Power-factor correction Rx for medical power supplies

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A power-factor-corrected power supply allows more instruments to plug into a single outlet, which is an important consideration for both industrial and medical settings. Power-factor correction also ensures adherence to international harmonic-current regulations.

High-frequency switching power supplies exist in nearly every home, office, and hospital room. Hospital admissions groups, ICUs, operating rooms, laboratories, and patient rooms use an increasing number not only of PC products, but also of other instrumentation that uses switching power supplies.

Unfortunately, switching power supplies, which pull current in narrow, high-amplitude pulses rather than sinusoidally from the ac mains, cause power disturbances at the ac power source. These disturbances, in the form of current pulses with significant harmonic content, can cause anything from a product's failure to meet international regulatory standards for harmonic content to an actual fire in an office, hospital, or industrial location.

@a glance

- Power-factor correction reduces rms currents and allows more equipment to operate from 15A service.
- It is likely that, within two years, power-factor correction may be critical to meeting international standards.
- The size of the power supply determines whether the correction stage can comprise a simple LC filter or a more complex active design.

The use of power-factor correction significantly reduces these high peak currents and makes the supply appear as a linear load to the power system. Although PFC can ensure compliance with a regulatory specification, a second and significant reason exists to use power-factor correction: It allows a high-wattage system to draw less rms-input current, which in turn allows for plugging equipment into a 15A rather than a 20A service. Although modern offices, homes, and hospitals are currently built with 20A service to the wall outlets, many established services still have 15A breakers.

In hospitals, there is an ever-increasing demand to have more and more electrical service at the bedside. A single patient can require a ventilator to deliver air and oxygen to the lungs, an IV pump to deliver prescribed fluids, a pulse oximeter to track metabolic functions, a CRT monitor to display critical waveforms, and an ultrasound machine for an examination. Although there is usually more than one outlet at a bedside, these outlets usually connect to the same service. With this burden on the electrical system at every bedside, it is critical for machines to be energy-efficient.

Most engineers understand the disadvantages of the radiated and conducted electromagnetic noise associated with the offline switchers. However, many engineers do not have an appreciation of the power disturbance that switching power supplies cause. Switching supplies pull current in narrow pulses once every 8 msec for a 60-Hz line frequency rather than sinusoidally. These current pulses have significant harmonic content, and the high-peak and in-phase currents of multiple supplies add up to create problematic IR losses in the mains wiring.

The international community rec-

PREPARE TO MEET INTERNATIONAL STANDARDS

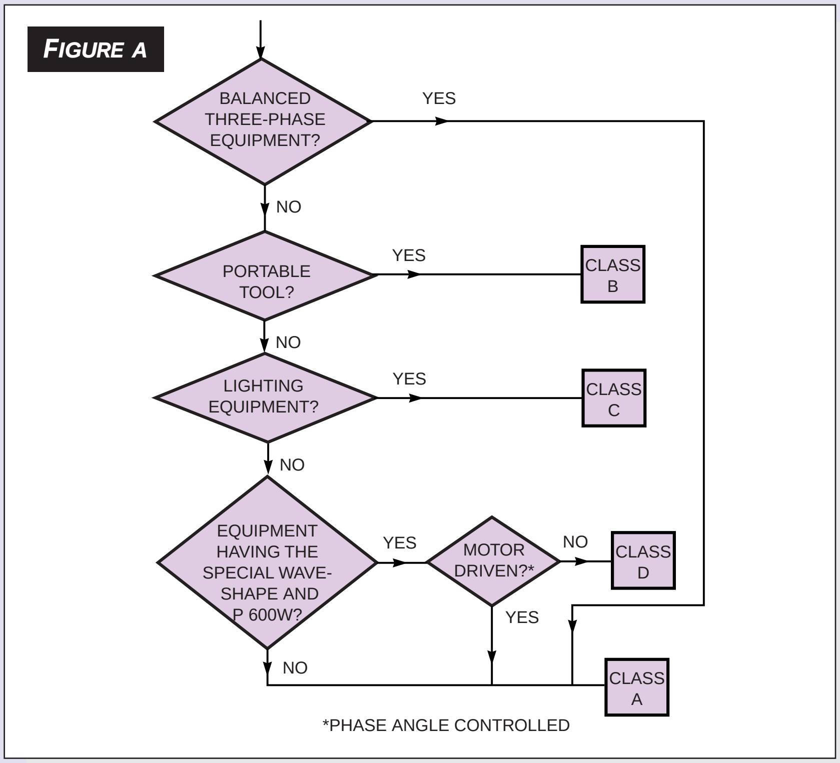


FIGURE A

A flow chart in the IEC 1000-3-2 specification helps to determine the classification of equipment.

