APPLICATION AND PERFORMANCE OF ROTARY PHASE CONVERTERS AS AN ALTERNATIVE TO UTILITY SUPPLIED THREE-PHASE POWER

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SUMMARY

A very common problem facing broadcast station owners is obtaining three-phase (3-phase) power service at prospective transmitter sites. Utility companies often charge exorbitant fees to extend service to remote areas. This often forces owners to select sites purely on the basis of affordable three-phase availability while compromising other desirable features of site selection.

The advent of the rotary phase converter in the early 1960's has contributed significantly to the broadcasting industry by providing the capability to produce three-phase power on site from any single-phase (1-phase) source. A rotary phase converter is an induction machine which operates on a single-phase supply and produces a true three-phase output. It is capable of supplying the full rated input requirement of any three-phase induction, resistance or rectifier load.

The cost savings to be realized by use of a phase converter can be breathtaking compared to the alternative utility costs. Documented savings of $100,000 or more are commonplace. However, the use of phase converters remains something of a mystery to many who could benefit from them most. Chief among the reasons for this are widespread anecdotal accounts of field problems and other misunderstandings of their application. Nonetheless, well over 1500 radio and TV stations worldwide including in 1000 in the U. S. are successfully operating on phase converters with a service record exceeding 45 years.

The purpose of this paper is to explain the construction and performance of phase converters and characterize their application on broadcast transmitters. It is anticipated that a broader knowledge of converter capability and performance among owners and engineers would enable them to approach transmitter siting with a broader range of options.

TRANSMITTER SITE SELECTION FACTORS

A natural result of growth in the broadcasting industry is that the number of ideal transmitter sites is reduced while their costs continue to increase. Finding a good site where 3-phase power is available can pose a real problem in some areas.

Transmitter site selection often becomes an economic compromise of many factors, some of which are beyond the scope of this paper. However, judging from hundreds of interviews and conversations with station owners and engineers, a consensus view is that most siting issues fall in the following list:

- Availability of three-phase power
- Land lease or purchase cost
- Site Accessibility
- Potential Interference

Availability of Three-Phase

Virtually all radio transmitters of 5 KW and larger and TV transmitters over 1KW require 3-phase power input. Equipment designers prefer 3-phase because its rectified output has much less ripple than 1-phase and requires less filtering to produce a clean DC output. However, in the real world, three-phase just does not exist everywhere and utility companies may not be willing to supply it within a reasonable cost or time frame.

Land cost

Antenna farms or other developed sites where power is already available can be very expensive. By contrast there may be attractive undeveloped areas or inexpensive BLM leases which would be ideal sites if 3-phase were available.

Interference

This becomes a critical issue whenever locating near existing stations. The availability of 3-phase power must be weighed against the added cost of circulators, traps, grounding systems, special antennas and other costs incurred to eliminate interference.

Site Accessibility

Even low cost sites which have 3-phase and are interference free may be unreliable locations if land owners are reluctant or unwilling to grant unlimited passage on private lands and roads. The availability or cost of access rights can drive up the price of an otherwise attractive site.

Final site selection may require a compromise on one or more of the above points. But it is unlikely that a site without 3-phase could be seriously considered even if that choice were highly ranked in every other category. There are three alternatives which the owner can consider where 3-phase power is not available. They are: 1) Request a utility line extension. 2) Install on-site power generation equipment. 3) Use a phase converter.

UTILITY POWER EXTENSION POLICIES

Every utility has its own policy on new service requests. However, it is useful to understand the general issues which impact the utility decision and the alternatives which they may offer.

The factor weighed most heavily is the proximity of the proposed site to the nearest sub-station or 3-phase power line with adequate capacity. A 3-phase line near the desired site does not guarantee the station a service drop if the line is loaded to its limit by other users. In such cases, the utility may choose to increase the capacity of the service transformer, install a new 3-phase line, upgrade an existing line to 3-phase, deny the request for 3-phase, or offer a 1 -phase service.

To convert an existing 1-phase line to 3-phase, the power company must string at least one additional cable and replace the 1-phase transformer with a 3-phase unit. In some cases, the utility may cut corners and simply add one more 1-phase transformer and thus supply open-delta three-phase. Open-delta is a very common practice in rural areas because it saves money on transformers. However, it has very poor voltage stability and often undergoes wide voltage swings.

