



Allen-Bradley

Regenerative AC Drives

Understanding Regeneration



Bringing Together Leading Brands in Industrial Automation

Diode

The diode allows current flow in only one direction, and can't be turned off. Current flows whenever the diode is forward biased.

IGBT

The IGBT can pass current in either direction. In the "reverse" direction, it acts as an uncontrolled diode. However, it also allows current flow in the "forward" direction, and in that direction the current can be switched on and off.

Regenerative AC Drives

Dissipation of regenerative power can be accomplished by returning power to the AC line. The first key to understanding regeneration is to recall the difference between a diode and an IGBT. The diode allows current flow in only one direction, and can't be turned off. Current flows whenever the diode is forward biased. The IGBT, on the other hand, can pass current in either direction. In the "reverse" direction, it acts simply as an uncontrolled diode. However, it also allows current flow in the "forward" direction, and in that direction the current can be switched on and off. This is what makes the IGBT useful for both regeneration and motor control.

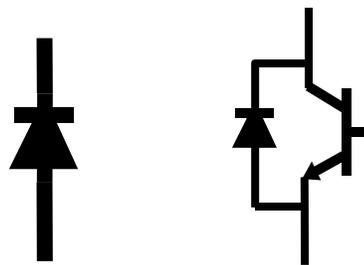


Figure 1

If we use these two components to build a three-phase bridge, the resulting circuits are uni-directional and bi-directional, as are the switches. The diode bridge rectifies the incoming voltage, but can't pass power back to the AC line. The IGBT bridge, because it uses bi-directional switches, can transfer current back to the AC line. Notice however, that in order to control the IGBT switches, their anti-parallel diodes must be reverse-biased. We'll see how this affects the operation of the 1336 REGEN later, especially in Regen Bus Supply applications.

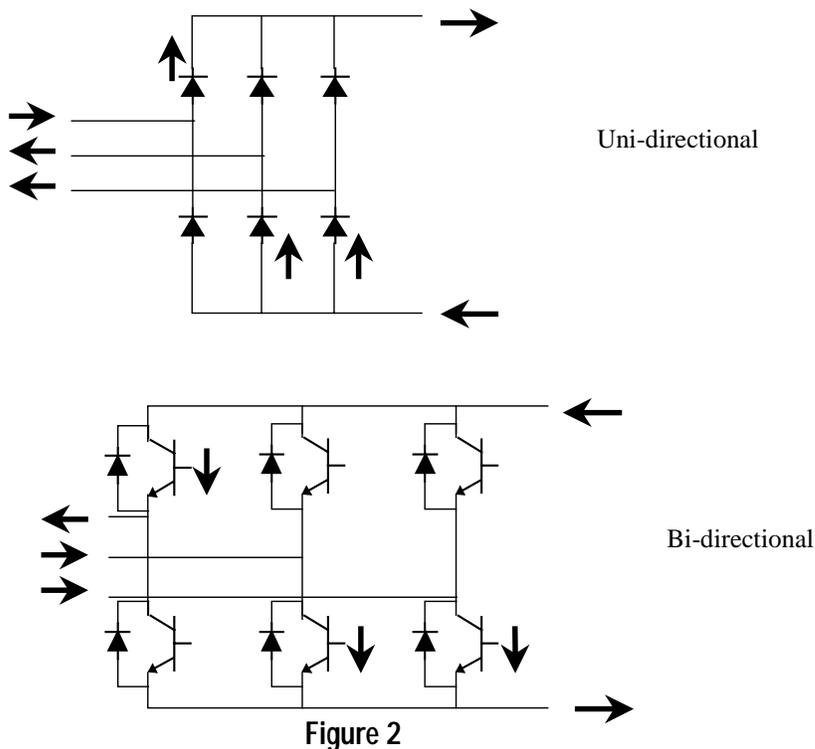


Figure 2

When an application requires operation in a quadrant where torque is in the opposite direction of motor rotation, the AC drive must remove energy from the mechanical system through the motor leads. This situation occurs whenever the drive is attempting to brake a rotating motor, such as when decelerating an inertia, when providing a load as in a dynamometer, or when holding back an overhauling load. As the drive removes the energy from the load, it charges the main DC bus capacitors of the drive. Without a method of removing that energy, the DC bus voltage would continue to rise until the drive eventually tripped on a bus overvoltage fault. Line Regeneration is a method of removing that energy from the DC bus capacitors and placing it back on the AC utility.

The primary piece of hardware that makes up the 1336R Line Regeneration Package is the 1336R Converter.