You may not need power-factor correction to reduce line current levels, but you may need it to receive your equipment's CE mark. IEC 1000-3-2 was published in 1995 and, like its predecessor EN60555-2, sets requirements for harmonic currents. The EN60555-2 document limited the applicability of the specification to nonprofessional devices. The IEC 1000-3-2 document is broader in scope, covering both professional and nonprofessional mains-attached devices that draw current as high as 16A.

The document sets current level maximums out to the 40th harmonic. CENELEC, the European Committee for Electrotechnical Standardization, published IEC 1000-3-2 in 1995 as EN601000-3-2, harmonizing it to the EMC directive. Compliance with this specification is imperative, but the effectivity date of the specification has been delayed once already. According to Robert Martin, senior technical manager with Intertek Testing Services (www.worldlab.com), the member states are currently negotiating the adoption of EN61000-3-2 into law, and the expected effectivity date is early 2001. During this transition period, manufacturers have the option of complying with EN60555-2 or EN61000-3-2. Although medical devices are not now required to meet EN61000-3-2, the specification is listed in the unpublished second edition of EN60601-1-2. Its acceptance date is also expected during 2001.

The odd-order harmonics that an uncorrected power supply generate are particularly problematic to three-phase systems with single-phase loads. Overheating of the neutral wires is a significant safety hazard. In an ideally balanced three-phase load, the currents in the neutral line cancel, yielding zero current. Even when the lines are unbalanced, there is some partial cancellation. If, however, the phased loads are switching supplies, no cancellation occurs.

The existence of triplen, or third-order, harmonics causes high neutral-current levels, which add in series in the neutral conductor. In three-phase wye-connected systems, each of the phases is 120° out from the other. The triplen harmonics are also 120° out of phase with the fundamental. The result is a neutral current that is higher than the individual phase currents. Circuit breakers protect the wires in the individual phase circuits for overcurrent conditions, but there is no protection for the neutral wires with the summing harmonic currents.

IEC 1000-3-2 addresses equipment with nominal line-to-neutral voltages of 220V and higher. The aim of the standard is to prevent power-control devices from generating low-frequency harmonics. It categorizes devices into four classes. The flow chart in Figure A aids in determining the equipment classification: Figure B shows the "special waveshape" for Class D equipment.

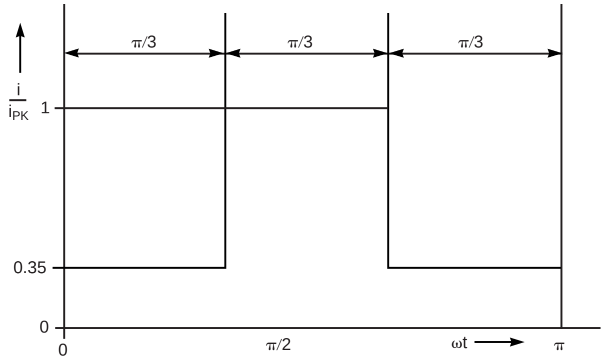
ognizes the harmonic-current problem, and the IEC 1000-3-2 specification establishes requirements that limit harmonic-current injection into the public supply system. IEC 1000-3-2 is also broader in scope than its predecessor, IEC 555-2 (see **sidebar** "Prepare to meet international standards.")

Offline power supplies typically rectify the line voltage, and a voltage-doubler circuit stores the peak voltage. The doubler technique (**Figure 1**), when configured for 120V ac, stores the positive line peak into one capacitor, C_1, and the negative line peak into another capacitor, C_2. When you configure the doubler for a 240V ac input, both capacitors charge at the same time. The resultant peak voltage is 1.414×240V=339V. With a 10% ripple voltage, the average dc voltage is then 322V. This voltage is

TABLE A—LIMITS FOR CLASS A EQUIPMENT

Harmonic order (n)	Maximum permissible harmonic current (A)
Odd harmonics	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
15 ≤n ≤39	0.15×15/n
Even harmonics	
2	1.08
4	0.43
6	0.30
8 ≤n ≤40	0.23×8/n

FIGURE B



To classify equipment as Class D, IEC 1000-3-2 defines a "special waveshape" of the envelope of the input current.