Three-phase line extensions are ideal but are very costly because they entail a complete new installation of poles, lines, insulators, supports and other hardware. The costs are further affected by terrain and accessibility to the new site.

As utilities come under increasing pressure from public regulatory agencies to justify capital investments (which include new distribution lines) when seeking rate increases, they have become very particular about where they extend new services. If the investment of extending a line is not paid back fast enough through energy revenues, the utility will charge the customer for the new service. There are no absolute rules governing the calculation of these charges, however, it is widely accepted that line extension costs range from $30,000 to $90,000 per mile with $50,000 being a common average.

Engine Generators

The diesel or engine driven generator is a commonly considered alternative to a converter. However, generators are expensive and are usually not justifiable as the primary 3-phase source when compared to a phase converter (assuming an adequate single-phase service is already available). In addition to high initial cost, the logistics of fuel supply can pose a serious problem in some geographical areas.

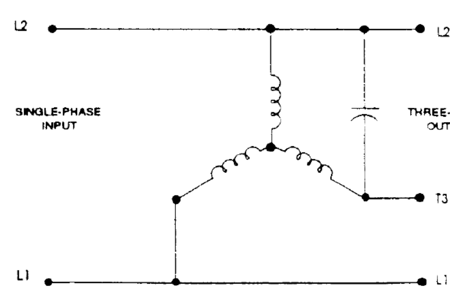
It is not uncommon that the energy cost alone of operating a transmitter on utility power will be 50-60% less than the cost of diesel fuel for the same transmitter power output. Those savings will often pay for a phase converter in a matter of months.

Further, the maintenance costs of engine generators tends to be quite high and downtime is longer than phase converters when outages occur.

PHASE CONVERTER FUNDAMENTALS

Types of Converters

A phase converter is simply a device which permits a 3-phase machine to be operated from a 1-phase source. It does so by producing a manufactured phase which becomes the third wire connection to the load. There are two types of converters, rotary and static. Static converters are less expensive than rotaries and are useful on light duty motor loads. They are not suitable for rectifier loads as found in transmitter applications. Therefore only rotary converters will be discussed here.



ROTARY PHASE CONVERTER SIMPLIFIED EQUIVALENT CIRCUIT

Converter Construction and Operation

A common misconception is that a rotary phase converter is similar to a mechanically coupled motor-generator set. In reality, the converter is a single armature device constructed much like a three-phase induction motor. It consists of a stator frame with a symmetrical three-phase winding and a specifically modified squirrel cage rotor. A large capacitor bank is placed across a set of windings between one of the input lines and the manufacture phase. A simplified equivalent circuit is shown in figure 1.

When the converter is energized, single-phase power is applied to one of the winding groups. This produces an internal magnetic field proportional to the applied single-phase line. The capacitor bank provides a phase shifted voltage to another coil group which creates a starting torque on the rotor. As the rotor spins, it picks up a replica of the utility supply through induction. As the rotor passes each stator coil group (each separated by 120 mechanical degrees) the single-phase field is replicated in the other two coil groups. The result is a three-phase sinusoidal output with each phase shifted by 120 degrees.

In this context, it becomes clear that a rotary phase converter is actually a rotating transformer where the rotor acts as a secondary winding on bearings.

