the "aux trap," is installed in shunt for each frequency.

The purpose of the main trap is to provide a low-impedance path for the pass frequency while presenting a high-impedance path on the reject frequency. The aux trap provides a high-impedance path to ground on the pass frequency while presenting a low-impedance path to ground on the reject frequency. Both types of traps can be created using either of two methods: series and parallel.

2.2 Main Trap Types

A series main trap design consists of a coil and capacitor in series resonance at the pass frequency. A third component is then placed in parallel with the series combination of the first two. This third component is in parallel resonance with the series combination of the first two components at the reject frequency. It is a capacitor if the reject frequency is higher than the pass frequency and a coil if the reject frequency is lower than the pass frequency.

A parallel main trap design consists of a coil and capacitor in parallel resonance at the reject frequency with a third component in series with the parallel combination. The third component is in series resonance with the parallel combination of the first two components at the pass frequency. It is a capacitor if the reject frequency is higher than the pass frequency, and a coil if the reject frequency is lower.

2.3 Aux Trap Types

Like main traps, aux traps can be designed as either series or parallel. The designs are identical to those of the series and parallel main traps, but the parallel resonance is on the pass frequency and the series resonance is on the reject, exactly opposite that of the main trap.

2.4 Antenna Resonator

In Q-matched diplexer designs (discussed later), it is necessary that the aux trap see resonance on the pass frequency. In these instances, a single component, called the “antenna resonator,” is placed in series between the main and aux traps. This component is chosen to cancel out any residual reactance in the conjugate impedance at that point, leaving a purely resistive impedance at the output of the main trap. In standard designs, this component is often omitted.

2.5 Prematch

Except in rare circumstances, the tower in a diplexed system will not present an ideal impedance on all frequencies in the system. Quite often, the resistance will be too high or low or there will be a high reactive component in the impedance on one or more frequencies.

Because each main trap stores energy at the pass and reject frequencies, it is desirable for the parallel resistance at the diplex point to be somewhere between 50 and 200 ohms and as close to zero reactance as possible. A parallel resistance of 50 to 200 ohms is not so high that the main trap’s Q will be excessively high at the reject frequency, and low reactances at the diplex point help keep component stresses low.

To help in achieving impedance values in the desired range at the diplex point, a prematch is sometimes used. A prematch consists of a combination of coils and capacitors. There is no set way of designing a prematch. Rather, it is a matter of judgment and experience on the part of the designer.

In the simplest case, where the parallel resistances are already in the proper range and it is desirable to lower the reactances to resonance or near resonance, a single series component or series network can be used.

2.6 Design Techniques

Most diplexer designs are made using what is referred to as the “standard design.” In this case, the value of the capacitor in each trap is selected so that its loaded Q is roughly the same on both the low and high frequencies. While this is a generally acceptable technique, it does not result in optimum bandwidth.

Another design technique is called the “Q-matched design.” In this case, the capacitor in the main trap is selected for a lower Q_H (Q on the high or pass frequenc) than would be called for in the standard design, and the components in the auxiliary trap are chosen to match the loaded Q of the main trap. This best capacitor choice will be one in which the equivalent Q of both traps in combination (Q_E) is roughly the same as the loaded Q (Q_H) of the main trap. Q_E is defined as the Q of an equivalent circuit that would produce the same sideband VSWR as the combination of main and aux traps. As stated earlier, in a Q-matched design the auxiliary trap must see a purely resistive load.

Using a Q-matched design, the main trap will have a higher Q and the reject resistance will thus be larger. This results in improved isolation (usually by 20 dB or more), and the reduced Q_E results in improved impedance bandwidth for the system.

3.0 Construction Considerations

Any reasonable diplexer design can perform well on paper, with the calculated isolation, impedance bandwidth and losses all within acceptable limits. Translating that paper design into real world cabinets, components and tubing in a way that the design performs as predicted is an art unto itself.