Each class has unique limits. Class A (Table A) covers balanced three-phase equipment and all others except those defined in specialized classes B, C, and D. For portable tools (Class B), which offer a low-duty cycle to the mains power, the limit is 1.5 times that of Class A. Table B lists limits for lighting equipment, Class C. Those devices that have a "special waveshape" and are not motor-driven or do not fit into Class A, B, or C are considered Class D (Table C).

A medical product typically has an extended development cycle when compared with a technically equivalent industrial product because of the increased safety requirements and regulatory submissions. Because of the high development costs, a medical product will also see a longer life in the market. The project manager of any mains-connected medical product currently under development should strongly consider having IEC 1000-3-2 as an applicable document for the system's power supply.

TABLE B—LIMITS FOR CLASS B EQUIPMENT

Harmonic order	Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency (%)
2	2
3	30 – λ*
5	10
7	7
9	5
11≤ n ≤39 (odd harmoics only)	3

* λ is the circuit power factor.

TABLE C—LIMITS FOR CLASS C EQUIPMENT

Harmonic order n	Maximum permissible harmonic current per watt (mA/W)	Maximum permissible harmonic current (A)
3	3,4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
13 ≤n ≤39 (odd harmoics only)	3.85/n	See Table A

the raw power that the converter uses to create the output supply voltages. Because the energy stored in a capacitor equals $\frac{1}{2}CV^2$, much smaller capacitors than those necessary for a linear supply can store the raw energy of the switching supply.

The capacitors charge near the peak of the voltage waveform. Conduction begins when the voltage level of the line rises above the voltage level in the capacitor (**Figure 2**). For a front-end system with minimal voltage ripple, the current flows into the capacitor near the very peak of the voltage waveform. The capacitor charge current ceases when the line voltage falls below the stored level. The waveform of the resultant current pulse is problematic because it is rich in harmonics and has a high rms value. The power system does not see a linear load but instead has to provide a series of current pulses.

At this point, you may wonder what the issue is: The supply still uses the same average current from the power company, whether the capacitor charges in 2 or 8 msec right? Understanding this issue leads to a full appreciation of power-factor correction.

Take the case of input-filter capacitors that have a peak storage of 339V and a droop of 34V between charges due to a 1A dc load from the converter. The capacitors charge during a 2-msec period, and when the voltage falls below the capacitors' stored voltage levels, the capacitors supply power to the converter for 6 msec.

You can determine the charge required to fill the capacitor using i=dq/dt, where i is the instantaneous current, q is in coulombs, and t is in seconds. For the steady-state current condition, I=Q/T. Therefore, Q=1A×6 msec=6 mC.

When the ac line must deliver this charge in 2 msec, the average current to charge each capacitor is 6 mC/2 msec=3A. The total line current during the charge segment also includes the converter current, for a total of 4A. The rms value of a function is known as the "effective value" and is defined as:

$$Y_{RMS} = \sqrt{\frac{1}{T}\int_O^T y(t)^2\,dt}.$$

As you can see from this equation, an increase in the function's magnitude disproportionately increases the rms value due to the squared term. You can approximate the rms current by assuming that the current pulse is sinusoidal during the 2-msec duration and integrating over the entire 8-msec period. For this example, the result of this calculation is 1.4A. The difference between 1.4A rms and the converter-required 1A-rms level demonstrates the increase of rms current that the short term and elevated amplitude of the current pulse causes.

Requiring that energy flows into the capacitors during only 2 msec of the 8-msec period places an increased burden on the ac-mains power system. The high current that flows during the 3-msec window can add with other devices on the same mains service, causing high IR losses in the neutral wires. The finite source impedance of the ac system can also cause clipping at the peak of the sinusoidal ac-mains waveform. Consequently, the building's wiring must be able to support more than double the rating of the equipment to maintain the expected voltage levels. Computer manufacturers have had to move from building to building because the company outgrew each building's power-system wiring.