Output Characteristics

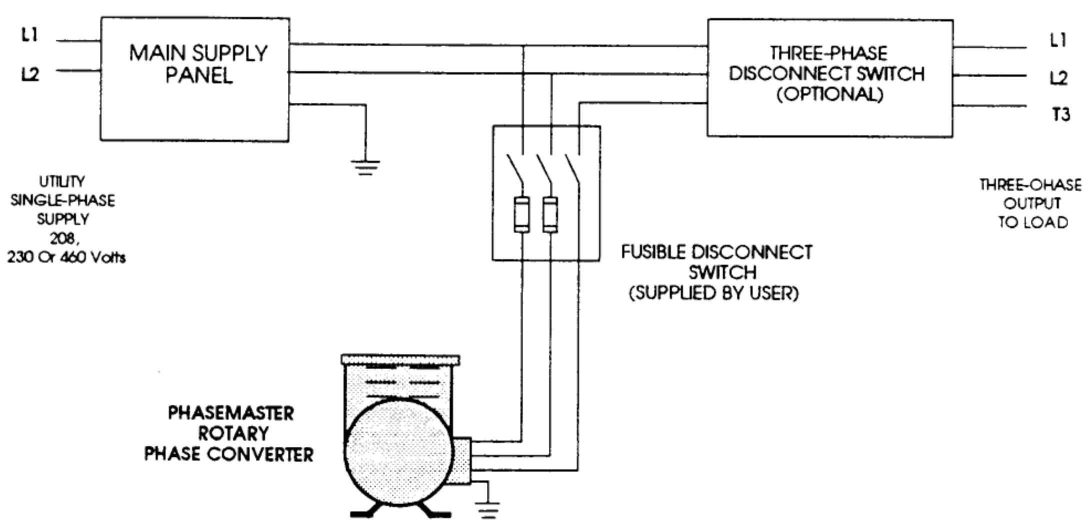
Two of the three lines in a converter system come right from the utility (figure 2). Therefore, the important output characteristic is the behavior of the manufactured phase in relationship to the two utility lines.

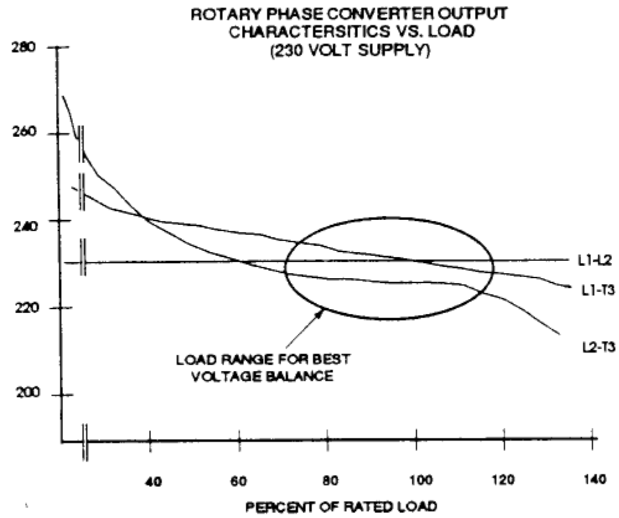
The energy which flows into the manufactured phase passes across the internal air gap between rotor and stator. The greater the load, the more energy has to cross the air gap. And since magnetic fields do not travel through air as well as iron the greater the effect on output voltage. The output diagram in figure 3 shows the behavior of the output voltages in relation to load. Note that at under no-load conditions, the manufactured phase voltage (L1 -T3) is substantially higher than the incoming line voltage. As load increases, the voltage drops so that under full load conditions, the three voltages are quite closely balanced. The significance of this load dependent voltage will be discussed in further detail.

Ratings

Standard single unit converter output ratings are available up to 100 KW. But there is no theoretical limit to the total load size a converter can service. They may be paralleled indefinitely for any load. The only restriction is the maximum 1-phase load allowed by the utility. In practice the only time converters have to be paralleled is on large TV transmitters.

ROTARY PHASE CONVERTER TYPICAL CONNECTION DIAGRAM





ROTARY PHASE CONVERTER OUTPUT CHARACTERISTICS VS. LOAD (230 VOLT SUPPLY)

Except for the largest sizes, converters are usually dual voltage rated at 230/460 volts. Output is three wire closed delta.

Physical Size

Phase converters are dense and compact. The footprint of a converter for a typical 20 KW FM transmitter is about 24"X24". It stands 30" high and weighs 800 lbs.

Design Operating Duty

Rotary converters designed for broadcast service are capable of continuous operation, 24 hours per day, every day. They need not be shutdown except for periodic scheduled inspection and maintenance. They can operate unloaded or at full load indefinitely without effect. However, losses are higher under no-load conditions.

Equipment Standards

Unfortunately because of the highly specialized nature of phase converter broadcast applications, there are no published industry standards governing their performance or ratings. The three best known approval agencies in North America, CSA, UL, and ETL do have approval procedures for converters. However, these approvals are little more than equipment material and safety audits. They verify none of the manufacturer's specifications or performance claims. In the absence of strict industry standards, the most reliable yardstick of relative performance is a comparison of the physical frame size and weight of the converter.