3.1 Enclosure Options

There are two general options for enclosing a diplexer: weatherproof cabinets and shielded enclosures. Because each trap must be electrostatically shielded from each other trap and network in the system, open-chassis designs such as often are used in antenna tuning units and phasing/coupling systems are not an option. One way or another, some sort of shielded enclosure must be used.

Weatherproof cabinets are an attractive option because they are self-contained and require no external shelter of any kind. Mounting options include posts and stands. A disadvantage of weatherproof cabinets is that the engineer and his test equipment are exposed to the elements when working on the circuitry within, a significant factor in inclement weather.

Shielded enclosures are essentially steel boxes similar to weatherproof enclosures that are mounted within a shelter of some sort. Such enclosures are most often housed within a large tuning house or shed. The advantage of this type of enclosure is that they (and the engineer with his test equipment) are protected from the elements. The main disadvantage is cost. They cost virtually the same amount as weatherproof cabinets and require an external shelter. Further, the tuning house or shed has its own set of maintenance costs.

3.2 Size and Layout Considerations

As a general rule, when it comes to diplexer enclosures, bigger is better. An enclosure the size of a school bus has many advantages electrically over one more reasonably sized. Such a large enclosure is not, of course, practical, but the general rule should be to go with as large an enclosure as available space and the budget will sustain.

A typical diplexer design will include a separate cabinet or cabinets for each frequency. One reasonably-sized cabinet for a station in the less-than-20 kW range can handle main trap, aux trap, antenna resonator and matching network. In situations where power levels exceed 20 kW or so, practical considerations may dictate separate cabinets for one or more of the networks.

There are a number of layout factors that influence the minimum size of a diplexer enclosure. Each trap must be placed in its own individual shielded compartment.

Traps within a common enclosure should not have common partition walls between them. Rather, they should each have a separate wall with an air space between them.


Figure 2

Coils should not be placed closer than 1½ times their diameter from enclosure walls or partitions. Coils in the same trap should be physically placed as far apart as possible and the axes should be perpendicular. Tubing near coils should be run parallel to coil axes.


Figure 3

Besides mutual coupling, which kills trap performance, a main reason for situating coils as far as possible from surfaces and objects of different potential is distributed capacitance. Large amounts of distributed capacitance along a trap coil's length will result in, among other things, a significant increase in circulating current in the trap. This brings increased heating and losses.


Figure 4

One other caveat about coils: in trap circuits, do not short unused turns. By doing so, mutual coupling creates a transformer effect with the shorted turns acting as a shorted secondary. The shorted turns will often become red hot, damaging or destroying the coil. Leave unused turns open.

A related caveat is that open unused turns can have a Tesla effect and a very high voltage can be present on the open end. If too many turns are left open this occurs, the only real solution is to use a coil with less inductance.

Capacitor placement is not particularly critical. Still, vacuum capacitors are usually large and some thought must be given to mounting. Vacuum variables should be mounted so that their shafts are easily accessible and, if in a shunt circuit, so that their shafts are at ground potential.

Figure 2 shows the interior of the high-frequency side of a 15 kW diplexer cabinet. The rightmost compartment contains main trap and antenna resonator; the leftmost compartment contains the aux trap. Another compartment to the left, not shown, contains the matching network. Note how coils in the same trap are at right angles to one another, and note the double wall with air space between compartments.

Figure 5

Figure 3 shows the diplex point of the system. The cabinet on the right is the prematch. The left foreground cabinet is for the high-frequency station; left background is the low-frequency station.

Figure 4 shows the prematch cabinet and tower feed, right. A custom high-voltage lighting choke is mounted beneath the prematch cabinet. Tower light wiring is contained within the tubing running from beneath the prematch cabinet and joining the tower feed tubing just downstream of the prematch output. Note the single turn in the tower feed close to the output insulator. This was done to present a high impedance to fast rise-time lightning energy.

Figure 5 shows the entire installation. Transmission lines enter the filter/matching networks from beneath on the left. The three weatherproof cabinets are mounted on custom stands set on a large concrete pad.

