

PHASE CONVERSION TECHNOLOGY OVERVIEW

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Introduction

A wide variety of commercial and industrial electrical equipment requires three-phase power. Electric utilities do not install three-phase power as a matter of course because it costs significantly more than single-phase installation. As an alternative to utility installed three-phase, rotary phase converters, static phase converters and phase converting variable frequency drives (VFD) have been used for decades to generate three-phase power from a single-phase source. However these technologies have serious limitations, which motivated Phase Technologies, LLC to develop a new digital phase converter, Phase Perfect[®]. This new patented technology overcomes the limitations of earlier phase converters, and is an affordable alternative to utility three-phase.

Construction of three-phase power lines can cost as much as \$50,000 per mile and can have an undesirable environmental impact. Even when three-phase lines are nearby, the cost of installation is considerable. Based on anticipated electricity demand for the three-phase application, the utility may or may not charge the customer for the cost of installation. Continuing monthly surcharges for the service are also common.

Phase converters have historically been employed where utility three-phase power was unavailable, or where the electricity demand did not justify the cost of utility three-phase installation. Reduced motor life caused by voltage and current imbalance, harmonics that pollute the power grid and damage equipment, or the inability to operate sensitive equipment or multiple loads are just some of the problems that have limited the use of phase converters.

Phase Perfect[®] is a new, patented technology that supplies three-phase power from a single-phase source to power inductive, resistive and capacitive loads with distinct advantages over any existing converter technology. Phase Perfect[®] has an input stage with electronic power factor correction, producing true, near unity power factor. The input current is sinusoidal with very low harmonic content. The output signal passes through an LC filter which blocks the high frequency harmonics from entering the load, producing a sinusoidal output with no external filtering required. A digital signal processor (DSP) monitors the process to generate balanced voltages and currents and to protect the load. Its many integrated features allow customers to avoid add-on costs associated with other phase converter technologies.

Electric Power Distribution

The backbone of every modern electric power distribution system is a three-phase (3- ϕ) alternating current (AC) transmission line. It consists of three primary current-carrying wires sometimes referred to as L1, L2, and L3 and in some cases a fourth wire called the neutral conductor. Single-phase distribution systems are also common because single-phase transmission lines costs significantly less than three-phase lines. They consist of one high-voltage line and a neutral. Most residential and rural areas are supplied with single-phase service. Three-phase power cannot be supplied from single-phase service unless a phase converter is used.

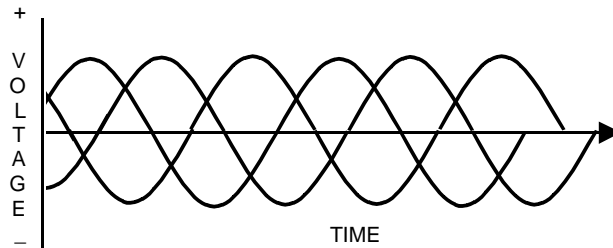
Single-phase power is a single voltage that alternates between a positive voltage and a negative voltage for a specific number of times per second (in the U.S., 60 times per second or 60 Hz). Three-phase power is three distinct AC voltages, each shifted in time 120 degrees relative to one another as depicted in figure 1.

The wave forms shown in figure 1 can be calculated using the sine function in trigonometry and are called sine waves. Notice that the voltage between L2 and neutral (L2-N) is delayed by 1/3 of a cycle from the L1-N voltage, and that the L3-N voltage is displaced 1/3 of a cycle from the L2-N voltage. A complete cycle of the one of the wave forms corresponds to one complete rotation

around a circle or 360 degrees. The phase delay in the L2 and L3 voltages is often referred to as 1/3 times 360 degrees or 120 degrees for L2 and 240 degrees for the L3 voltage

Customers are supplied with electricity from the distribution system by placing transformers on the high voltage distribution system to reduce voltage to a level compatible with electric devices, for example, 240 volts. Three-phase service requires three transformers compared to one for single-phase service, and requires different metering equipment as well. Because of this, three-phase service costs more to install, so utilities usually prefer to install single-phase service unless there is a specific demand for three-phase power at the site.