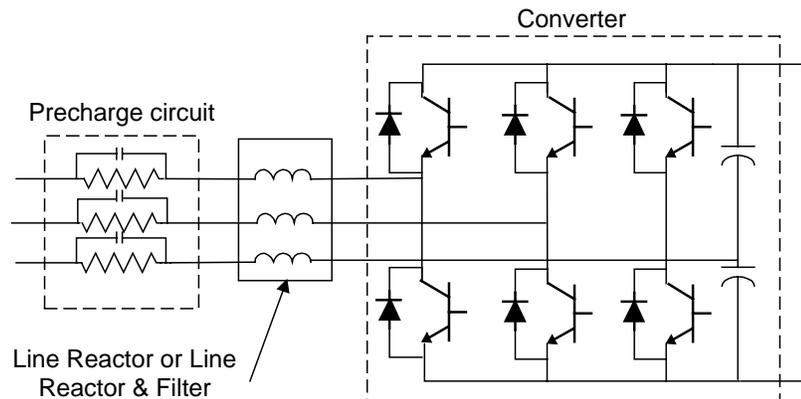


Figure 3

The primary piece of hardware that makes up the 1336R Line Regeneration Package is the 1336R Converter. The Converter looks very much like a 1336 family drive because it is based on the 1336 family power structure. However, as a regenerative converter, the power section is connected opposite to the normal way, with the three-phase IGBT power stage connected to the AC line. The output of the converter is a DC bus connection that will connect into the DC input terminals of one or more DC-input AC drives.

Because the power stage is relatively unchanged from that used on the other 1336 family AC drives, a separate precharge assembly is needed with the 1336R Converter. This precharge assembly contains a three-phase precharge contactor and resistors, and a circuit that monitors the phase and magnitude of the AC line for the control board that is located in the 1336R converter. A three-phase line reactor is needed with every 1336R package, although the exact characteristics of the reactor change depending on the type of application and the 1336R Converter operating mode. In some applications, a harmonic filter may also be needed.

Line Regeneration applications fall into two broad categories and the 1336R Converter has distinct parameter-selectable operating modes for each type of application.

For stand-alone AC drive applications, the Converter operates in "Regen Brake" mode.

For applications that require a fixed or regulated DC bus voltage, the 1336R Converter operates in "Regen Bus Supply" mode. In this mode, the 1336R Line Regeneration Package regulates a common DC bus that feeds one or more common bus (DC-input) AC drives.

Regen Brake

In this configuration, the Regen Brake is connected to the DC bus terminals of a standard AC-input AC drive. The function of the Regen Brake is to remove braking energy from the drive and return the energy back to the AC utility whenever the load requirements are for regenerative power. In this configuration, the 1336R Converter operates in Regen Brake mode and requires only a 3% three-phase line reactor (along with the precharge).

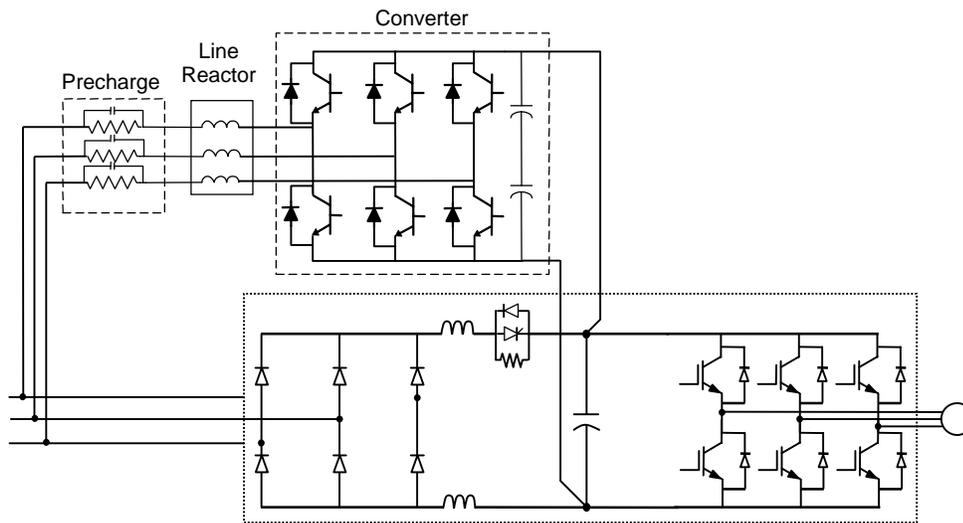


Figure 4

If we go back to the three-phase bridges mentioned earlier, we get some insight into how a Regen Brake works. The IGBT bridge inside the 1336 REGEN Converter is connected in parallel with the diode bridge of the drive. When one of the diodes in the drive's diode bridge is forward biased, the diode in the same relative position in the IGBT bridge is also forward biased. Remember that the two bridges are basically connected at the DC bus and the AC line terminals. (The Regen front end also has a line reactor in front of it, but it does not change the basic circuit operation.)

