Active Power Factor Correction

Tufts EE 171 - Nicholas Andre - 5/3/2016

Abstract

Electrical loads present different levels of distortion and power factor to the power line. Historically, many loads took the form of purely resistive sources or mechanical loads like toasters, lightbulbs, and AC motors. With the increased affordability of power electronics and devices which fed off a DC intermediate, an increasing proportion of modern loads incorporate rectifiers with energy storage components. The switched nature of such supplies can present very high THD and poor power factor to the electrical supply.

Implications of this transformation are widespread in terms of both the local and larger engineering of the power delivery system -- increasing reactive power requires provisioning for a larger electrical infrastructure to deliver the same amount of real power; the distortion requires active or passive correction upstream or presents abnormal electrical stress on generation equipment. With the construction of modern datacenters that employ tens of thousands of Switched Mode Power Supplies or equivalent devices, a solution which improves the THD and Power Factor of such units stands to provide for vastly improved power systems engineering.

Such a method, called Active Power Factor Correction, incorporates an actively controlled boost converter into the Switched Mode Power Supply. This boost converter serves to modulate the incoming current to more closely match the magnitude and phase of the incoming voltage waveform, thus vastly reducing the apparent harmonic distortion and improving the overall power factor presented to the electrical supply line.

Introduction

Many modern electrical loads require some form of DC intermediate -- while it is possible to convert AC to AC directly with the use of power electronics, in practice this operation is not frequently performed in this manner. It essentially requires a three phase supply and requires the use of bidirectional switches, which must be very tightly matched.

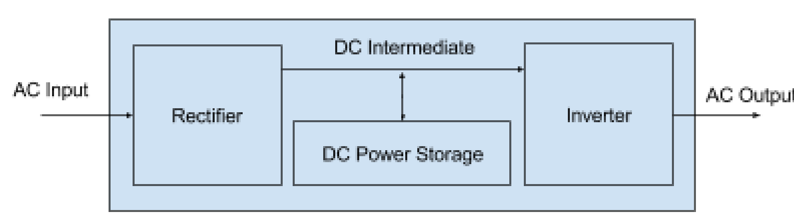


Figure 1 - Online UPS' internal block diagram

The use can be illustrated with an Online Uninterruptible Power Supply (Online UPS). This device operates as the AC Electrical equivalent of a buffer; incoming power is first rectified to DC where it can be stored in a battery bank or passed through directly to the output stage. Output power is then inverted to a fixed voltage and frequency. Given that very tight control is possible on the DC intermediate stage, the AC output can be very tightly regulated as well to match specifications.

The power factor is a ratio of the usable “real” power delivered to the output to the apparent power as calculated from the total voltage and current waveforms at the input

This device has a number of advantages:

1. When AC input power is distorted, varies in voltage, or drops out entirely, the output will remain entirely uninterrupted and stable.
2. The DC intermediate makes the device asynchronous, such that the output frequency can be arbitrarily varied to run any equipment that may require different frequency input than the region in which it is being operated.
3. When AC input power drops in voltage, output power remains constant. The UPS can either run at a reduced load delivery capacity (since it is current-limited on the input to draw proportionally less than the rated power) or can utilize power storage to “ride out” the brown out condition.
4. Any distortion passed to the input, such as the abysmal state of power in Curtis Hall during the summer “months of the window air conditioner,” is entirely isolated such that only the rectifier portion must contend with it. Any equipment which is poorly engineered so as to be very sensitive to such distortion will not be affected.

This equipment similarly illustrates the problem of power factor and distortion: given that the input circuit will typically be provisioned for a fixed amount of power (a standard 15A circuit would budget 1500 VA), any power factor less than ideal on the input side will limit the total usable power by that amount.

Somewhat interestingly, so long as the output inverter can handle the distortion and poor power factor, any distortion on the downstream side will be “entirely” isolated from the rectifier stage. The downstream electrical supply will still need to be over-provisioned to allow for this, but the upstream will not see anything more than the input rectifier of the O-UPS.

There are several downsides to this architecture: maintaining a continuous output load and assuming ideal power factor, the device will appear as a negative resistor when viewed from the line perspective. In addition, though the power factor can be largely corrected using an A-PFC circuit, a purely resistive load will still appear as having the reduced PF of the input rectifier.

Power Factor Correction

Motivation and Prior Techniques

In isolation, a full-bridge rectifier does not have significant distortion -- the input power is rectified using four diodes and the output power is presented in non-negative Direct Current. The input distortion is provided for only by the non-idealities of the diode switches. The problem is that absent energy storage of some sort, the DC power is highly distorted in that it presents as the absolute value of a sine wave.

