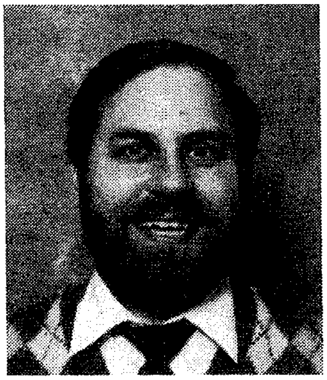
A POWER FACTOR CORRECTED, MOSFET, MULTIPLE OUTPUT, FLYBACK SWITCHING SUPPLY



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ABSTRACT

This paper discusses the subject of power factor correction and its importance in the field of power conversion. Present industry techniques are discussed, and by combining portions of these methods, a new circuit is created that provides power factor correction at 90% or greater. A multiple-output blocking oscillator and a P.W.M. were built to prove the theory with test results given.

INTRODUCTION

DEFINITION OF POWER FACTOR

The traditional textbook explanation of power factor is cos θ when reactive components of capacitors and inductors were in the load. The current either lags or leads the voltage as indicated in figure 1A and figure 1B.

In inductive circuits, the most commonly found industrial electrical loading, the current lags the voltage in time. The inductance is created by motors of every type, heater coils, and coils such as solenoids and pull-in coils for relays, contactors, valves and ballast coils.

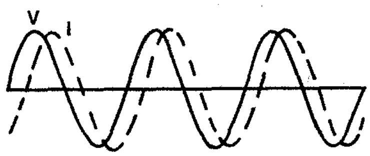
The inductive portion creates no use of electrical energy, but the inductance requires a current flow. This current flow causes additional loading on the electrical generating equipment. The electrical distribution system (see figure 2) must carry the extra current, which results in more loss in wires carrying the energy to the load, and reduces the energy available to the load. The power in the load has been described by:

$$\text{Watts} = E \cdot I \cdot \text{Cosine } \theta$$

The cosine θ is the lead or lag time created by the reactance which can be expressed as a shunt component to the resistive load. Thus, the power factor expressed as the cosine θ, states how closely the load is resistive.

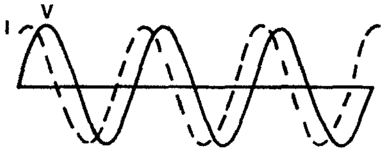
CORRECTING LEADING OR LAGGING POWER FACTOR

Correcting leading or lagging power factor was easily accomplished by placing inductors or capacitors across the power line. Most of the industrial circuits were inductive and had lagging power factor. The lagging power factor was created by motors. Large capacitors were placed across the power lines. These large capacitors tune out some of the inductance: figure 3 shows the phasor diagram. The equivalent circuit of the added capacitors appears as a tank circuit as in figure 4.



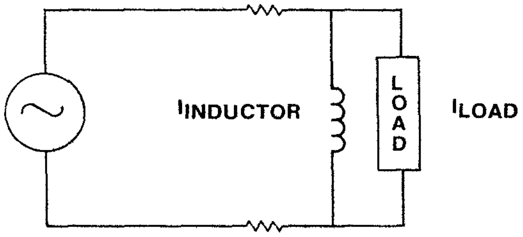
CURRENT LAGGING THE VOLTAGE

FIGURE 1A



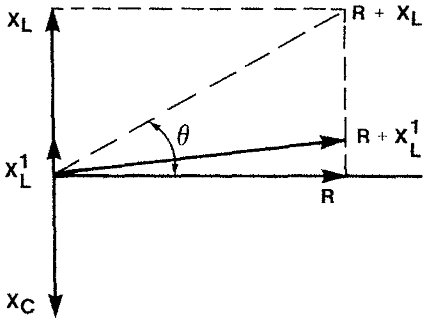
CURRENT LEADING THE VOLTAGE

FIGURE 1B



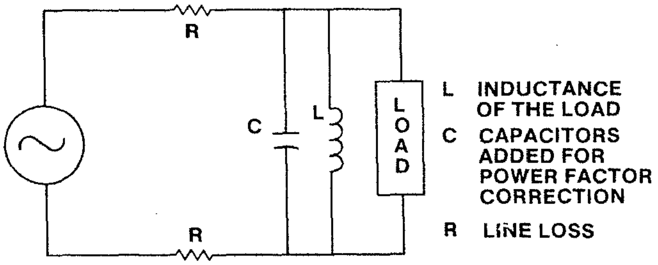
INDUCTIVE LOAD

FIGURE 2



PHASOR DIAGRAM FOR
POWER FACTOR CORRECTED
CIRCUIT

FIGURE 3



POWER FACTOR CORRECTED CIRCUIT

FIGURE 4

ELECTRONIC POWER SUPPLIES

Today, electronic circuits with large electrolytic filter capacitors create a different type of current waveform. The waveform is in high peak pulses. The pulses occur when the AC voltage exceeds the electrolytic capacitor voltage. The current waveform on a first order approximation neither leads nor lags the voltage. On a second approximation, the current slightly leads the voltage. This can be seen by examining the peak AC voltage and measuring the t_1 time and the t_2 time as seen in figure 5. When using a wattmeter, analog or electronic, the results are the same

$$\text{WATTS} = \text{VOLTS}_{rms} \cdot \text{AMPS}_{rms} \cdot (\text{POWER FACTOR})$$

The power factor now has a new meaning which indicates the amount of time that the current is following.

