OPERATION OF A CAT® FLYWHEEL-BASED UNINTERRUPTIBLE POWER SUPPLY (UPS) SYSTEM

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INTRODUCTION

This paper describes the operation of the Cat® flywheel-based UPS system. A battery-free line interactive UPS system, this family of products features high efficiency and generator set-friendly design.

OPERATING MODES

The UPS simplified one line diagram as shown below in Figure 1 will be used to explain the various system operating modes.

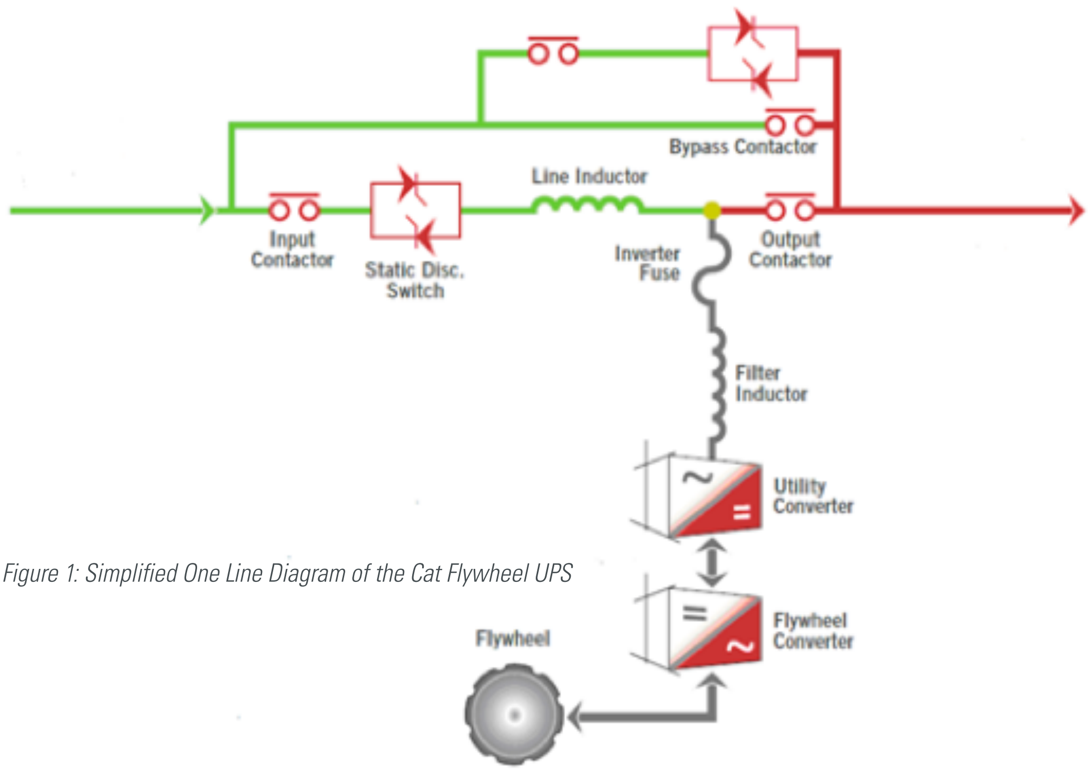

Figure 1: Simplified One Line Diagram of the Cat Flywheel UPS

Start-up

Start-up should be performed by a trained Cat Service Technician. The UPS output is energized on bypass as soon as power is applied to the system. It is started using a completely automated process by placing a key switch in the online position. The UPS performs internal checks to ensure all control and monitoring functions are operating properly and the input contactor closes.

The static disconnect switch turns on and the conduction angle is rapidly increased from zero to an angle that causes the direct current (DC) bus voltage between the utility converter and the flywheel converter to reach approximately 650 volts through the rectifying action of the freewheeling diodes in the utility converter. As soon as this DC value is reached, the static switch turns on fully.