Figure 1



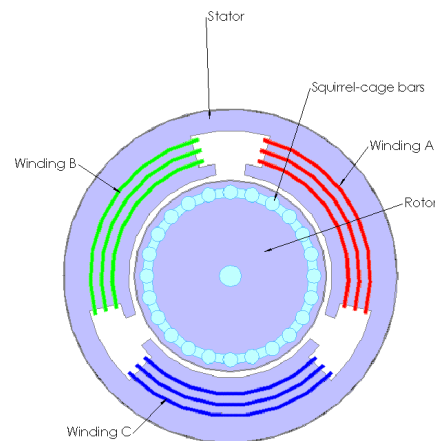
Why Is Three-Phase Power Desirable?

Motors that convert electrical energy to mechanical energy are a large portion of the industrial demand for electricity. Most of these motors are three-phase squirrel-cage induction motors which consist of an arrangement of coils wound in slots in a stack of iron laminations shown in cross section in figure 2 below. This part of the motor is stationary and is called the stator. The coils in the stator are connected in a manner to produce at least three separate windings which are at angles of 120 degrees with respect to each other. This is shown schematically in figure 2.

If a set of 3- ϕ voltages is applied to the windings shown, a magnetic field will be produced in the center portion of the stator which is constant in magnitude, and which rotates at the frequency of the applied voltages (either 50 or 60 Hz depending on what country you're in).

The second part of the motor (the rotor) is a set of round iron laminations that have been attached to a shaft with bearings. There are slots in this set of laminations as well. In this instance the slots are filled with very low resistance bars of aluminum that are shorted together at the outer edges of the laminated stack of iron. If the rotor is inserted into the center part of the stator, the magnetic field generated by the stator will cross through the shorting bars of the rotor causing a large current in the rotor. These rotor currents react with the magnetic field generated by the stator and cause the rotor to spin. The rotor will continue to accelerate until the shaft rotation speed is nearly equal to the velocity at which the magnetic field of the stator is spinning.

Figure 2



The important point here is that if the stator had only a single coil driven by a 1- ϕ voltage, then the magnetic field generated by the stator would not rotate--it could for example point either up or down, but not left or right. The motor could never start because there would be no rotational component of the magnetic field. Thus a 3- ϕ system allows the mechanical energy being fed into the generator to be transferred to 3- ϕ induction motors very efficiently. Three-phase motors also have the advantage of being very simple and reliable--there are no electrical switches contained in them. If they are not overheated, the only thing that wears out is the bearings, which are replaceable.

Other heavy equipment such as welders or electronic power supplies can be made lighter and less expensive if it is powered from a 3- ϕ source. Consequently, most industrial electric equipment is three-phase.

Three-phase vs. Single-Phase Motors

Single-phase motors are readily available, especially in smaller sizes for loads requiring less than 5 HP. These motors have a primary winding which is used all the time, and a secondary winding which is used primarily for startup. On some 1- ϕ motors, the secondary winding is also used when the motor is running. The secondary winding is connected to the input voltage in series with either a resistor or a capacitor to produce the necessary phase shift to get the motor started. Usually there is a switch inside the motor that either disconnects the secondary winding altogether or connects it to a different value of capacitor once the rotor is spinning. From the previous discussion we see that the single phase motor will have more losses than a 3- ϕ motor of the same capacity and will have to be designed to accommodate these losses. For motors up to about 5 HP the 1- ϕ solution is usually acceptable. Above 10 HP it becomes increasingly difficult to handle the extra heat generated in a 1- ϕ motor and they are not common. If reversing capability, such as on machine tools, is needed or if the motor is subjected to frequent start-stop cycles, a three-phase motor is much more desirable. It is much more convenient to reverse a 3- ϕ motor since all that is required is to reverse two of the leads to the motor.

Another consideration is the reliability of the motor. The primary failure mechanism of 1- ϕ motors is failure of the switch that controls the secondary winding. When the contacts eventually become corroded, the switch will fail to close and the motor won't start. This will overheat the primary winding and may cause destruction of the motor. Since 3- ϕ motors don't have this internal switch, they do not have this failure mechanism. Long motor life is an important consideration for deep-well submersible pumps where the labor cost for replacing the pump can be more than the cost of the pump itself.