BENEFITS OF POWER FACTOR CORRECTION

When the power factor is 1.0, the current is in phase with the voltage. This is an ideal condition; most electronic circuits, with a diode bridge followed by an electrolytic capacitor, have a power factor ranging from 0.50 to 0.70. If a circuit required 100 watts of power and the supply voltage was 100 V_{rms}, the current required would be 1 ampere if the power factor was 1.0 or unity. If the circuit has a diode bridge followed by a large electrolytic capacitor, the power factor could be 0.50; the current requirement would then be 2.0 amperes.

In practical terms, this means that consumer appliances can not have a wattage greater than 600 watts unless they are power factor corrected. This rating comes from the fact that U.L. limits products to 0.80 of the maximum current handling for an electrical circuit. Wall plugs in homes have a 15 ampere rating and a low line voltage of 105 Volts rms. Maximum current is then 15 · 0.80 = 12.0 A. Maximum power is 105 Volts · 12 Amps · 0.50 pf = 630 Watts.

One benefit of power factor correction is a reduction in the rms current by the reciprocal of the power factor. A second benefit is a reduction in the peak current that the front end bridge diodes must carry. The reduction in the line current harmonic content is a third benefit.

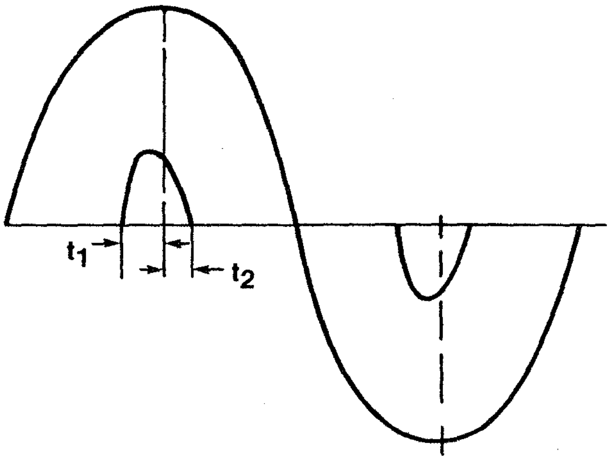
CONSIDERATIONS OF THE THIRD HARMONIC

When the line current from a non-power factor corrected circuit is examined using a spectrum analyzer, both the amplitude and the frequency of each harmonic can be measured. Circuits with power factor between 0.50 and 0.65 usually have a third order harmonic that is of the same amplitude as the fundamental. These harmonics add to the neutral line when a wye electrical distribution system is used. Thus it is possible for the neutral line to carry three times as much current as mains L_1, L_2, and L_3.

To explain how the neutral line can carry up to three times as much current as each line, the following should be considered: First, each of the three lines (L_1, L_2 and L_3) are phase shifted 120 degrees from each other. Second, the total current flowing in each line is the square root of the sum of the squares of each frequency. Each harmonic frequency has an rms value that is measured by a frequency selecting technique such as a spectrum analyzer or a distortion analyzer.

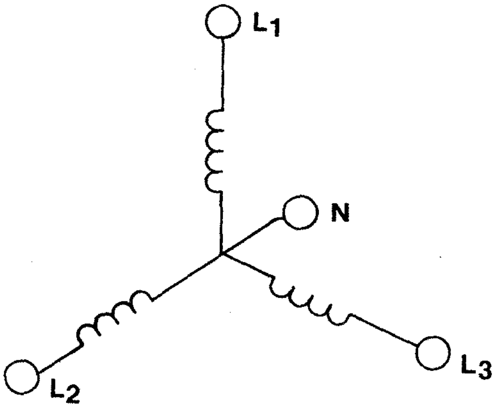
$$I_{rms} = \sqrt{(I_{60Hz} + I_{120Hz} + I_{180Hz} + \ldots)}$$

A wye electrical distribution system is shown in figure 6. The wave forms for both current and voltage are shown for a non-power factor corrected system in figure 7. The current in the neutral or return now appears as a 180 hertz signal. When these



INPUT VOLTAGE AND CURRENT

FIGURE 5



WYE DISTRIBUTION NETWORK

FIGURE 6

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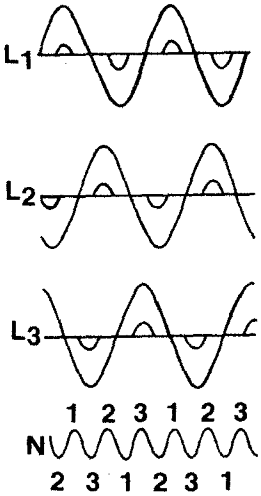