The utility converter's insulated gate bipolar transistor (IGBT) begins to operate, which allows the converter to act as a rectifier, a regulating voltage source and an active harmonic filter. The DC bus is then increased to normal operating voltage of approximately 800 volts and the output bus is transferred from bypass to the output of the power stage.

The transfer is accomplished by closing the output contactor and opening the bypass in a make-before-break manner.

The firing of the silicon controlled rectifier (SCR) in the static disconnect switch is now changed so that the SCR in each phase is only turned on during the half cycle, which permits real power to flow from the utility supply to the UPS. This firing pattern prevents power from the flywheel from feeding backward into the supply and assures all of the flywheel energy is available to support the load.

Immediately after the output is transferred from bypass to the power stage, the flywheel field is excited, which also provides magnetic lift to unload the flywheel bearings. The flywheel inverter is then turned on and gradually increases frequency at a constant rate to accelerate the flywheel to approximately 60 rotations per minute (rpm). Once the flywheel reaches 60 rpm, the flywheel inverter controls the acceleration to keep currents below the maximum charging and the maximum input settings. Once the flywheel reaches 4,000 rpm, the UPS is fully functional and capable of supporting the load during a power outage. Acceleration continues until the flywheel reaches full charge at 7,700 rpm. Total time to complete the start-up sequence is less than five minutes.

Normal operation

Once the system is started and the flywheel is operating at greater than 4,000 rpm, the UPS is in normal operation. In this operating mode, the UPS regulates output voltage and supplies reactive and harmonic currents required by the load. At the same time, it cancels the effect of load current harmonics on the UPS output voltage. Analyzing the components of the input and output currents as shown in Figure 2 makes it easier to understand normal operation of the UPS.

One component of the input current is real current, which supplies power to the load. Real current is current that is in phase with the supply voltage and supplies real power (kW) to the load. When flowing through the line inductor, this component of the input current causes a phase shift across the line inductor rather than boosting or bucking voltage. The line inductor impedance is chosen to limit the phase shift to less than 10 degrees at full load. Keeping the phase shift this small ensures the UPS can instantaneously transfer to bypass without causing unacceptable voltage or phase transients to the load.