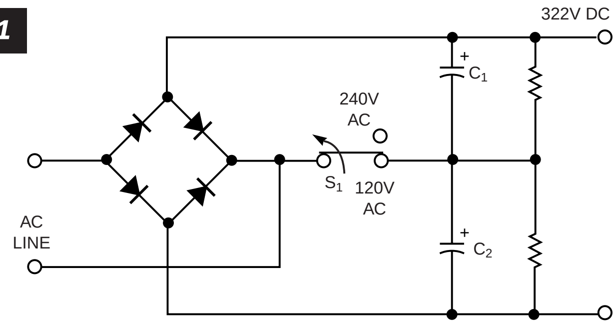
Power-factor basics

Theoretically, power factor, PF, equals Cosθ, where θ is the phase difference between voltage and current. Although this power-factor definition is a nice rule of thumb, its application is limited to pure RLC circuits and generally to circuits with sinusoidal current and voltage waveforms.

Strictly speaking, power factor is the ratio of real power, P_R, to apparent power, P_A:

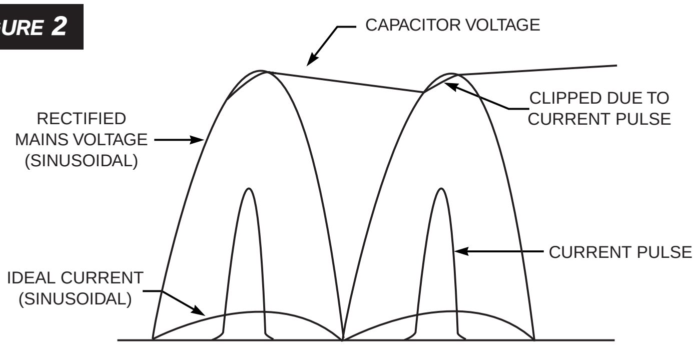
$$PF = \frac{P_R}{P_A}.$$

FIGURE 1



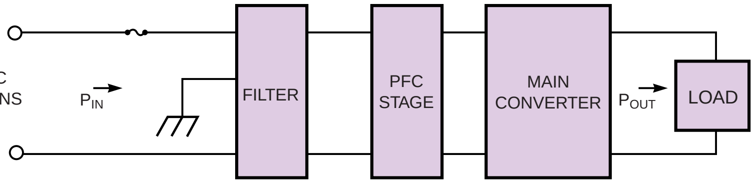
The front end of a switching power supply typically implements a voltage-doubler technique. S_1 allows for 120 or 240V-ac operation.

FIGURE 2



Switching power supplies have input currents in the form of pulses.

FIGURE 3



Adding a power-factor-correction stage results in two power conversions between the ac-mains voltage and the load. The power-factor-correction stage reduces the rms current that the supply draws from the mains and mains-attached devices. Note that this scheme does not include a voltage doubler.

Thus, PF is an indicator of how close the apparent power is to the real power. A PF of 1.0 is ideal for the power system. More stress than necessary is incurred by the power system when the PF is less than 1.0.

You can calculate real power, P_R, as the average of the instantaneous product of voltage and current taken at each instance in time over the full period, T, as follows:

$$P_R \frac{1}{T}\int_O^T e \bullet i\,dt.$$

where e=voltage and i=current:
A true rms power meter can measure the real power.

The apparent power, P_A, is simply the product of the rms current measured over a full period and the rms voltage measured over the same period.

$$P_A = V_{RMS} \bullet I_{RMS}.$$

True rms volt and current meters can measure V_{RMS} and I_{RMS}. In the case of an uncorrected switching power supply, the current and voltage may be nearly in phase due to the capacitor charging near the peak of the voltage waveform. Using PF=Cosθ would misleadingly yield a PF of 1.0 when the PF may be very low indeed.

Draw more power

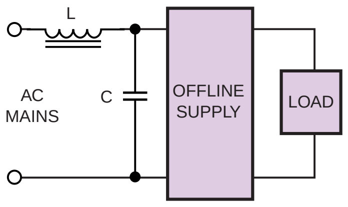
Power-factor correction allows a single instrument or a combination of instruments to draw more power from an outlet. You can add correction that substantially reduces the peak and rms currents by adding a power-factor stage within the offline power supply. To understand this concept, it is helpful to understand a few definitions. First,

$$PF = \frac{P_R}{P_A} = \frac{P_{INPUT}}{V_{RMS} \bullet I_{RMS}} = \frac{P_{OUT/\eta}}{V_{RMS} \bullet I_{RMS}},$$

where η is the efficiency of the supply and $\eta = P_{OUT}/P_{IN}$. Rearranging the terms yields:

$$I_{RMS} = \frac{P_{OUT}}{\eta \bullet PF \bullet V_{RMS}}.$$

FIGURE 4



Passive components can implement power-factor correction for an existing offline supply.