THIRD HARMONIC IN THE NEUTRAL

FIGURE 7

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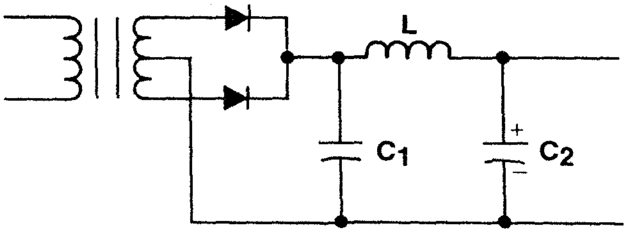

π NETWORK

FIGURE 8

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types of line currents are analyzed using a spectrum analyzer, the third order harmonic, which is 180 hertz, has the same amplitude as the 60 Hz fundamental frequency. Since amplitudes of the same frequency are additive, the amplitudes of the third order harmonic of each line are added together. It is possible that the neutral wire will carry more current than any of the power lines. This also implies that the size of the neutral must be larger than the power lines. An ideal electrical distribution system that is power factor corrected and has load balance presents no current in the neutral line.

As an example, let all three mains have the same current. The current has the following harmonics: 1 amp at 60 Hz and 1 amp at 180 Hz. The current flowing in each main is $\sqrt{2}$ or 1.414 amps. The current flowing in the neutral is the sum of the third order harmonics in each line, which in this example is 3 amps.

There is another guideline on the amplitude of the third order harmonic. The third order should be 25 percent below the amplitude of the total rms line current, or the third order harmonic should be 33.3 percent below the amplitude of the fundamental. ANSI and IEC have specifications for different products. Please refer to the standards for exact specifications of harmonic content.

PRESENT TECHNIQUES USED BY THE INDUSTRY

π FILTER

The first system to be discussed will be the π filter, which is shown in figure 8. This type of filtering was used with vacuum tubes and in particular with color TVs and the high quality audio systems before transistors were manufactured. The inductor, L, was a large iron core that had an air gap to keep it from saturating. The first capacitor, C_1, was a film or paper type that could accept large ripple currents. The second capacitor, C_2, was an electrolytic type that provided the final filtering. The size of the inductor determined the amount of filtering and power factor correction that was obtained.

This was a very effective technique, but, like all systems, there were some problems. The size of the choke is extremely large. If the core was not assembled correctly, the choke hummed. The power supply required a choke for each supply voltage. To reduce the number of chokes necessary, the choke was placed in front of the transformer, which resulted in the development of the constant voltage type of transformer.

CONSTANT VOLTAGE TRANSFORMERS, FERRO-RESONANT TRANSFORMERS

The basic schematic of both the constant voltage transformer and the ferro-resonant transformer is shown in figure 9. The system consists of three components: L, C, and T. The magnetic components, L and T, are wound around the same core. The inductor, L, is operated in the linear portion of the B-H loop and very loosely coupled, if at all, to the transformer, T, which is operated in the quasi-saturated region of the B-H magnetic structure.

The voltage wave forms are also shown in figure 9. The input voltage is a sine wave while the capacitor voltage is a mild square wave with rounded corners. The amplitude of the capacitor voltage is constant. With constant voltage applied to the transformer primary, the secondary delivers a constant voltage square wave to the bridge rectifiers. Because of the square waves, there is a very short transition time between the positive and negative portions of the voltage. The size of the filter capacitor can be much smaller than that of other types of supplies.

The computer industry, with large power demands for the mainframe computer, has used the constant voltage transformer and the ferro-resonant transformer. The consumer industry for microwave ovens has also been using a resonant type of

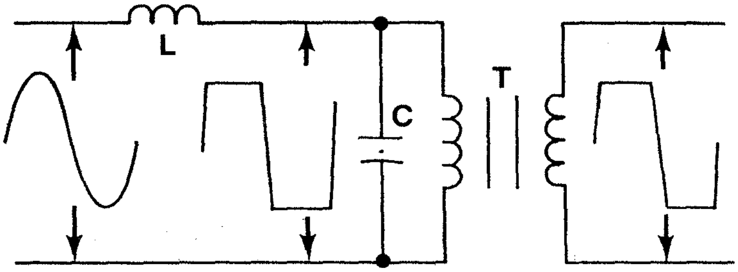


FIGURE 9 CONSTANT VOLTAGE TRANSFORMER K6129

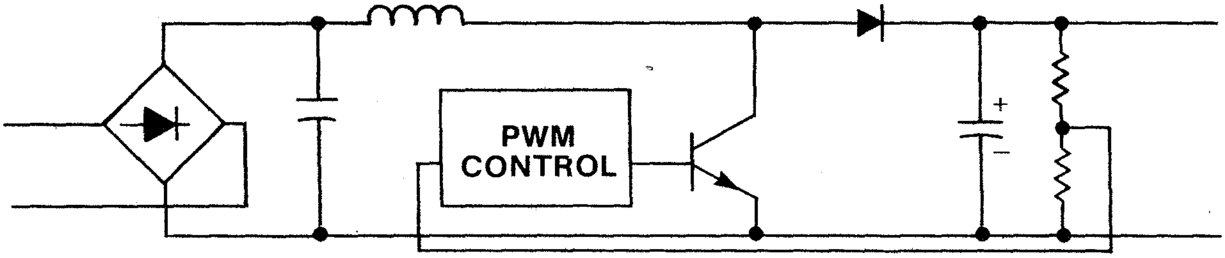
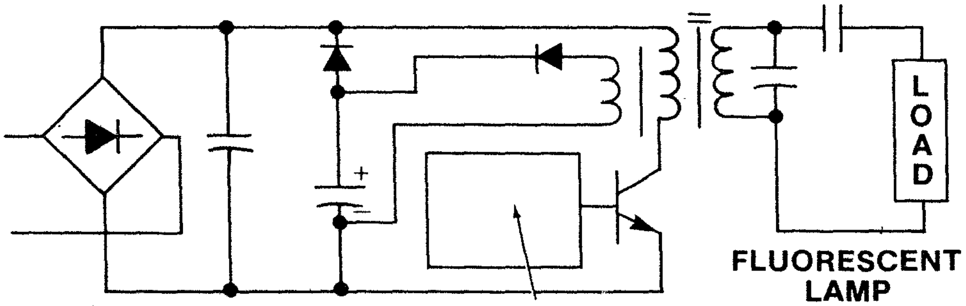