If the DC bus voltage rises above the peak of the line-to-line voltage, the diodes will no longer be forward biased, and no current will flow to or from the AC line through either bridge. However, if the IGBTs are switched in the proper sequence, i.e. matching the phasing of the AC line, current will flow through the IGBTs back to the AC line. That is all the Regen Brake is doing – switching the IGBTs in phase with the AC line. When the bus voltage is low, current naturally flows into the DC bus, but as the voltage rises, current flows back into the AC line.

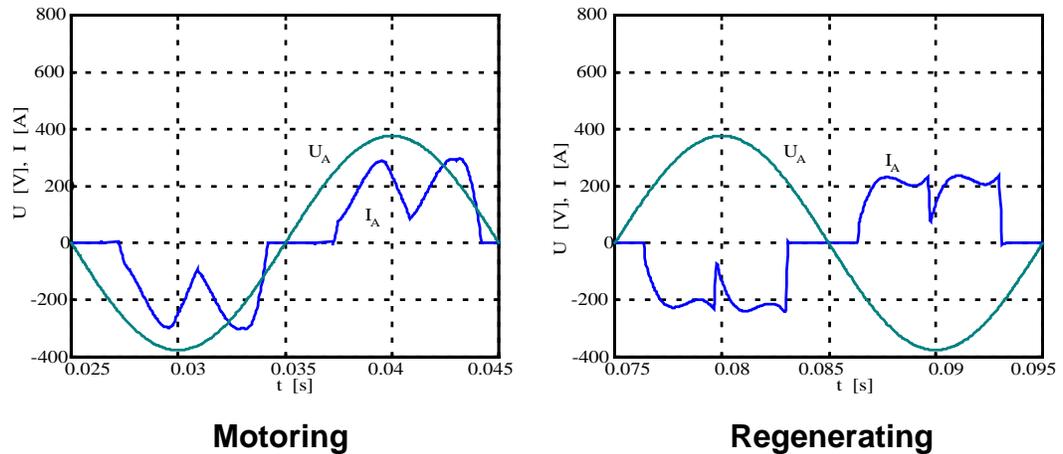


Figure 5

The graph on the left shows the AC line current and line-to-line voltage of an AC drive with a Regen Brake as it appears during motoring. This is the same waveform as a drive operating without a Regen Brake.

The graph on the right shows the AC line current and line-to-line voltage as it appears during regeneration. This current is flowing through the Regen Brake, thereby removing energy from the DC bus and returning it to the AC utility. Notice that during regeneration, the current is 180 degrees out of phase with the voltage, resulting in power flow in the opposite direction as the first graph.

The 1336R Line Regeneration Package operating in Regen Brake mode is intended to be used in stand-alone AC drive applications with standard AC-input AC drives.

One of the major advantages of the Regen Brake configuration is that the 1336R Line Regeneration Package can be sized independently of the power required for the application when motoring. The 1336R Package is sized to provide whatever amount of braking the application requires, up to the AC drive and motor rating. Another advantage is the external hardware costs required for Regen Brake applications. In this configuration, only a 3% line reactor is needed, versus the 10% reactor and harmonic filter required for the Regen Bus Supply applications. For applications requiring continuous braking, high duty cycles, or high braking torques, line regeneration can be an energy-efficient method of providing braking capability. Regen brakes can also be paralleled, just like choppers can, for higher HP braking applications.

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Regen Bus Supply

This is the configuration for a common bus application. The 1336R Line Regeneration Package acts as a regenerative supply for the DC bus, and the DC bus is used to supply power to the AC drives.