The severity of transmitter applications requires a physically larger frame and rotor than would be necessary to operate an induction motor load. If a motor is difficult to start, capacitors may be added to boost starting torque. Boosters are not effective on transmitters and are never a substitute for a larger converter frame size. It is recommended that users stick to converters which have been specifically designed for use on transmitters and have a demonstrable service record.

BROADCAST APPLICATIONS OF PHASE CONVERTERS

Operating Benefits

The most obvious benefit of phase conversion is the ability to operate 3-phase equipment while avoiding utility installation charges. But there are several other economic and technical advantages to converters which can be beneficial to owners and engineers.

1. Immediate Power Availability
A very important factor in the decision of whether to go with utility or a converter is the time required to extend the new lines. Depending on the distance or the utility work load, new services may take from weeks to months before the user can energize. The converter is a simple solution to this dilemma. It can be installed very quickly to allow start-up with minimal delay. Even if utility 3-phase is brought in later, the relatively small converter investment may save much greater revenues which would be lost in delays.

2. Elimination of Utility Demand Charges
The rate structure of 3-phase electric power often includes a component known as a demand charge. This charge seldom applies to 1-phase services. Over the years, many station owners have discovered that their power supplier serviced them with a 1-phase which did not include demand charges. The use of the converter was not only a satisfactory alternative to utility 3-phase, but the rate structure was more favorable when purchasing as a 1-phase customer.

3. Reduction of Utility Line Transients
Almost everyone who has operated a transmitter is familiar with the phenomenon of utility line noise. Such transients result from system switching disturbances and load changes, and can damage equipment or take a station off the air. Since a converter is capable of storing a large amount of energy in its rotating magnetic field, it can ride through momentary voltage sags by generating energy back into the systems during the voltage drop. This type of event accounts for nearly 80% of all line disturbances and the effects are greatly reduced or eliminated by the converter. The converter also buffers voltage spikes.

4. Stabilization of Open-Delta Service
Open-delta service as previously discussed is a common form of three-phase which has very poor voltage regulation on one leg. By contrast transmitters require stable power supply voltage. Voltage swings are a very common nuisance to stations unlucky enough to have open-delta service. Phase converters are an effective method of closing the delta and stabilizing the wild leg and eliminating the unplanned downtime caused by open-delta service.

Converter Selection Criteria

When properly selected and installed, converters are capable of output and performance which is nearly indistinguishable from utility three-phase. The typical data required to insure a successful application includes the following:

- Type of transmitter, AM, FM, TV
- Manufacturer
- Input Power consumption in KW at operating ERP
- Day-Night output, if different

Once this data is known, selecting the proper converter is a straightforward procedure. The key to successful sizing is to match the converter output as closely as possible to the load. This requires knowing the true input power consumption at the actual operating output of the transmitter. On AM transmitters this is usually expressed at 100% modulation.

This sizing technique produces the best possible voltage balance. A properly sized rotary converter will provide operating load voltage balance (% regulation) ranging from a maximum of 5% and most commonly 2-3% or better.

Load matching is important to sizing because as discussed earlier, the output characteristics of converters vary with load. The phenomenon is only significant when attempting to operate a transmitter which draws considerably more than OR less than the rated output of the converter. The resulting voltage imbalance can cause an increase in AM noise level. This condition is easily avoided by proper selection. Field remedies are also available.

Load matching and voltage balance issues also affect AM stations which operate at reduced nighttime power. This situation is easily handled one of two ways. The first is by employing an output voltage control switching arrangement that reduces the converter output voltage characteristics by dropping a portion of the capacitor bank. The second method is by splitting the load between two parallel converters (figure 4). One converter is .

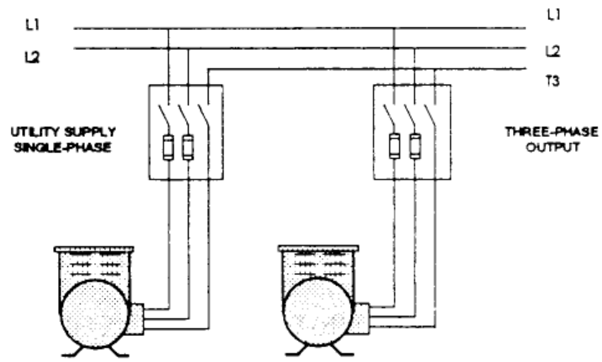


FIGURE 4

ROTARY PHASE CONVERTER CONNECTION
FOR PARALLEL OPERATION

sized for the night load only. During the day they run together. At night one converter is switched off and the other unit carries the entire reduced load

SITE ENGINEERING CONSIDERATIONS

Phase converters have clearly demonstrated the ability to handle high power installations on all types of transmitters. Nonetheless, the potential for misapplication is always present unless all system operating requirements are reviewed. When these issues are addressed, engineers and owners can approach the use of phase converters with total confidence.