An uncorrected 750W supply operating on a 120V-ac line with an efficiency of 75% and a PF of 0.65 would require that

$$I_{RMS} = \frac{750W}{0.75 \bullet 0.65 \bullet 120V} = 12.8A\ RMS.$$

This level of current presents a problem to the OEM manufacturer—the user of the supply. Safety limits established by the National Electric Code require that a device on a mains service operate at 80% or less of the maximum current. Thus, for a common 15A service, a device must draw less than 0.8×15A, or 12A.

With no design change, the 750W device would require a 20A plug, which would rule out 15A-service markets. The designer could attempt to make the supply more efficient unless this optimization has already been performed. Adding a power-factor-correction stage (**Figure 3**) allows the usage of a 15A plug and smaller fuses and EMI-filter components. It also permits more devices to plug into the same 120V-ac service.

Adding a power-factor-correction stage decreases the efficiency of the supply but provides the benefit of lowering of rms currents. Typically, a PF stage is 92% efficient. Efficiency losses result from housekeeping currents that are necessary to operate the PF stage and from the IR losses in the power-factor-correction switch-mode FET. You modify the efficiency term for the supply system by multiplying the PF stage efficiency by the converter efficiency: System efficiency=PF-stage efficiency× converter efficiency. For this example, system efficiency=0.92×0.75=0.69.

The added power-factor-correction stage can easily increase the power factor from 0.65 to 0.95. Even levels of 0.97 to 0.99 are attainable. With this information, you can determine the rms current level for the corrected 750W supply, with η=0.69 and PF=0.95:

$$I_{RMS} = \frac{750W}{0.69 \bullet 0.95 \bullet 120V} = 9.53A\ RMS.$$

The 9.53A rms is well below the 12A limit set by the National Electric Code and now even allows the equipment to use a standard 12A cord set with an IEC 320-style plug.

Power-factor correction

Power-factor correction is necessary because of the incongruity between the type of power a main converter needs and the type of power the ac mains has to offer. Often, the standard main converter has a forward topology to regulate a mains-isolated 5V-dc output. The power-supply designer must select the converter's frequency of operation, a switching transformer, and an output choke based on the input dc voltage. For this PWM scheme to work, the dc source must be stable to within approximately ±25% to keep the fixed inductors from saturating.

As previously discussed, the goal is for the mains power source to see a sinusoidal load current that appears resistive. Therefore, the requirements for an ideal power-factor-correction stage are known. The stage should appear as a resistive load to the ac line, pulling current sinusoidally and storing the power for the main converter so that the regulated voltage exists while the line voltage sinusoidally varies.

Passive techniques

Passive design approaches are appropriate for applications with low power levels and when the design of an existing supply must remain the same. A common method to filter the harmonic currents is to use a passive LC filter (**Figure 4**). The LC filter can be effective if the line voltage, line frequency, and load are steady. If space allows, you can retrofit the filter into a design between the system breaker and the offline power supply.