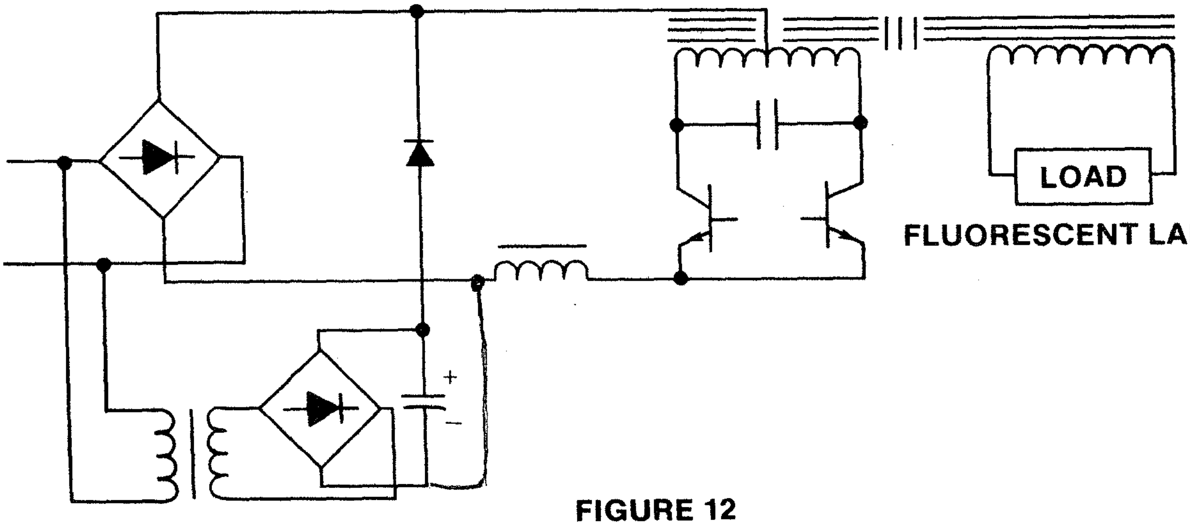
FIGURE 10 POWER FACTOR CORRECTED BOOST CIRCUIT K6130



FLUORESCENT LAMP

BLOCKING OSCILLATOR CONTROL

FIGURE 11 K6131



FLUORESCENT LAMPS

FIGURE 12

transformer in order to obtain the 1200 watts needed to power the magnatron power oscillator tube. The telephone operating companies use this type of system to maintain the constant voltage on the batteries used to power the standard telephones.

BOOST CIRCUIT

D. Chambers and D. Wang published a paper (1) demonstrating power factor correction in a boost converter circuit. Data published provided input sine wave current that is in phase with the voltage, providing an excellent power factor in the 90's. A simplified boost converter diagram is shown in figure 10. The boost circuit was also shown in the paper with an isolated output and a lower output voltage.

ELECTRONIC BALLAST

The fluorescent lamp ballast industry has been aware of the need for power factor correction. They have been supplying ballast systems that are typically 0.985 power factor corrected. There are several papers and patents (2,3) telling of the improvements that occur when high frequency converters are used with fluorescent lamps. Two items have kept these innovations from being mass produced: cost and power factor correction.

Three approaches are noteworthy.The first proposed by Lloyd Perper (2) is shown in the block diagram in figure 11. The second proposed by Koshimura (3) is shown in figure 12 and is a current feed sine wave inverter. A third approach is manufactured by Advanced Transformer, a division of North American Phillips and is shown in figure 13. The block diagram schematic is similar to the Koshimura circuit, but it has no added transformer. The charging energy is obtained from the main power transformer by an additional winding.

All three of the above circuits use the same technique of power factor correction. The voltage on the positive rail modulates between the peak ac line voltage and 50 percent of the ac line voltage. This is shown in figure 14. Power factors of 90 to 95 percent have been reported by these techniques.

A NEW TECHNIQUE

DERIVATION OF THE NEW CIRCUIT

Improved performance can be obtained by recognizing that over 94 percent of the energy in ac voltage and current waveform in a resistive load occurs between 30 degrees and 150 degrees of the positive portion and between 210 degrees and 330 degrees of the negative portion of the cycle. Power in watts is the product of both voltage and current and has a sine squared function variation with time.