Proper grounding is critical. A four-inch ground strap runs from the ground ring around the tower base pier to a 4-inch bus beneath the cabinets that provides the ground connection to each cabinet and the low side of the lighting choke.

4.0 Tune-Up Procedure

The tune-up procedure for a typical diplexer is reasonably straightforward. It consists of initial (or coarse) tuning followed by final (or fine) tuning).

The complement of test equipment needed to properly tune a diplexer includes a bridge (such as a General Radio 1606A), oscillator (such as a Potomac SD-31 or Delta RG), and an operating impedance bridge (Delta OIB-1).

Some sort of detector, which can either be the built-in detector in the SD-30 or RG, a communications receiver or FIM, will be needed. Because of its switchable-scale meter and sensitivity, an FIM such as the Potomac FIM-21 or 41, is preferred.

Optionally, a vector impedance meter (HP 4815A) is a very useful tool for diplexer tune-up. An RF current transformer such as a Delta TCT (or the pickup transformer from a Delta TCA) will also be needed.

For the purposes of this discussion, it is assumed that series main and auxiliary traps are used.

4.1 Initial Trap Adjustment

Start the tuneup procedure by adjusting the series network in each trap for zero net reactance using the bridge or impedance meter. Main trap series networks should be adjusted for zero net reactance on the pass frequency; aux trap series nets should be adjusted for zero net reactance on the reject frequency.

Next, one at a time, connect the output of the oscillator to the input of each trap through an RF current transformer. Ground the other side of the trap (aux traps will already be grounded on one side). Connect the output of the transformer to the FIM input. While observing the meter on the FIM, adjust the parallel resonator for minimum current. For the main traps, adjust for minimum on the reject frequency; for the aux, minimize current on the pass frequency.

4.2 Prematch Tuning

As mentioned above, prematch networks are by no means universal and can vary considerably in configuration from one system to another.

Tuning is generally done by setting each component to its design value using a bridge or impedance meter and then checking the impedance at the prematch input for the desired value. Some fine tuning may then be needed to achieve the desired results.

4.3 Antenna Resonator Tuning

Setting the antenna resonator is a simple matter of measuring the impedance at the point where the aux trap connects to the resonator for zero reactance. With the antenna and prematch connected, use the bridge or impedance meter to measure the impedance on the pass frequency at this point and adjust out the reactance. The test equipment should show a pure resistance when the resonator is properly adjusted.

4.4 Initial Matching Network Tuning

With the system completely plumbed through from trap input to diplex point to antenna, measure the impedance on the pass frequency at the input to the traps (at the point where the matching network connects to the trap input — a J-plug should be provided at this point). Calculate the proper leg values for the tee network and using the bridge or impedance meter, set each leg appropriately.

Install the J-plug shorting bar between the matching network and the trap input and measure the impedance at the input to the matching network (a J-plug should also be provided at this point). Make small adjustments to the input and shunt legs to achieve 50 ohms nonreactive at this point. Repeat this matching network setup for each side of the system.

4.5 Main Trap Fine Tuning

One at a time, turn on each station's transmitter at reduced power and check for proper load. Also check for little or no indicated current on the other stations' RF ammeters. If necessary, re-check trap initial tuning and touch up matching networks using the OIB for a proper load on each transmitter.

Once each transmitter can be operated successfully into the system, turn on all transmitters in the system. One at a time, connect the FIM to the modulation monitor port on each transmitter and tune to the reject frequency. Carefully adjust the parallel resonator in the main trap for minimum reject frequency voltage at each station's transmitter modulation monitor port. The tuning should be quite sharp.

Likewise, carefully adjust the series network in each aux trap for minimum reject frequency voltage at each station's mod monitor port. Shut down all transmitters and use the RF current transformer, FIM and oscillator to reset the parallel resonator in each aux trap for minimum current on the pass frequency.

4.6 Final Matching Network Tuning

With all modules of the system connected, use the bridge or impedance meter to fine-tune the input and shunt legs of the each station's matching network for 50 ohms nonreactive. This will compensate for any minor impedance shifts that may have come about as a result of the fine trap tuning.