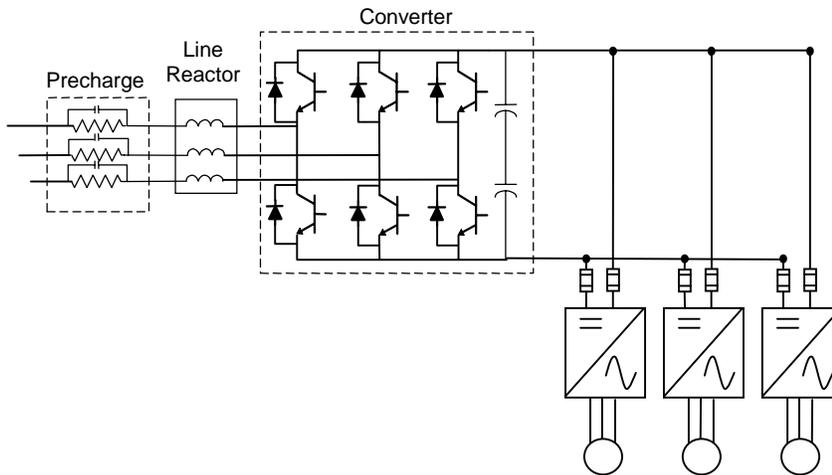


Figure 6

The AC drives used in this configuration are modified internally so they can be powered directly by a DC power source, and are not standard AC input drives. In this configuration, the 1336R Converter operates in Regen Bus Supply mode, and requires a 10% three-phase line reactor, and in many cases a harmonic filter.

One analogy that helps describe Regen Bus Supply application is this DC power conversion circuit, called a boost converter. The operation of this converter is relatively straightforward.

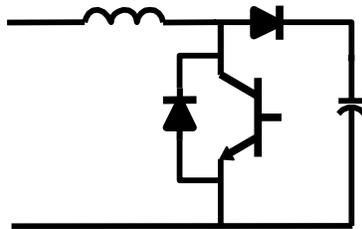


Figure 7

The IGBT is turned on, shorting the inductor across the DC source. Once current is flowing in the inductor, the switch is turned off, forcing the energy previously stored in the inductor into the output capacitor. The load is connected across the capacitor. Note that the output voltage must always be regulated at a higher voltage than the input voltage. If the output voltage is lower, current will continue to flow through the inductor to the cap bank even if the switch remains off. The

fact that the output voltage is higher than the input voltage gives the circuit its name – “Boost Converter”.

In Regen Bus Supply mode, the IGBT bridge is switched in a different pattern than it was in Regen Brake mode. The Regen Brake switching algorithm was a 360Hz pattern that just connected the DC bus to the AC line when the phasing was appropriate.

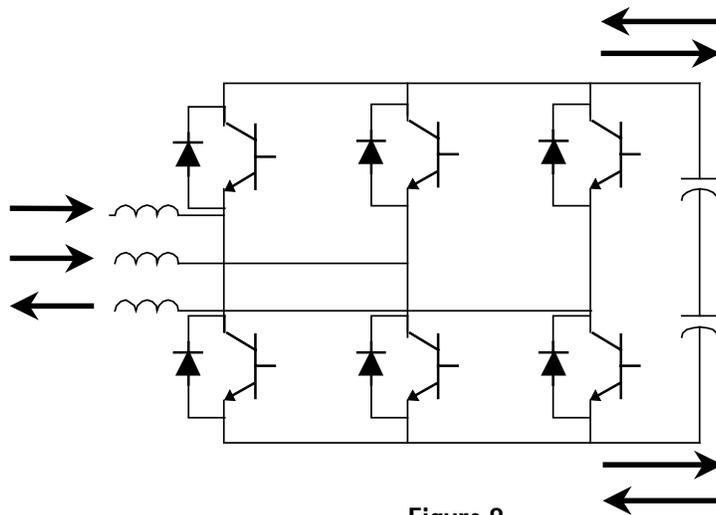


Figure 8

The analogy to the boost converter gives us some insight into Regen Bus Supply operation. The switching is more complicated because the source is three-phase AC, but the concept is similar. The DC bus voltage is regulated at some voltage above the maximum line-to-line voltage so the diodes are never forward-biased. The IGBTs can then be used to control the current in whatever manner we desire. Of course, the ideal is to have the current using a PWM algorithm, resulting in a very low current harmonics.