As an example, let the voltage be 1 sin t and the load be 1 ohm. The current becomes 1 sin t. Calculating power by any number of means, the wattage is 1 $\sin^2 t$. Using only the positive portion of the waveform, integrate $\sin^2 t$ from 30 degrees to 150 degrees which equals 1.480. Now integrate from 0 to 180 degrees which is $\pi/2$.

Dividing 1.480 by 1.570 equals 0.942 or 94.2 percent of the available energy. Because the watt meter reads the total voltage and only the current that flows, a power factor of 94 percent is not what is obtained. A power factor somewhat less is usually obtained.

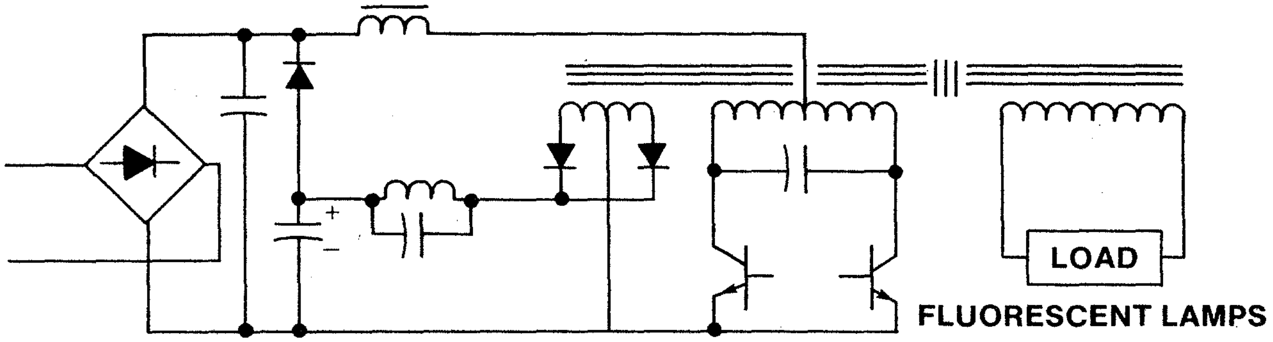


FIGURE 13

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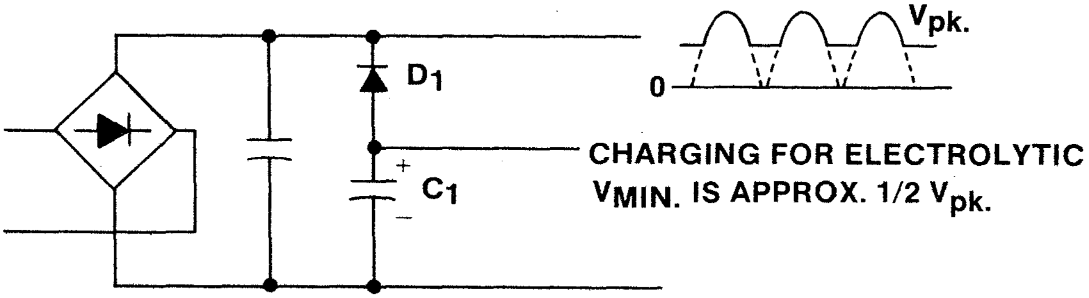

CHARGING FOR ELECTROLYTIC $V_{MIN.}$ IS APPROX. 1/2 $V_{pk.}$

COMMON CAPACITOR CIRCUIT FOR FIGURES 11-13

FIGURE 14

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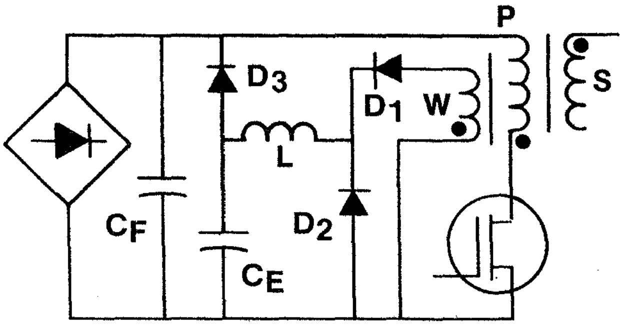

NEW POWER FACTOR CIRCUIT

FIGURE 15

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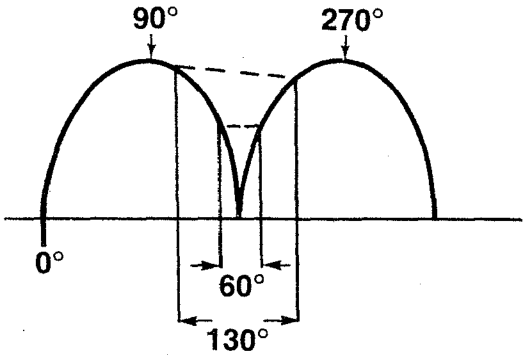

CAPACITOR WORKING TIMES

FIGURE 16

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By modulating the voltage between 50 and 60 percent of the peak ac line voltage and the peak value, large increases in power factor are possible over non-power factor corrected systems. To keep the positive rail from going below 50 percent and to keep the current spike from flowing in the circuit, figure 15 was developed for a flyback circuit topology.