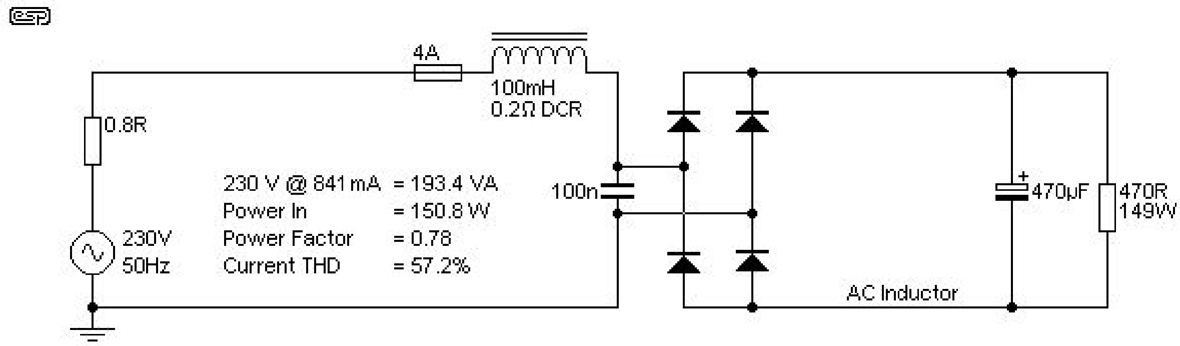


Fig 2: Passive PFC Topology with AC side inductor.

Adding an energy storage component like a capacitor solves one problem but creates another -- the DC output waveform is vastly improved but at the expense of the input current becoming significantly uglier. The output voltage is divided into two phases -- the capacitor charges as the absolute value of input voltage rises above the capacitor voltage, then the voltage falls until the next charging period.

The power factor can be improved by reducing the size of the energy storage capacitor, but this directly corresponds to increased voltage ripple on the output of the rectifier. As this isn't a great strategy, several topologies exist to use purely passive components to improve the power factor of the circuit. They usually involve some form of inductance on the AC or DC side in an attempt to smooth out the current ratings, but in practice Passive PFC will not surpass 0.75 power factor.

There are cases in which Passive PFC is still utilized, for example a very cheap device with Compact Fluorescent Lightbulb or cheap LED circuits. Such devices can afford to trade off output performance to improve power factor and distortion, and due to the fact that they are not typically deployed up to the limit of household circuit breakers, they can afford a mediocre power factor (plus the fact that their 75%+ energy savings on a lumen/watt basis compared with conventional incandescent or halogen units more than offsets the poor power factor in terms of bulb capacity per circuit).

However, higher power or more densely deployed services stand to benefit from increases in power factor and overall THD performance, as well as the smaller sized passive components. In these cases, the designer can opt for an active approach to addressing Power Factor.

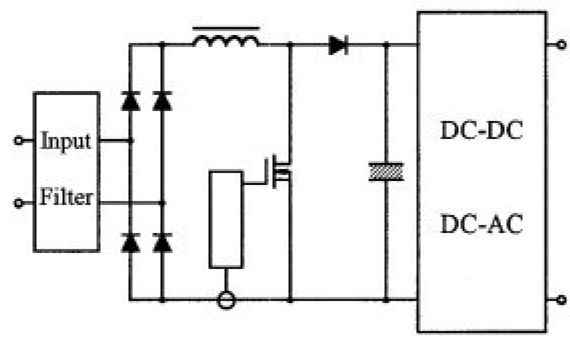
Active Topologies

In principle, Active PFC can implemented by placing an intelligently controlled boost converter in between the rectifier and the DC storage element of the rectifier.

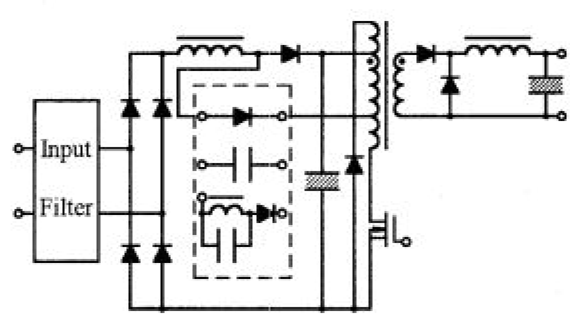
The concept is straightforward: in a capacitor-based rectifier, diodes will only conduct when the voltage of the input is greater than the DC storage capacitor. Absent this converter, this will only occur during a small portion of the voltage waveform (to maintain low output voltage ripple). However, if a converter can boost the voltage arbitrarily so that the diode is forward biased, said controller can very accurately control the current input into the device during all portions of the waveform cycle.

In practice, such a filtering technique would be employed in tandem with passive filtering techniques and other input filtering networks to attain maximum rejection of power supply harmonics.

Active topologies have the distinct advantage of requiring smaller passive components for an equivalent Power Factor and power delivery requirement, however they do incorporate active control and switching which increases overall cost. Though these devices are unlikely to be deployed in the cheapest and lowest power environments, the decreasing cost of power electronics especially at this scale, as well as the ready availability of existing components with the functionality implemented and produced at scale, support their deployment in many modern systems.