Size of Utility Service

Undersized utility service transformers are a very common field problem. Engineers should work with the utility to insure the incoming service is adequate to supply the entire site load without excessive voltage drop. An FM transmitter with a rating of 20 KW will actually draw more like 35 KW at full operating load. If the site also has an air conditioning load, tower lights, etc. totaling an additional 10 KW, then 45 KW becomes the total 1-phase demand which the utility must be able to supply. However, the converter is sized only for the amount of connected 3-phase load.

Planned Operating Load Levels

A phase converter should always be sized for the maximum power which the transmitter consumes at normal operating levels. If a different output power is anticipated at a future date, consultation with the converter manufacturer is recommended to assure that converter design takes future needs into account.

Converter Control Systems

The most common and least expensive control scheme uses a fusible disconnect switch for isolation and short circuit protection. The converter is manually switched on and runs continuously until manually shut down. However, there are operating conditions which call for a greater degree of control. For this reason, engineers may want to consider specifying automatic controls to start and stop the unit remotely.

Automatic controls use a magnetic contactor to start and stop the converter from a remote control station. A timing relay locks out the load until the converter reaches full speed and is producing three-phase (about three seconds). Automatic controls should be considered for sites which are unattended at any time or stations which sign-off at night. The convenience of this feature is widely appreciated by existing users.

Another key advantage of automatic controls is improved system reliability. Utility service in remote areas is notorious for frequent outages. Stations which use emergency back-up generators must have a way of isolating the converter when the transfer switch changes over to the emergency source. The automatic control provides this function as well as the ability to restart the converter in advance of switching back to the primary supply. It also prevents the converter from attempting to restart into a load when power returns after an outage.

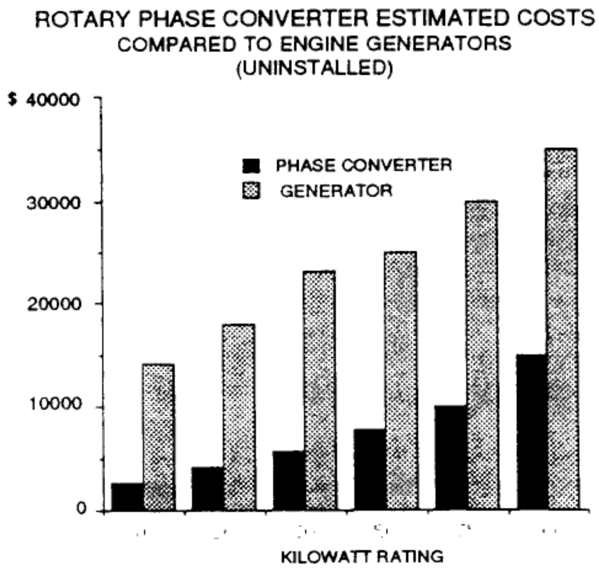
ANALYSIS OF CONVERTER FEASIBILITY

The question of whether to consider a phase converter as an alternative to utility 3-phase reduces to an evaluation of economics and relative risk factors. A complete economic analysis of the converter should include 1) Installed equipment cost, 2) Utility charges to bring in the three-phase line, 3) The difference in rate structure between single and three-phase service, 4) The operating cost of maintenance and losses, and 5) An analysis of the reliability record of converters.

Converter Costs

Approximate converter costs through 100 KW are shown on the graph in figure 5. Large rating units can be priced as parallel combinations. Estimating prices of generators are shown for comparison. (Generator costs do not include fuel storage tanks).

A review of utility rate structures is strongly encouraged. The analysis of rates will reveal if they favor a customer metered at 1-phase or 3-phase.