The circuit of figure 15 uses a flyback transformer and differs from the circuits of figures 11-13 because of the wave forms and the energy stored in the inductor. The ballast circuits of figures 11-13 are sine wave, while the flyback is square wave. The second diode, D_2, releases the stored energy in the inductor.

The electrolytic capacitor, C_E, is charged by the main transformer through winding W. The charging current is limited by inductor L. Diodes D_1 and D_2 provide a forward converter along with inductor L. D_3 is a steering diode which is forward biased whenever the ac rectified line voltage drops below the C_E voltage. The turns ratio for W is between 80 and 90 percent of P, which is the primary winding. S is a number of secondary windings. Capacitor C_F is a film type capacitor in the range of 0.47uF at 250 VDC.

The charge winding, W, is presented as a forward converter in figure 15. Both forward converter and flyback charging techniques work. The forward converter is easier and provides better results when different ac line voltages are used. Fewer turns are required when the forward converter system is used.

The circuit works in the following manner. When the MOSFET is on, energy is stored in the primary, P, and also energy is coupled to the winding W. The winding, W, is phased such that D_1 is forward biased and current flows through inductor L to charge C_E. When the MOSFET is turned off, the voltages change polarity and the diode, D_1, is now reverse biased. The stored energy in the inductor must be released safely. D_2 becomes forward biased and releases the energy stored in the capacitor C_E.

ADVANTAGES OF THE NEW CIRCUIT

- The circuit is extremely simple and uses five components and an additional winding on the main transformer.
- There are no active components or feedback loop to stabilize.
- The power factor can be 90 percent or greater.
- The peak current handling of the input rectifiers has been reduced because the current is spread over 120 degrees versus 40 degrees for an non-power factor corrected unit.
- The input inrush current to charge the large electrolytic capacitors has been eliminated.
- The voltage and size requirements for the electrolytic capacitor have been reduced.
- The capacitor voltage now can be 100 volts for a 120 VAC unit.
- The size of the capacitor in uf is reduced because the capacitor now only has to support the circuit for 60 degrees while the non-power factor corrected system has to support the circuit for 130 degrees (see figure 16).

THE RESULTS

Two circuits were built to prove the concepts for a multiple output switching power supply with outputs at +5, +12, and -12 volts. Both units used power MOSFETs in a flyback topology. One circuit was a blocking oscillator in a current mode type control, while the other used a PWM control IC in a voltage mode type control. The schematics are shown in figures 17 and 18.

The input voltage waveform along with the current is seen in figure 19 from a scope camera. The voltage is a sine wave while the current is a first order square wave. The top of the current waveform is curved. The reason for the curve is that the load remains constant and therefore power is held constant over the entire time. The voltage increases and then decreases; the current must therefore be the inverse of the voltage in order to hold the power constant.

The units were tested using the following equipment. The power factor, and line voltage and current were measured with an RFL 636 Power Analyzer. The power supply for the 120 VAC was an Elgar 6000B Line Conditioner. The spectrum analyzer was an H.P. 3585. A photo was taken of the spectral response and is seen in figure 20.

The spectrum analyzer gave a read out of voltage and frequency from the current probe. The voltage readings were converted to current readings and the results are presented below in Table 1. The even harmonics readings of 120 Hz, 240 Hz, 360 Hz, etc. were taken but are not presented because the readings were extremely low (in the micro-ampere area).

TABLE 1

Power factor and frequency component current for the two test circuits.

	TEST CIRCUIT	
	Blocking OSC.	PWM
power factor	0.9321	0.9415
Total current rms	0.375 Amps	0.3747 Amps
60 Hz	0.354 Amps	0.3584 Amps
180 Hz	0.0876 Amps	0.0330 Amps
300 Hz	0.0708 Amps	0.0700 Amps
420 Hz	0.0669 Amps	0.061 Amps
540 Hz	0.0211 Amps	0.0134 Amps
660 Hz	0.0284 Amps	0.0236 Amps
780 Hz	0.0494 Amps	0.0354 Amps
900 Hz	0.0129 Amps	0.0163 Amps

From the data in Table 1, the ratio of the 3rd order harmonic current to the total current and the ratios of the harmonic currents to that of the fundamental are calculated and presented in Table 2.