Rotary and Static Phase Converters

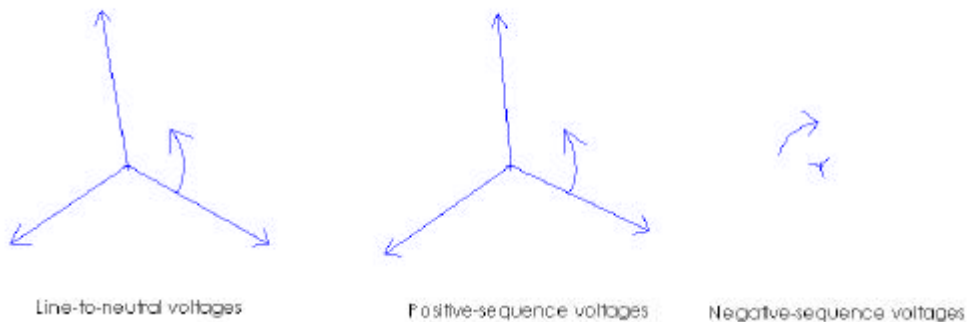
Phase converters provide 3- ϕ power from a 1- ϕ source, and have been used for decades. The simplest type of old technology phase converter is generically called a static phase converter. This device typically consists of one or more capacitors and a relay to switch between the two capacitors once the motor has come up to speed. These units are comparatively inexpensive. They make use of the idea that a 3- ϕ motor can be started using a capacitor in series with the third terminal of the motor. It is almost guaranteed that a static phase converter will do a poor job of balancing the voltages on the motor. Unless motors operated on static converters run only for short periods or deliver significantly less than half of their rated output, they will be damaged from overheating.

The second type of old-technology phase converter is generically called a rotary phase converter. This device consists of a 3- ϕ motor (usually without external shafts) and a bank of capacitors wired together to act as a single large capacitor. Two of the leads to the motor are connected to the 1- ϕ power source and the third lead to the motor is connected in series with the capacitor bank to either one of the 1- ϕ inputs. The output leads from the phase converter are connected across the three motor terminals. Typically the motor used in the phase converter is larger than

the loads it is supplying. For example, a rotary converter designed for a 7.5 Hp load might use a 10 Hp motor frame. The electrical interaction between the capacitor bank and the free-running phase converter motor generates a voltage on the third motor terminal which approximates the voltage needed for a balanced 3- ϕ system. However, it usually isn't a very good approximation. For example, measurements on a 7.5 Hp rotary converter in an actual machine shop installation resulted in line-to-line voltages of 252 V, 244.2 V and 280.5 V, which is about a 12% imbalance in the voltages.

To understand how this voltage imbalance will effect a motor is useful to first transform these line-to-line voltages into their equivalent line-to-neutral voltages, which are shown in figure 3 below. These voltages are shown in what is called a phasor diagram. The magnitude of each voltage is proportional to the length of the arrow or vector and the relative phase angle of each voltage is proportional to the angle between any two arrows. The L1-L2 voltage has been arbitrarily drawn with an absolute angle of zero degrees. If one imagines that these vectors are spinning around the center point clockwise at a rate of 60 times per second, then the value of a voltage at any particular instant in time would be the projected length of its vector onto the horizontal axis. This set of vectors, which represent unbalanced voltages, rotating clockwise, can be further separated into two balanced sets of vectors, one rotating counterclockwise and called the positive-sequence voltages, and one rotating clockwise and called the negative-sequence voltages. These are also shown in figure 3 below.

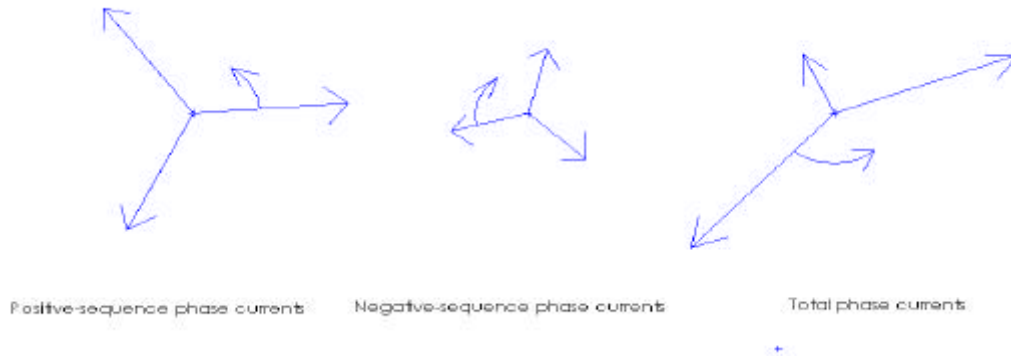
Figure 3



An induction motor responds quite differently to the positive-sequence voltages as compared to the negative sequence voltages. The positive-sequence voltages are rotating at 60 Hz (3600 cycles/min) and if we take the example of a 2-pole motor, the rotor is spinning at about 3450 rpm. The slip speed between the field created by the positive-sequence voltages and the actual rotor velocity is low and the inductance seen by these voltages is relatively large.