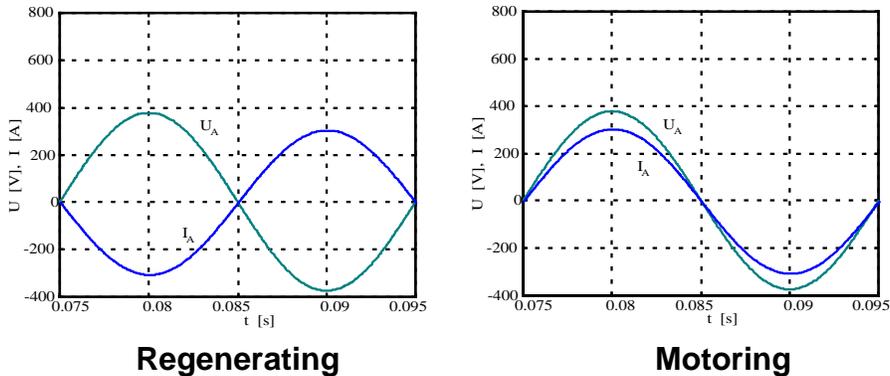


Figure 9

The graph on the left shows the AC line current and line-to-line voltage at the input to the 1336R Precharge module as it appears during regeneration, and the graph on the right shows the AC line current and line-to-line voltage as it appears during motoring. In both cases, the 1336 REGEN is controlling the current using a PWM algorithm, resulting in very low current harmonics.

In Regen Bus Supply mode, the 1336R Converter regulates the DC bus at a predetermined voltage. If the net power requirement of the AC drives is for motoring power, energy will flow from the utility to the common DC bus, and if the net power requirement is for regenerative power, energy flows from the common DC bus back to the utility.

Common bus arrangements work extremely well for multiple drive applications, since a single 1336R package can supply a number of DC input AC drives. The DC bus voltage regulator provides excellent immunity to the line and load transients, since the DC bus voltage is controlled by the 1336R Converter as long as the AC line is within the specified range.

As was mentioned earlier, the Regen Bus supply mode does, however, require special hardware in addition to the 1336R Precharge and Converter. A custom-designed 10% line reactor is needed, and an additional harmonic filter is also required for many applications.

In the Regen Bus Supply mode the 1336R Converter uses pulse-width modulation (PWM) to shape the AC line currents to be sinusoidal, and in phase with the AC line voltage. In this mode, with the specified hardware, the 1336R Line Regeneration Package is designed to meet the current and voltage distortion limits of IEEE 519-1992. Sizing a 1336R Line Regeneration Package for Regen Bus Supply operation is simply a matter of adding up the connected horsepower or kW and making sure the 1336R package chosen can supply the required power.

The 1336R Line Regeneration Package can be used for either Regen Brake or Regen Bus Supply (common bus) applications.

Mode Selection

In summary, the 1336R Line Regeneration Package can be used for either Regen Brake or Regen Bus Supply (common bus) applications. If the only application requirements are to remove braking energy from a single AC drive and return the energy back to the AC utility, the Regen Brake will be the preferred solution because of its simplicity and lower cost. However, if the application requires multiple drives on a common bus, if part of the system objective is to meet a utility distortion specification such as IEEE 519-1992, or if there is a desire to operate the drive from a regulated DC bus, then the Regen Bus Supply mode and common bus configuration must be used.

Regen Brake Sizing

Sizing a Regen Brake is very similar to sizing a dynamic brake or chopper module. From the load characteristics and application requirements, the peak power that must be removed from the AC drive can be calculated. From the 1336R Line Regeneration Package ratings, the peak power that can be dissipated by a Regen Brake mode can be calculated. Comparing these numbers can choose the correct Regen Brake.

Inertia Calculations

Motor inertia	200 ft-lb ²
Load inertia	31200 ft-lb ²
Gear ratio (Output RPM/Input RPM)	0.5 :1
Total inertia	8000 ft-lb ²

From the motor inertia, load inertia, and the gear ratio the reflected inertia can be calculated. This is the total inertia the drive and motor must decelerate as it slows or stops the load.

The next step is to calculate the torque that will be required to decelerate the load. The torque depends on the total change in speed, the amount of time the deceleration will occur over and the load inertia that was calculated previously. Once the torque is known, the peak power the Regen Brake must remove back to the utility can be calculated. The peak power at the motor shaft is the product of the top motor speed and the shaft torque required to decelerate the load in the desired amount of time. Any losses that occur in the motor and drive will reduce motor/drive efficiency is an estimate of how much of the actual peak braking power must be absorbed by the Regen Brake.

Load Calculations

Total system inertia	8000 ft-lb ²
Maximum shaft speed	3600 rpm
Desired deceleration time	3 min
	50 sec
Minimum shaft speed to decelerate to	0 rpm
Motor/drive efficiency	96 %
Torque required	406.5 ft-lbs
Peak power required (kW)	199.6 kW
Peak power required (HP)	267.6 Hp

Sizing the Regen Brake may be an iterative process. By increasing the deceleration time, the required torque and peak power requirement will be reduced, and a lower rated Regen Brake can be used.