Efficiency

A common engineering concern is phase converter efficiency. The response to this question lies in understanding the difference between the converter efficiency taken alone and the overall *system* efficiency. The phase converter only sees one third of the system energy, so its efficiency taken out of context is not significant. Two of the three load connections come right from the utility supply without passing through the converter. Converters like most rotating machines are nominally 90% efficient at the upper end of their load range. Thus the full load system losses are approximately equal to 10% times 33% or 3.3% of the rated load.

Operating Costs

No-load operation is the most inefficient running mode of a converter (or for that matter, any machine). As discussed above, the actual losses incurred by operating a converter system are quite small at full load. In fact, the large power factor correction capacitors in the converter will commonly improve the overall system efficiency enough to compensate for converter losses. Even without regard to these possible savings, the estimated cost of losses for a converter running a 20 KW FM transmitter operating at 70% efficiency running 24 hours per day would be less than $100 per month based on energy costs of fifteen cents per kilowatt-hour. Maintenance costs alone on a generator of this size would average 1.5 cents per kilowatt-hour or $300 per month.

INSTALLATION AND MAINTENANCE

Converter installation is neither costly nor complicated. Careful attention should be given to the manufacturer's instructions. Most start-up problems are traceable to installer deviations from recommended practices.

The converter is usually installed near the main power service entrance. An inexpensive fusible switch isolates the converter and provides its primary short circuit protection. A converter does not have to be bolted down since it does not have to be braced against starting loads. A typical converter installation can be made in four hours or less.

Rotary converters require very little ongoing maintenance. The most effective maintenance program starts with strict adherence to recommended installation procedures. Once in service, the units should be inspected periodically. The ventilation slots must remain open and bearings lightly lubricated at intervals of 12-18 months. No further formal maintenance is required or recommended.

RELIABILITY RECORD

Many station engineers have observed the converter has far fewer outage occurrences than the utility supply. Of course this is not unexpected in many areas where weather conditions play havoc with rural distribution systems.

One make of converter has been used successfully in service on transmitters for more than 45 years. There are presently more than 1200 stations known to be operating on these rotary converters. Many have been operating around the clock for 10 years or more without being shut down for maintenance.

The field failure rate averages well under one percent per year. This includes all types of failures regardless of cause or severity. Direct lightning strikes remain the most common cause of catastrophic converter failure. The addition of lightning arrestors as a standard phase converter accessory on transmitter applications has greatly reduced but not totally eliminated this failure mode.

By nature, phase converters are not service prone. Except for add-on controls they contain no contacts or switches. Apart from the rotor and bearings all other components are static devices. The most . common cause for service of rotary converters are failed capacitors usually resulting from external utility system transients or lightning. Less common service issues are wiring and connector related. The connector and wiring problems usually stem from abrasion of taped joints or connections which are not sufficiently tightened during installation.

Film type capacitors, if defective generally fail open. Capacitors rarely fail to a short circuit condition. Usually the only sign of defective capacitors is poor starting performance or sagging voltage on the manufactured phase. Both problems are easily corrected.

Bearings are the most commonly expressed concern of converter owners. In service, however, bearing failures are uncommon. The principal reason for that is that the bearings carry only the load of the spinning rotor. There is no external shaft extension on a phase converter and consequently no outside mechanical load on the bearings. Bearing life of 15 to 20 years is not uncommon with five year life a minimum expectation for installations operated continuously without shutdown.

A note of caution is in order here. Most rotary converters on the market have been designed for motor loads and are not well suited for transmitter service. Even subtle design differences in rotor construction and accessories can make a significant difference in transmitter performance. Owners and engineers will naturally want to examine and verify the service record of a manufacturer's experience on broadcast transmitter applications.

CONCLUSION

Specialized designs of rotary phase converters have been field tested for 45 years on virtually all makes of broadcast transmitters. The experience with these machines has clearly demonstrated them to be suitable replacements for utility supplied three-phase power without sacrifice of transmitter performance or reliability.

In view of their accumulated performance record and significant economic advantage, phase converters must be considered an important alternative power source which owners and engineers should not overlook when selecting transmitter sites.

This is a reprint of the paper which originally appeared in the 1988 NAB Engineering Conference proceedings. For more information about rotary phase converters for broadcast transmitter applications contact:

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