If we take the example of a 7.5 Hp 240 V motor, the no-load running current is about 14 A. The phase-to-neutral voltage is $240/(3)^{1/2}=139$ V, and the phase-to-neutral inductance is: $L=139/(377*14)=26$ mH (1 mH=1 Henry/1000, a Henry being the basic unit of inductance). The negative-sequence voltages are rotating in the opposite direction to the rotor velocity and the slip is almost twice the rotor velocity. This sequence of voltages sees an inductance nearly equal to that which would be measured if the rotor were locked in position. The locked-rotor inductance is about one sixth of the normal running inductance or about 4.4 mH for a 7.5 Hp motor. The figure below shows the individual positive and negative sequence currents and the combined current for the voltages shown above.

Figure 4



Notice that while the voltages were only 12% out of balance, the currents differ by almost a factor of three. Since the negative sequence voltages feed into an inductance which is one sixth of the inductance seen by the positive-sequence voltages, a rather modest imbalance in the voltages produces a totally unacceptable imbalance in the currents. In this example, the lead to the motor carrying the smallest current could be totally disconnected and it would not significantly change the performance of the motor.

If a single motor is always run at a constant load, and the rotary phase converter and its associated capacitor bank are carefully adjusted, then it is possible to achieve better than a 12% voltage imbalance as discussed in the example above and get acceptable operation of the motor. The procedure would involve setting up the system of phase converter, motor and load; then measuring the generated voltages and the currents in each motor phase. If the current balance were unacceptable, then capacitors would need to be either added to, or taken out of the capacitor bank until the currents were balanced. In some cases, it might be necessary to switch to a different size phase converter to get the system balanced.

If the motor were required to operate over a wide range of load conditions, or if several motors were powered using the same phase converter, it would be nearly impossible to get good voltage balance over the whole range of operation. If none of the motors were run at their full capacity, the job of getting everything to work properly would be easier. If the motor(s) were run at their full capacity for extended periods, such as in pumping applications, they would not tolerate voltage imbalance.

In summary, phase imbalance adversely impacts both the performance and the life of a motor. Even modest voltage imbalance between the phases will require a motor to be de-rated as indicated in Table 1.² Phase imbalance will significantly reduce the life of motors that have a high duty cycle and operate at their maximum rated capacity.

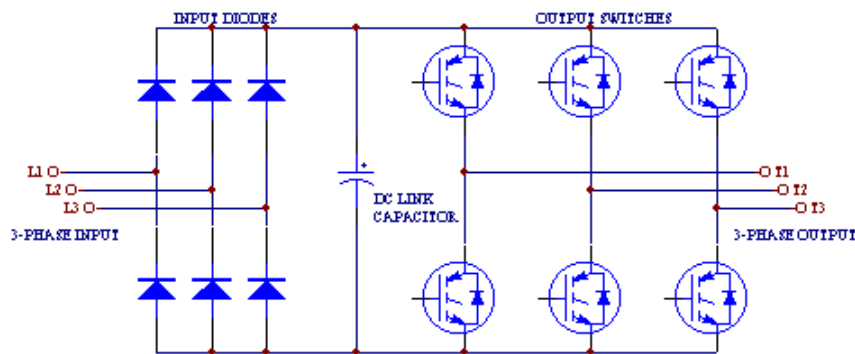
Table 1

Voltage Imbalance In Percent	Derate Motor to These Percentages of the Motor's Rating
1%	98%
2%	95%
3%	88%
4%	82%
5%	75%

Variable Frequency Drives

Variable frequency drives (VFDs) are designed primarily to control the speed of AC motors, but can be adapted to function as phase converters. They also have some problems with power quality.