Measure the impedance on the sideband frequencies at the input to the matching networks. Calculate the SWR on each sideband frequency and determine if the impedance bandwidth is adequate.

4.7 Interaction Check

Turn on each transmitter in the system one at a time and while it is operating, remove the J-plug shorting bar on the output of the other station's filter module. Check for no change in the antenna current or indicated reflected power/VSWR on the operating transmitter.

4.8 Temperature Check

Operate all transmitters at full power and modulate them at normal levels. It may be necessary to adjust the spacing of the arc gap on the output of the prematch at this point. Allow the transmitters to run for 30 minutes or so, then check the temperature of all components in the system. The safest way to do this is to use an infrared thermometer, which can be pointed at each component in turn while power is applied. Otherwise, shut down all transmitters, immediately and carefully feel each component. If there are any hot components, investigate the cause and take corrective action.

Hot coils can occur when, as mentioned above, unused turns are shorted rather than left open, when a coil with too low a current rating is used, or when the coil is mounted too close to cabinet walls or partitions. Hot capacitors can occur when they are defective and have a high internal resistance, or when they are undersized. Other hot components, such as J-plugs, tubing and the like, occur most often because of poor electrical connections.

4.9 Emission Check

The last step in the tune-up process is the spurious and IM emission check. Start by calculating all the second- and third-order product frequencies and making a list. This will include A+B, 2A+B, 2B+A, 2A-B and 2B-A.

Take the FIM to a clear location about 1 km from the site and measure the fundamental field strength for each station. Then measure each product frequency and calculate the number of dB below each fundamental. If all fall below the FCC-specified maximums, make a full set of occupied bandwidth measurements and simply make a note in the station log. Otherwise, investigate the cause of the high product.

One or more high products does not necessarily indicate a problem with the diplexer design or tuning. In fact, if the diplexer tuned up properly, it is likely that the cause of the high product is external to the system.

Check grounding of all transmitters and equipment racks, check shielding of audio and external RF drive cables. Experiment by disconnecting audio, external drive, mod monitor and remote control cables one at a time from each transmitter and checking the product. For tube-type transmitters, check amplifier tuning and neutralization. Chances are, the problem will be isolated to a transmitter problem.

5.0 Wrap-Up

In addition to good design and construction, documentation is the key to long-term reliable diplexer operation. Good documentation should include a notation of all the impedances in the system (every point at which they were measured) both in notes kept in a safe place and on the diplexer equipment itself. Adhesive labels from Kroy or P-Touch label makers can be affixed at strategic points in the system, such as in the vicinity of the J-plugs at which the impedances were measured.

Coil settings should also be noted. In notes, indicate the number of turns from the open end of each coil at which the tap is set and note which quadrant the tap is at (top, bottom, front or back). Mark the coils themselves with a spot of paint so that the coil clip can be easily returned to the exact spot should it come loose. Indicate the color paint used in the field notes, and should a subsequent adjustment/modification place any coil taps in a different location, use a different color paint.

Write down impedance bandwidth data along with IM product measurement data and anything else that may be pertinent to the installation, tuning or operation of the system, such as system losses as determined by measuring and subtracting output power from input power. If measured with an IR thermometer, note temperatures of any components that are above ambient. Also note the ambient temperature at the time the measurements were made.

Keep all original field notes in a safe place somewhere other than at the transmitter site, placing a set inside the diplexer cabinets.

Who to provide with keys is always a hot issue in diplexed transmitter sites. Each station or contract engineer working at the site will naturally feel that he is entitled to full access to at least his station's diplexer cabinet. The trouble here is that any adjustment, modification or repair that takes place in any station's cabinet will have some effect on all the other stations.

The best solution is to give charge of the system to one independent third party, such as a local consulting engineer. If this is not an option, a good understanding, preferably in writing, should exist between all the parties outlining the responsibilities and expectations of each of the parties.