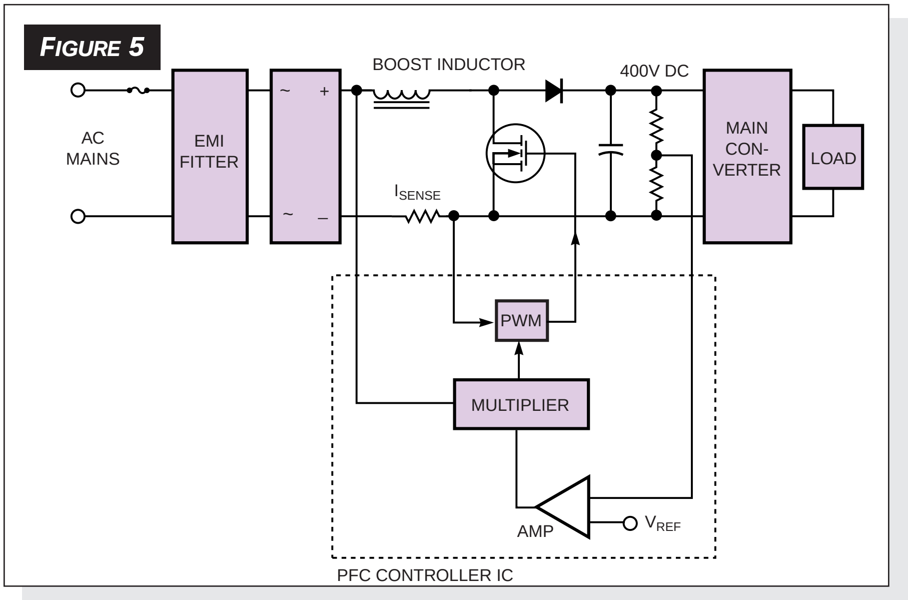
Because the inductor and capacitor must filter low-frequency harmonics and allow 60-Hz current to pass, these components can be quite large. An additional penalty is that the PF may only be 0.90 for the simple LC approach. Further filtering with additional resonant-pass circuits can improve the power factor. However, these passive iterations are load- and frequency-sensitive.

This passive approach is common in small power supplies for which the capacitor and inductor aren't excessively large and a power factor of 0.95 or less is acceptable. The passive approach has the advantage over the active approach in that its parts count is much smaller and therefore has a higher MTBF.

Active PFC techniques

You can design active power-factor correction into switching power supplies between the rectification diodes and main converter stage **(Figure 5)**. The correction stage can easily achieve a power factor of 0.97 to 0.99. Although the parts count is higher than the passive approach, the circuit is significantly smaller.

FIGURE 5



Active power-factor correction adds circuit complexity, but high power factors of 0.97 to 0.99 are achievable.

This size difference results from the fact that power-factor controllers typically operate at 20 to 300 kHz and therefore require a much smaller choke element than in the passive implementation. By using surface-mount components, power-supply companies, such as Resonant Power Technology Inc (respwrtech@worldnet.att.net), have been able to add power-factor-correction stages to standard products and not increase the overall size.

Typically, the power-factor stage has a uniquely controlled boost topology. The circuit full-wave rectifies the mains ac voltage and boosts the voltage to 400V dc. The MOSFET and choke charge the capacitor in a typical boost manner with high-frequency switching. The current level that the choke draws during each pulse follows the rectified ac waveform. Specialized power-factor-correction-controller ICs perform the control function. The circuit feeds the IC with a rectified ac voltage signal, the output-voltage sense signal (capacitor voltage), and a current-sense signal.

The IC internally creates an error signal by amplifying the difference between the output-voltage sense signal and a reference voltage. The IC then multiplies this error signal by the rectified ac voltage, compares this signal to the current-sense signal, and uses the result in the PWM circuit to shape the current waveform. EMI filtering is necessary to reduce the conducted noise that the boost circuit causes. The boost topology allows for operation over a range of line-input voltages from 85 to 264V ac.