While a phase converter will supply a 3- ϕ output at the same frequency as the input voltage from the power line, a VFD has the ability to create voltages that vary in frequency. A VFD has an input rectifier (either 4 or 6 semiconductor diodes) which charge up a DC link capacitor. Three pairs of semiconductor switches are also connected to the DC link capacitor. Each switch pair is connected in series and has connections to the two capacitor terminals. The center connection of each switch pair is connected to one of the output terminals. If the top switch is on, the output terminal will be connected to the top or positive terminal of the link capacitor. If the bottom switch is on, then the output terminal will be connected to the bottom or negative terminal of the DC link capacitor. Each of the three output terminals is connected to one of the leads of a 3- ϕ induction motor.



A VFD cannot produce a sinusoidal output voltage. It can only connect the output terminals to either the positive or negative terminal of the link capacitor. For example, the voltage on the top terminal of the capacitor is +170 V and the voltage on the bottom terminal of the capacitor is at -170 V. If during some short time interval the top switch is on half the time and the bottom switch is on half the time, the average voltage at that output terminal would be zero. If the top switch were on all the time, the average voltage would be +170V, and if the bottom switch were on all the time then the average voltage would be -170V. Thus, the switches can produce average voltages over a short interval that can have any value between +170V and -170V.

The inductance of a motor powered by a VFD responds to the area beneath the curve of a plot of the voltage as a function of time. So, even though the voltage isn't sinusoidal, if the on/off times of the switches are chosen correctly then the current in the leads to the motor *can* be sinusoidal as long as the *average* value of the voltage is sinusoidal. Since the torque generated by the motor is proportional to the currents and not the voltages, then to a first approximation the motor behaves as if it had sinusoidal voltages applied to it.

Problems can arise with VFDs if they are used to power loads other than motors, if there are multiple loads on the VFD, if the motor needs to provide braking action, if the distance between the motor and the VFD is appreciable, or if the current drawn by the VFD is large compared to the rating of the utility step-down transformer.

VFDs were not originally designed to function as phase converters, in fact most VFDs are powered from a three phase source. When used in this manner, six input diodes rectify the 3- ϕ input signal and are used to charge up the DC link capacitor. If a 1- ϕ source is used instead, then 2 of the input diodes go unused and all of the current into the unit has to be carried by the

remaining 4 diodes. Also, the ripple current in the DC link capacitor will be significantly larger, so the power handling capability of all these components has to be increased if the unit is to be powered from a 1- ϕ source. This type of input rectifier typically produces large harmonic distortion in the input current. Table 2 below gives typical values of the harmonic distortion expressed as a percentage of the fundamental component of the input current at 60 Hz.

Harmonic	3 rd	5 th	7 th	9 th	11 th	13 th	15 th
Percent	73.2	36.6	8.1	5.7	4.1	2.9	0.8

The harmonic component of the current will be a problem when the current flowing into the VFD is a significant portion of the total current load that the step-down transformer is capable of delivering. If a very large VFD is used or if multiple smaller VFDs are all attached to the same line then there may be problems. The relatively large current drawn by the input circuit of the VFD at the peak of the voltage sine wave can distort the voltage waveform and cause problems for other users on the power system. Input line reactors are often used between the VFD and the power system to help alleviate this problem.

VFDs are designed to drive a single motor load. The manufacturer's recommendations usually are that the wires to the motor be solidly connected to the VFD and that the connections not be broken under normal operating conditions. That is, one would not normally install a contactor between a VFD and a motor because the high voltage and arcing that are a normal part of the contactor opening and closing can have unpredictable effects on the semiconductor switches in the VFD and increase the risk of failure. If multiple loads are connected to a VFD with individual contactors for each separate load, the VFD may not be able to handle the current surges which occur when individual loads are switched on and off. If a VFD were connected to a piece of equipment which contained 3- ϕ motors as well as other controls, it is very likely that both the VFD and the equipment would be damaged. For example, if there were any capacitors in the equipment connected directly across the VFD outputs, the VFD would have to shut down immediately or be destroyed by the extremely high currents that would flow when the output voltage pulses were applied to the capacitors.

The starting sequence of a VFD is carefully controlled to avoid damage. When the start button is pushed, the pulse sequence to the output switches is adjusted so that the average voltage applied across the motor has a low value, with low frequency. As the motor starts to spin, the voltage is allowed to increase and the frequency is increased until the motor reaches full operational speed. A start at full voltage and max frequency would overload the output switches. If a VFD is putting out full voltage at 60 Hz to one motor on its output, and a second motor is suddenly connected by closing a contactor, then the VFD will probably either shut down if it can respond to the overload, or be damaged if it can't.