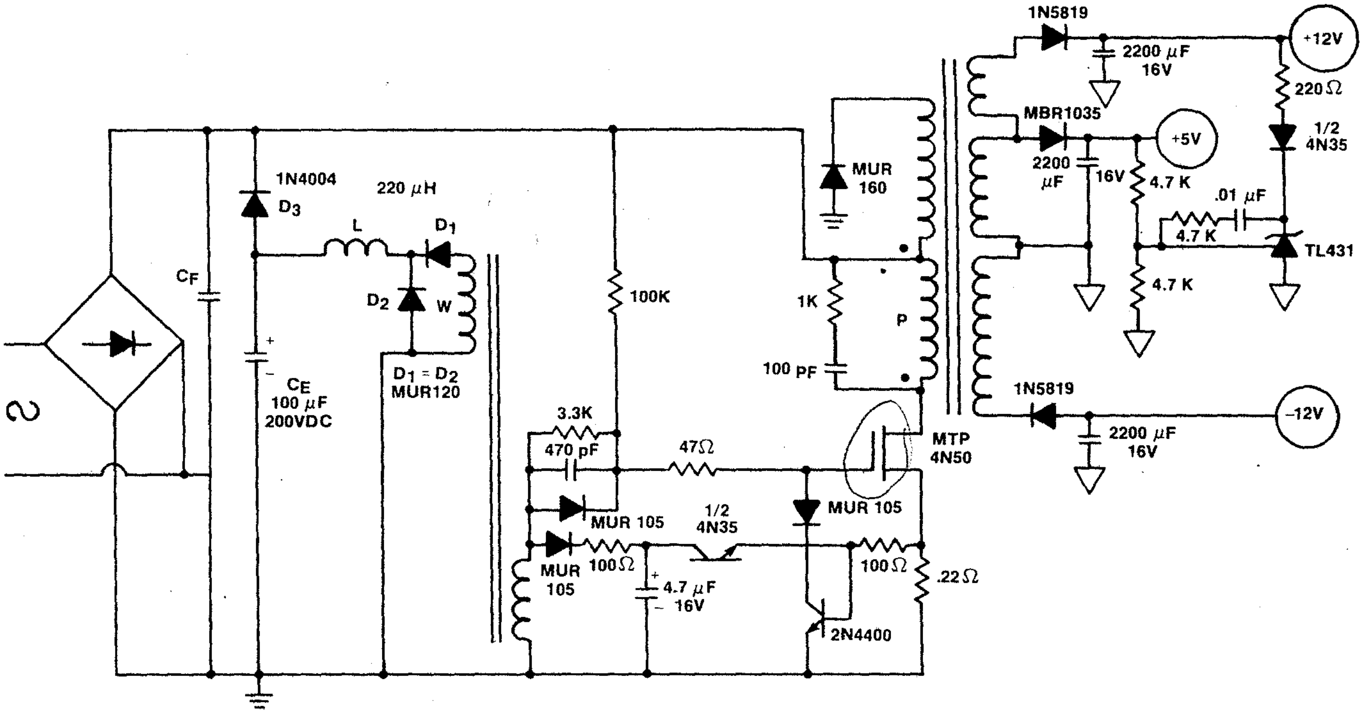


FIGURE 17

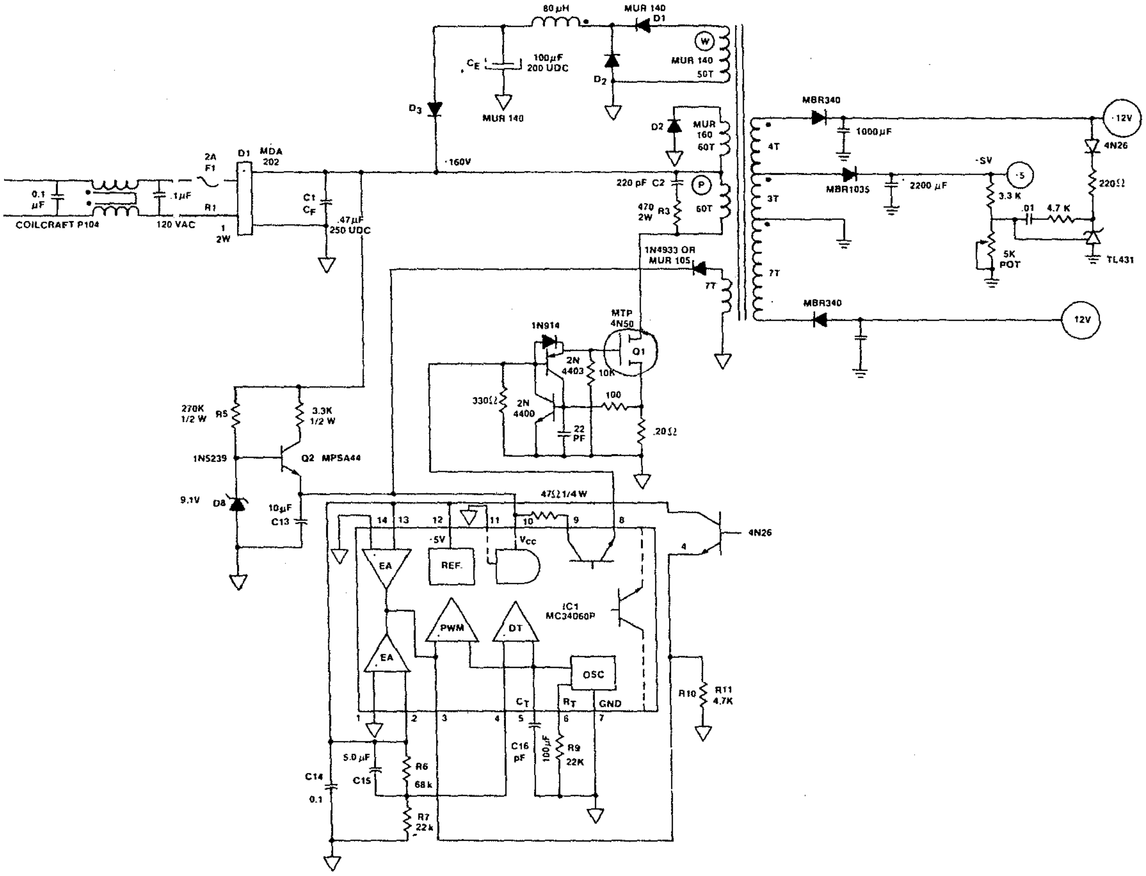
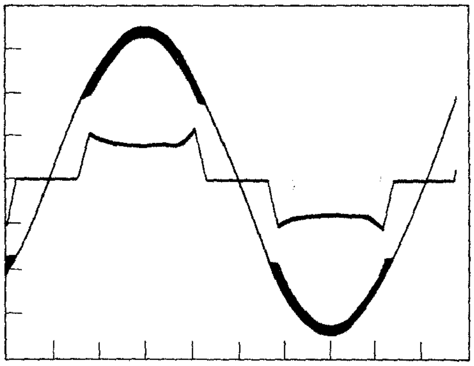