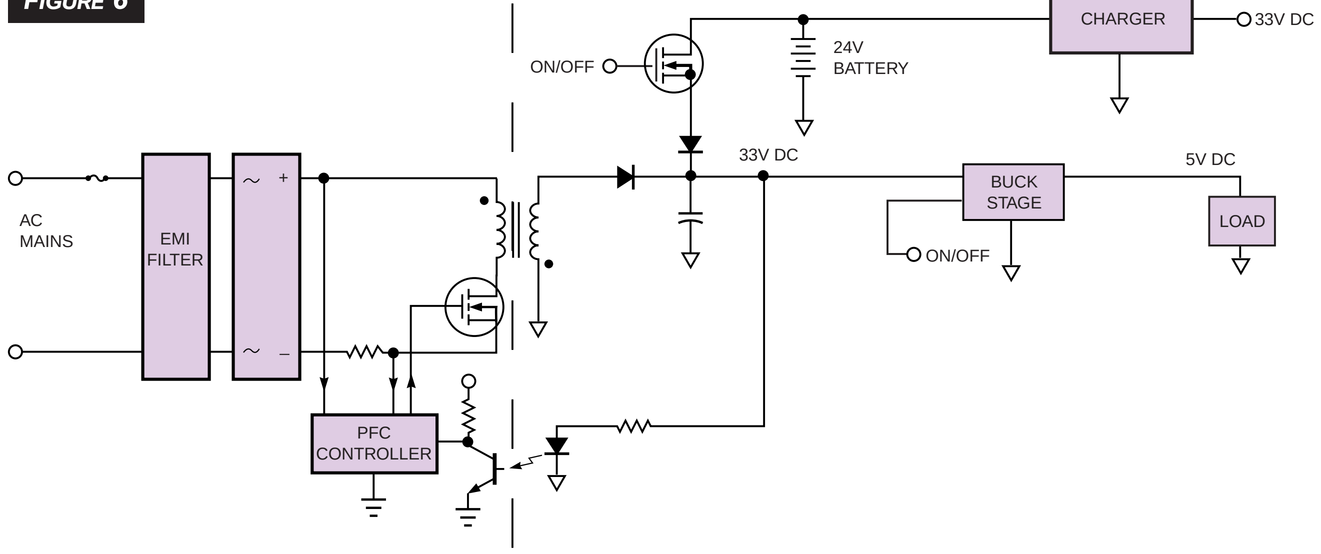
The main converter is still necessary to isolate the mains-connected circuit and step down the voltage. The 400V-dc voltage is a convenient level because the filter capacitor can be smaller than when a bus voltage is 322V (energy=$\frac{1}{2}CV^2$, so $C=2\times\text{energy}/V^2$), and the higher voltage reduces the main converter's MOSFET current. One disadvantage of the active approach, in addition to the increased parts count, is that the power switches twice, which adds some inefficiency.

Add battery backup

In medical systems, it is often important to have battery-operation capability to protect against the loss of ac power. Patient bedsides usually have an ac outlet that is backed up by the hospital's own emergency generator. These outlets are limited in number, and only the most critical equipment can be on this service.

Many hospitals have a schedule to test the generator weekly by manually

FIGURE 6



A unique topology implements both power-factor correction and battery-backed capability using only two stages of conversion instead of the more typical three-stage design.

starting the generator and then switching over from the power-company mains to the generator. The generators are expected to start up and produce power within 10 seconds. These switchover tests produce momentary power sags and voltage transients. The generator start-up test causes power losses and sometimes is unsuccessful. Problems are much worse in Third World countries that lack a sound power-utility infrastructure. Because of these power quality problems, it is extremely advantageous to have battery-backed capability.

Typically, a battery-backed system has a circuit that boosts the battery voltage to the 400 V-dc bus. A circuit detects the loss of ac power and activates the boost circuit. Many systems with power-factor correction have a boost stage for harmonic-current minimization, a second stage to boost the battery voltage, and a third converter to transform the 400V-dc to the secondary outputs.

Condor DC Power Supplies (www.condorpower.com/~condordc) a manufacturer of medical supplies, uses a unique topology that eliminates one of these stages. The design uses a flyback transformer, rather than a choke, to store the energy when the MOSFET is on (**Figure 6**). The circuit mutually couples the inductive energy to the secondary and stores the energy in a capacitor at a 33V-dc level. Closing the loop using optical feedback to the power-factor-controller IC regulates the 33V bus.

The 33V bus can supply power to a buck circuit for a single supply or can power a forward-converter stage with multiple isolated outputs. The 33V bus can also supply power to a charger circuit to recharge the 24V backup battery. You can diode-OR the battery into the 33V bus. When the ac power fails, the bus discharges toward 24V, at which point a smooth transition to battery power occurs.

As customers and OEMs realize the advantages of power-factor correction, they will specify this technique more often for offline switching supplies. Although the previous use of power-factor correction has been limited primarily to supplies greater than 750W, power-factor correction will become more common with the need to improve growing power-quality problems. Compliance with the EN61000-3-2 specification will force companies selling into the European Union to use power-factor correction. Reviewing EN61000-3-2 for specific levels is recommended, and any new medical power supply designs for the European Union should plan compliance now, because of the lengthy development process.

Author's biography

Danis Carter is a Principal Engineer for Nellcor Puritan-Bennett. He designs analog systems for medical electronic products and holds a patent on a medical air-delivery system. He holds a BSEE from the University of Dayton (Dayton, OH). In his spare time, he enjoys golfing, rollerblading, and running.

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