The circuitry in a VFD does not allow power to flow from the motor back to the power system, as is required when the motor acts as a brake. If the application requires this feature, then one or more braking resistors and additional switches must be added to the VFD so that this power is absorbed without destroying either the output switches or the DC link capacitor. Rotary and static phase converters intrinsically have the ability to absorb braking currents because two of the wires to the motor are connected directly to the supply system. A Phase Perfect unit is able to feed power from the generated phase back into the power system as well.

The output voltage from a VFD is not sinusoidal, but rather a series of pulses which have average values that are sine waves. The switches that control these pulses have to make their on/off transitions very rapidly (in about 0.2 microsecond) for the VFD to operate efficiently. The high frequency components of these pulses travel from the VFD to the motor through the connecting wires, which become an electrical transmission line. Transmission line effects are normally not a

problem at 60 Hz to the average user because the wavelength of a 60 Hz signal is about 2200 miles (assuming the signal travels at 0.8 x the speed of light in the wires). However, at 5 MHz the wavelength drops to about 180 feet and the effects become important. The electrical impedance of the transmission line is unpredictable but typically has values between a few tens of ohms to a few hundred ohms. On the other hand, the impedance of the motor and the VFD is usually just a few ohms. This mismatch between the line impedance and the impedance of the terminations at the motor and the drive causes standing wave patterns to be set up in the line with resultant voltages that can be much larger than the voltage at the drive output. These standing-wave voltages can damage the wiring, the motor and the drive. If the distance between the VFD and the motor is short (less than 10 feet), there shouldn't be any problem. As the distance approaches 50 feet or more, most VFD manufacturers recommend that output line filters be used on each of the output leads.

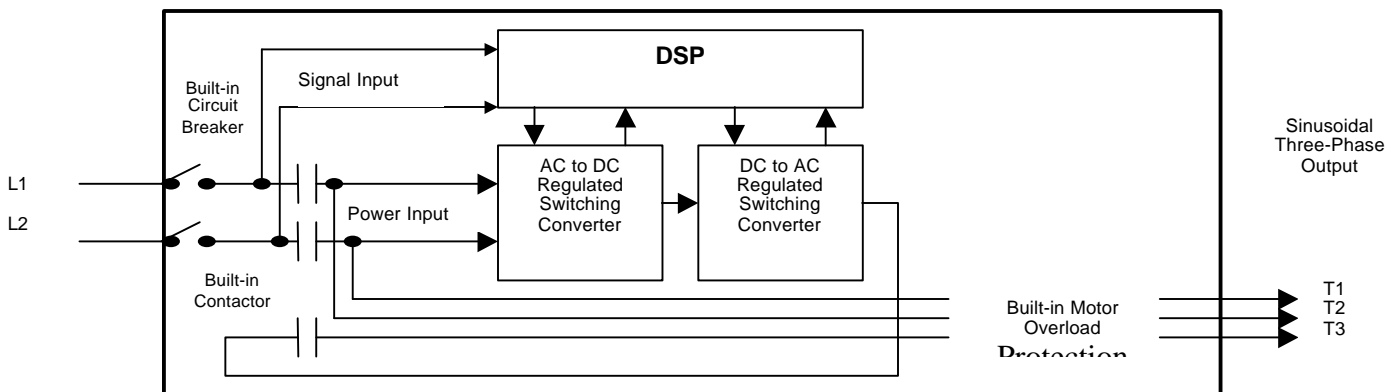
In their simplest form these filters consist of an inductor in series with each output line with a capacitor connected to the second terminal of each inductor. The other terminal of each capacitor is connected to a common point. This filtering does not make the output voltages sinusoidal, and so even with filtering, residual harmonics may have some impact on the wire and motor in installations where the motor and drive are far apart. At distances of 200 feet or more, as would be typical for a deep-well submersible pump, output line filters are a necessity and will add to the cost of the drive installation.

Phase Perfect[®] Digital Phase Converters

Both rotary and static converters have difficulty adjusting voltage balance to accommodate changing load conditions. Voltage regulation schemes for rotary converters are available which switch in different amounts of capacitance as the load changes. However, it is still difficult to get good control, and the high current pulses created in the system as the capacitors are switched in and out can be a problem. What is needed is a circuit configuration that can quickly adapt to changing load conditions.

The Phase Perfect system is similar to static and rotary phase converters in that two of the phase leads to the load come directly from the power line. At that point the similarity ends.