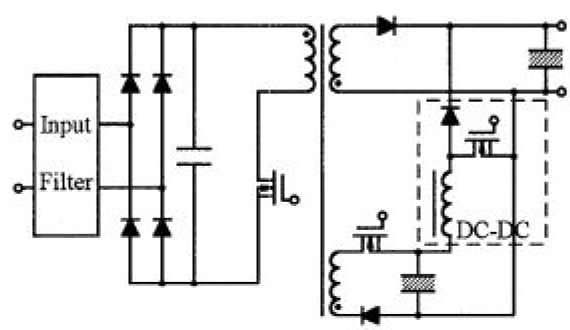
(a) Cascade type



(b) Single-stage type

Implications of PFC

Power electronics-based loads make up an increasing proportion of the modern electrical grid load, especially in localized installations like data centers and office buildings. Such power delivery installations suffer greatly from the increased provisioning, both of material and overall design, required to accommodate high proportions of reactive power. Further, the distortion presented to the electrical grid provides further cause for concern from utility operators.



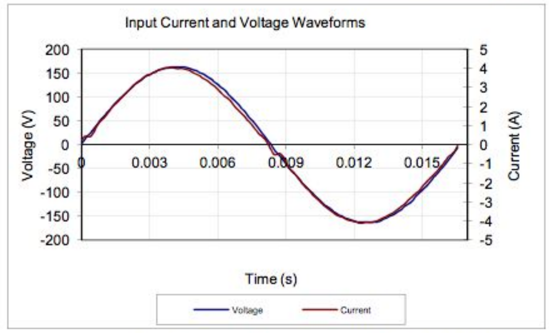
(c) Parallel type

PFC, while not a necessity, provides for much higher efficiency of electrical installations, lower harmonic distortion and noise, and combined in tandem with other Switched Mode Power

80 PLUS Verification and Testing Report

TYPICAL EFFICIENCY (50% Load):	**92.48%**
AVERAGE EFFICIENCY :	**91.06%**
80 PLUS COMPLIANT:	**YES**

Ecos ID #	3134
Manufacturer	Super Micro Computer Inc.
Model Number	PWS-605P-1H
Serial Number	P605A1145A00264
Year	2012
Type	1U
Test Date	5/22/2012



Input AC Current Waveform (ITHD = 3.08%, 50% Load)

Rated Specifications	Value	Units
Input Voltage	100-240	Volts
Input Current	7.5	Amps
Input Frequency	50/60	Hz
Rated Output Power	**600**	**Watts**

Note: All measurements were taken with input voltage at 115 V nominal at 60 Hz.

I_{RMS} A	PF	I_{THD} (%)	Load (%)	Input Watts	DC Terminal Voltage (V)/ DC Load Current (A)					Output Watts	Efficiency %
					12V (cumulative of 12V1, 12V2, etc.)	-12V	3.3V	5V	5Vsb		
0.65	0.97	9.92%	10%	71.88	12.3/4.2	11.9/0	3.3/0.9	5.1/1.1	5.1/0.3	61.57	**85.65%**
1.19	0.99	5.71%	20%	135.69	12.3/8.3	11.9/0.1	3.3/1.8	5.1/2.2	5.1/0.5	123.40	**90.94%**
2.89	1.00	3.08%	50%	332.60	12.3/20.8	11.9/0.2	3.3/4.5	5.1/5.5	5/1.3	307.60	**92.48%**
5.93	1.00	2.50%	100%	681.90	12.3/41.6	11.9/0.4	3.3/9.1	5.1/10.9	5/2.5	611.92	**89.74%**

Supply optimization techniques can help provide very high quality, efficient power supplies that behave well with the conventional loads and distribution systems of our power grid.

For example, the Supermicro power supply test report above shows the impressive performance of a modern SMPS, performing with a power factor of 0.99 or above for much of the rated operating loads and with efficiency breaking 90% at typical operating conditions.

The problem of rectifier and power supply noise raises additional questions about the future of power distribution and power electronics:

1. Will DC power distribution increase in efficacy as power electronics decrease in price in tandem with new processes and semiconductor technologies? How will these changing distribution paradigms affect the conventional model of AC distribution to the device with onboard rectification and DC supply?
2. With an increasing percentage of devices running off a DC intermediate, can individual buildings be converted to rectify at a single location and distribute low and high voltage DC?

(2) above has already been demonstrated in many larger data center deployments -- Cisco equipment comes standard with a DC power connector enabling an entire rack of equipment or larger to share a power supply. Often modern servers are set up in a “blade” configuration, in which server processing units share common computer infrastructure, among them the power supply. Such changes are motivated by the higher optimizations that are possible for power supplies with a more predictable load -- handling more power and handling a more regular load enables designers to optimize for a single operation point, attaining higher efficiency and better noise and power factor performance at “typical” loads.

The future of power electronics and electrical engineering will be a very interesting story to follow.

References

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