FIGURE 18 PWM POWER FACTOR



INPUT VOLTAGE AND CURRENT AT 120Vrms.

FIGURE 19

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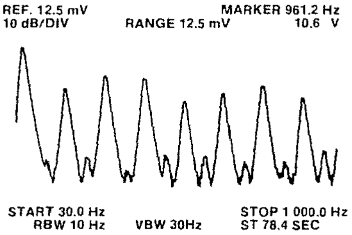

SPECTRUM ANALYZER

FIGURE 20

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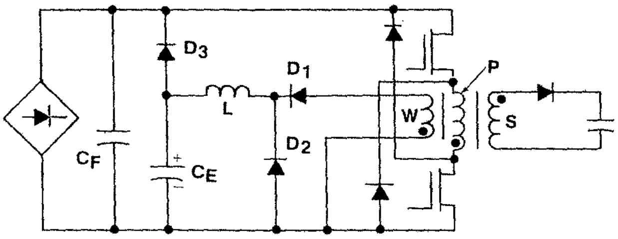

DUAL MOSFET SWITCHER, POWER FACTOR CORRECTED

FIGURE 21

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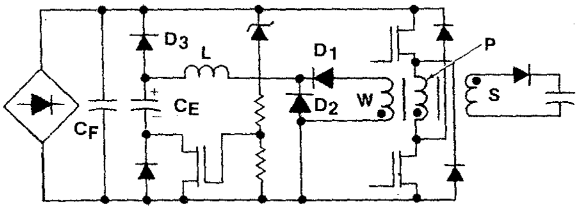

DUAL MOSFET FLYBACK SWITCHER, POWER FACTOR CORRECTED, WITH AN ACTIVE CAPACITOR CHARGING NETWORK

FIGURE 22

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TABLE 2

Ratios of the frequency component currents for the two test circuits.

	TEST CIRCUIT	
RATIO of:	BLOCKING	PWM
3rd order/total	0.100	0.088
3rd order/fund.	0.100	0.092
5th order/fund.	0.200	0.195
7th order/fund.	0.189	0.170
9th order/fund.	0.0596	0.037
11th order/fund.	0.080	0.066
13th order/fund.	0.1395	0.098

From the above Table 2, it can be seen that the third order harmonic is well below the goal of 0.25. The other harmonics such as the fifth, seventh, and thirteenth are higher in this circuit than the third and the even harmonics are negligible. The author is unaware of any problems that the above condition might present to the power utilities.

OTHER CONFIGURATIONS

By using the basic configuration identified in figure 15, i.e. an additional winding, three diodes, a film capacitor and a choke, a number of circuit topologies can now be power factored. For larger powers, an active switch may be required. Figures 21 and 22 show a two transistor flyback with and without the active switch for the charging circuit. The active switch is used to stop charging the electrolytic when the voltage is below the set level. This may be required when ten amperes are required in the primary circuit. At such power levels, a continuous duty flyback is preferred over the discontinuous duty type because of the peak currents in the power switches.

CONCLUSIONS

The concept of an inexpensive power factor correction circuit for off line switching power supplies has been demonstrated. This concept could easily be extended to any number of different topologies; the forward converter, push-pull, full bridge and some half birdges. This circuit has provided the following:

1. Power factor 90 percent or greater
2. Third order harmonic below 25 percent
3. Lower inrush current
4. Lower total average current for the input diodes
5. Lower electrolytic capacitor voltage requirements
6. and Few components, easy to implement.

REFERENCES

1. D. Chambers and D. Wang, "Dynamic Power Factor Correction In Capacitor Input Off Line Converters," Proceedings of POWERCON 6, Miami Beach, FL., May 2-4, 1979, pp. B3-1 B3-6.

2. Lloyd J. Perper, "Power Source For Fluorescent Lamps And The Like" U.S. Patent #4,017,785, April 12, 1977.

3. Y. Koshimura, et al., "Apparatus For Operating Discharge Lamps" U.S. patent #4,388,561, June 14, 1983.