Phase Perfect[®] Block Diagram



Power to generate the voltage for the third lead flows into the digital phase converter through an inductor and a set of semiconductor switches which feed a DC (constant voltage) link capacitor. The switches on the input can control the waveform of the input current and insure that it is sinusoidal, so as not to create harmonic distortion on the power grid. The DC link capacitor is connected to a second set of semiconductor switches which feed a second inductor and a filter capacitor to smooth out the high-frequency pulses created by the switches.

The system is controlled by a small microcontroller, specifically a digital signal processor (DSP) which can measure voltages and feed controlled pulses into the switches, in addition to performing high-speed calculations. The DSP is constantly monitoring the system voltages and current to insure that the input current is sinusoidal, and the output voltage is also sinusoidal. The output voltage can be made equal in magnitude to the input voltage to an accuracy that is primarily determined by the measurement accuracy of the DSP.

Typically, the line-line output voltages of Phase Perfect[®] are balanced to within 1-2%. As the load on the system changes, the DSP senses any drop in the voltage and adjusts the pulses to the semiconductor switches to maintain this accuracy from no load up to full load. Any motor load, or any combination of motors up to the maximum rating of the digital phase converter can be connected without creating unbalanced voltages. This is the first product to apply modern technology to the problem of phase conversion.

Power Quality

Voltage Balance

Because the voltages from a Phase Perfect[®] converter will be balanced as long as the total load on the converter is less than or equal to its load rating, there isn't any engineering work required by the customer. If you examine the product literature provided by manufacturers of rotary phase converters, one thing conspicuously absent is any mention of the phase balance provided by the converter. Since a rotary converter has no control over the output voltage, each motor and each load represents a different situation and manufacturer is not able to predict how their converter will behave.

Sensitive CNC equipment may not even turn on if it is powered by a rotary converter. In the example of the 7.5 HP rotary converter used in a machine shop where one of the line-line voltages from the rotary converter was at 280 V, the electronics unit of a CNC would probably be damaged if it were operated at such a high voltage. A typical utility standard for voltage balance is nominal voltage +/-10%, so a Phase Perfect converter is achieving voltage balance about 5-10 times better than what the utility can guarantee.

Harmonic Distortion

The harmonic distortion limit for utility power on 2.3-6.9 kV lines (which covers most distribution lines) is 5.0% for total harmonic distortion, and 3.0% maximum for an individual harmonic¹. The harmonic content in the output of a typical Phase Perfect[®] converter is given below in Table 3. The n=2,3 etc. values represent the amplitudes of the sub-components of the output voltage at frequencies of 2 x 60, 3 x 60Hz, etc. expressed as a percentage of the voltage at 60 Hz. The total harmonic output is the square root of the sum of the squares of the individual components. It can be seen that the amplitudes of the individual components as well as the total harmonic output are better than what utility supplied 3- ϕ power is expected to provide.

Table 3 Phase Perfect[®] Output Harmonic Content

Harmonic	2 nd	3 rd	4 th	5 th	6 th	7 th	Total
Percent	1.41	2.7	0.38	0.86	0	1.16	3.4

The input current to a Phase Perfect is sinusoidal with low harmonic current. Typical values of the harmonic components are given below in Table 3.

Table 4 Phase Perfect[®] Input Harmonic Content

Harmonic	2 nd	3 rd	4 th	5 th	6 th	7 th	Total
Percent	.72	1.13	0.04	1.6	0.03	0.98	2.3

Power Factor

The total current into a digital phase converter with a motor running at full load will have a phase angle which leads the input voltage by about 5 degrees. This is referred to as a leading power factor and in this case is about 0.99. A typical induction motor has a lagging power factor of about 0.85 and the combination of a rotary phase converter and induction motor load has a combined power factor as low as 0.6. Power factor is important because for a given load in kilowatts the current supplied has to increase as the power factor decreases.

Let's take an example of a 10 Hp single-phase load supplied from 240 V single phase with unity power factor. The required 1- ϕ current to supply this load is:

$$I = 10\text{Hp}(746 \text{ Watts/Hp})/240\text{v} = 31 \text{ amps.}$$

If the power factor drops to PF=0.6, the current required is:

$$I = 31 \text{ amps}/0.6 = 51.8 \text{ amps.}$$

The increased current caused by the poor power factor will require larger wire sizes and larger switch gear than the load with unity power factor.