The amount of power a specific rating of 1336R can dissipate back into the utility can be calculated. Three-phase power transfer is a product of RMS line voltage, RMS line current and power factor. The utility voltage determines the RMS voltage.

The continuous regenerative capacity of a 180A Regen Brake operating on a 460V utility is approximately 183HP. The overload capability is 150% of rated current for 1 minute. Therefore, the peak regenerative capacity is about 274HP.

Regen Brake Calculations

AC current rating	180 Amps rms
AC Line voltage	460 Volts rms
Continuous regenerative capacity	136.2 kW 182.6 Hp
Peak regenerative capacity	204.4 kW 273.9 Hp

The peak regenerative capacity calculated here must be greater than the peak dissipation that was calculated on the previous slide. If the required power dissipation is greater, either a larger Regen Brake is needed, or the deceleration time must be extended.

The 1336R Converter is current limited by an "IT" algorithm, in the same way the 1336 family drives are. The 1336R Converter keeps track of the overload current and "adds up" or integrates the amount of overload over time. If the result of the integration reaches a level equivalent to 150% overload for 1 minute, the converter will fault.

For applications like a centrifuge, where the load is being decelerated, the amount of power the Regen brake must dissipate falls as the speed decreases. The Regen Brake removes "real" power from the load and real power is the product of shaft speed and shaft torque. As the load decelerates the speed decreases and the real power that must be removed decreases.

IT Algorithm

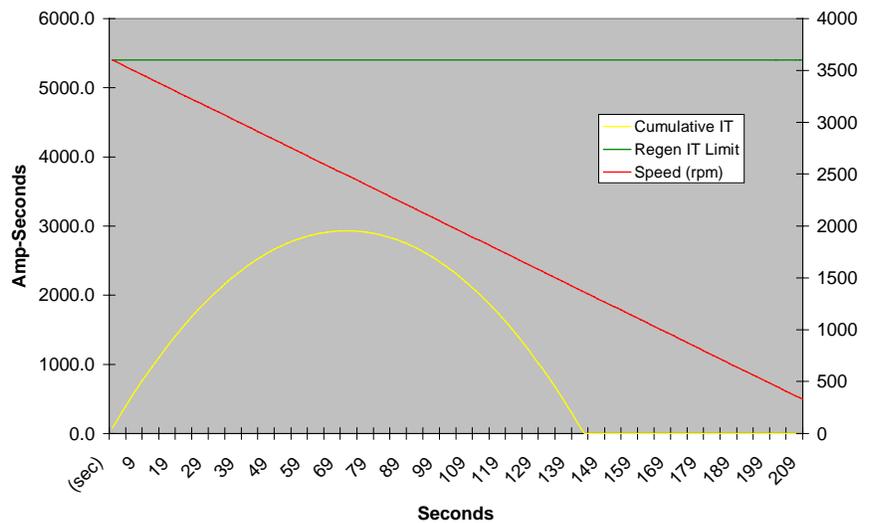


Figure 10

The above graph shows the result of the integration that would take place in the Converter in this application. The green line represents the IT limit for the 180A 460V Regen Brake. The red line shows the speed coming down, and the yellow curve shows the result of the IT calculation. At the beginning of the deceleration, the 1336R Converter is operating in overload, but as the speed comes down, the AC line current will also decrease. Although the total deceleration time is nearly 4 minutes, after about half of that time the Regen Brake AC line current has dropped below rated due to the reduced power being provided by the AC drive. If the yellow curve were to cross the green line, the 1336R Converter would trip. In this case, there is no problem with tripping on overload.

Energy Savings

Because the 1336R Converter transfers the energy back to the AC line, the Regen Brake represents an energy savings over the same application using a dynamic brake or chopper/resistor combination where the energy would be dissipated as heat in a resistor.

The energy savings can be calculated if the cycle time and energy costs are known. For our example, if the Centrifuge is decelerated once every 15 minutes, and runs two shifts per day, 6 days per week, the yearly energy savings will be over \$11,000. The real savings could be even greater if the alternative is to dissipate the energy in an indoor resistor grid where the heat produced by the resistors must be removed by the building air conditioning system.

Total cycle time	0 hr 15 min 0 sec
Average power per cycle	25.51 kW
Energy costs	\$0.09 \$/kW-Hr
Run hours per day	16 Hr/Day
Run days per week	6 Days/Wk
Run weeks per year	52 Wks/Yr
Energy savings per week	\$220.41
Energy savings per year	\$11,461.45

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