Protection for the Load

Phase Perfect[®]'s digital computer control and inherent design characteristics provide protection for the operated load that other phase converters and utility three-phase do not offer. It is programmed to shut down in overvoltage and undervoltage conditions, and provides inherent protection against single-phasing that can occur with utility three-phase service. Some models are also rated as a motor starter and include a breaker switch, contactor and adjustable overload relay. In most single motor applications this reduces cost by eliminating the need for a separate starter panel. A control circuit is also integrated into many models, which allows a remote switch to control both the converter and the load.

Conclusion

A Phase Perfect[®] digital phase converter provides excellent power quality with voltage balance under all load conditions, near unity power factor and essentially no harmonic distortion on both the input and output. Consequently, it can safely power virtually any three-phase load within its rated capacity. Three-phase applications such as submersible pumps, center pivot irrigation, machine tools, saw mills, elevators, HVAC equipment and CNC equipment can be powered easily and reliably in areas where three-phase power is not available.

Even when three-phase transmission lines are nearby, small or medium sized applications may not justify the cost of installing three-phase service. In these cases, Phase Perfect[®] offers an affordable alternative source of three-phase power from a single-phase source.

1. C.K. Duffey and R.P. Stratford, "Update of Harmonic Standard IEEE-519 IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems," IEEE IAS Transactions, Nov./Dec. 1989, pp. 1025-1034
2. Cooper Bussman, "Motor Protection Against Single-Phasing", Bulletin PSP

Phase Perfect[®] CASE STUDY

Study Design

A 10 HP model DPC-10 Phase Perfect[®] digital phase converter was connected to two legs of a 208V grounded wye three-phase service. The converter generated the third leg voltage. Two loads were connected to the output of the phase converter. One was a centrifugal pump powered by a 7.5 HP three-phase motor, the other a squirrel cage fan powered by a 3 HP three-phase motor. A load distribution panel allowed the loads to be switched in or out of the circuit independently.

Measurements

The input voltage to the phase converter was measured on terminals 1 and 2, and is referred to below as V_{12} . The generated voltage occurs on terminal 3. The voltages on the phase converter output under various load conditions are given in table 1 below.

Table 1

Load Condition	V_{12}	V_{13}	V_{23}
No load	201.0 V	204.3 V	200.3 V
3 Hp load	199.4 V	201.1 V	199.2 V
10.5 Hp load	193.4 V	194.1 V	196.4 V

The single-phase input current supplied to the phase converter is expressed as I_{in} . The currents measured on the output are I_1 , I_2 and I_3 , with I_3 being the generated phase. The phase currents and the total input current to the system under the two loading conditions are given in table 2 below.

Table 2

Load Condition	I_1	I_2	I_3	I_{in}
3Hp	4.7 A	4.6 A	4.8 A	7.6 A
10.5 Hp	22.6 A	23.6 A	25.1 A	39.0 A

Results

The NEMA definition for voltage imbalance is that the percentage voltage imbalance is given by

$$\% \text{ imbalance} = \frac{(\text{max. voltage on any line}) - (\text{average voltage})}{\text{average voltage}}$$

A similar equation gives the current imbalance. If this definition is applied to the above results, the voltage imbalance is 1.2% at no-load, 0.6% with a 3 Hp load, and 0.9% with a 10.5 Hp load. The current imbalance is 2.1% with the 3 Hp load, and 5.6 % with the 10.5 Hp load.

As the load on the system increased, the voltage supplied from the service panel decreased as evidenced by the figures in table 1. This is due to voltage drop in the single-phase line supplying the unit as the current demand reaches 39 amps. Larger wire supplying the phase converter or more capacity in the utility service would reduce this voltage drop. It is important to note that the digital phase converter followed this drop in line voltage and balanced the phases on the output.

Discussion

The voltage imbalance at the output of the phase converter under all load conditions from zero to full load did not exceed 1.2% which is significantly better than the +/- 10% value that utility power is expected to maintain. The above result was obtained with no adjustments to the phase converter, that is, the unit self corrected to maintain the above voltage balance with no operator intervention.

The current imbalance to the motors never exceeded 5.6%. This amount of current imbalance would have no perceptible impact on the life or proper functioning of the motor. The overall power factor of the system when it was operating at full load was 0.99. The near unity power factor reduces the input current to the system and under some utility billing programs will significantly reduce the power costs to the user.