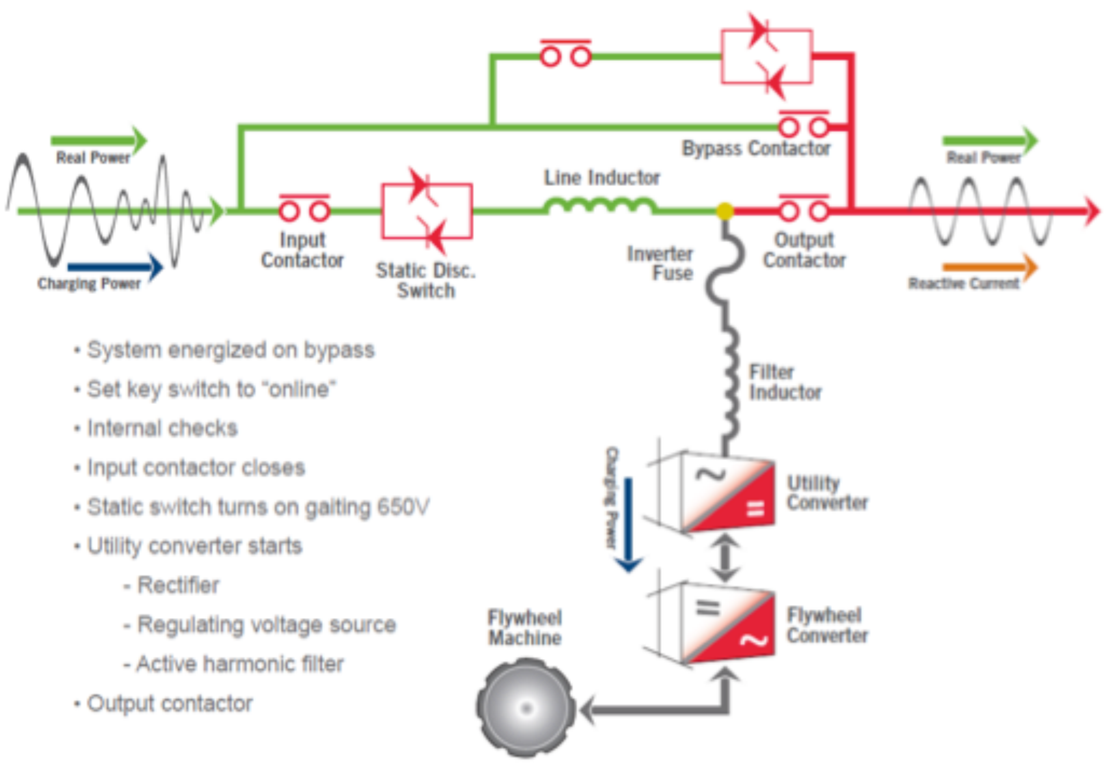

Figure 2: Simplified One Line Diagram of Flywheel UPS in Operating Mode

Normal operation – voltage regulation

Reactive current, which is the second component of the input current, circulates between the input and the utility converter to regulate the output voltage. Leading reactive current (90 degrees ahead of the voltage) through the line inductor causes a voltage boost across the line inductor from input to output. Lagging reactive current (90 degrees behind the voltage) causes a bucking voltage. By controlling the utility converter to maintain nominal output voltage, just enough leading or lagging reactive current flows through the line inductor to make up the difference between the input voltage at any point in time and the nominal output voltage. The input voltage is sampled every 50 microseconds to allow the utility converter to react very quickly to input voltage transients and steady state voltage fluctuations.

The final component of the input current is real current that is used to keep the flywheel fully charged or to recharge the flywheel after a discharge. The power required to maintain full charge is less than 2 kW, resulting in low current draw during normal operation. The utility converter rectifies the AC voltage and supplies DC power to the flywheel converter. The IGBTs of the flywheel converter are gated to provide small pulses of motoring current to keep the flywheel charged.

Normal operation – harmonic cancellation

In addition to the real current that is supplied from the input source, the load current has two components: reactive current and harmonics current that are supplied by the utility inverter. Since these two components of the total load current contribute no net power to the load, no flywheel energy is used to supply these currents. They circulate between the utility converter and the load. The power stage controls analyze the harmonic current requirements of the load and set the firing of the IGBTs to make the utility inverter a very low impedance source to any harmonic currents that are present. Therefore, highly non-linear load currents are supplied almost entirely from the utility converter with little effect on the quality of the UPS output voltage waveform and with almost no transmission of load harmonic currents to the input of the UPS. If the harmonic currents of the load current change, utility converter gating is changed to provide dynamic harmonic cancellation for the changing load.

Normal operation – power factor correction

Because the utility converter supplies the harmonic and reactive components of the load current, load power factor has little effect on input power factor. The amount of reactive current on the input is determined almost entirely by the difference between the actual root mean square (RMS) input voltage and the nominal RMS voltage. At nominal voltage, the input power factor is unity regardless of the load power factor. For a given input voltage deviation above or below nominal, a specific amount of lagging current or leading current, respectively, must flow between the input and the utility converter to correct the voltage deviation. Because the input power factor is the ratio of real current to total current, the input power factor depends on both the amount of reactive current and the amount of real current. Therefore, the input power factor is a function of both the deviation of the input voltage from nominal and the load power (kW).

Discharge mode

The UPS senses the deviation of voltage or frequency beyond programmed tolerances and quickly disconnects the UPS from the supply by turning off the static disconnect switch and opening the input contactor. In most instances, the UPS disconnects instantaneously, but in all cases it will disconnect in less than one-half cycle. At the same time, the utility converter starts delivering power from the DC bus to the load and the flywheel converter changes the firing point of its IGBTs to deliver power to the utility converter through the DC bus. The UPS maintains a clean output voltage to the load, and the output voltage transient for loss and return of input voltage at full load is less than three percent.

The UPS uses several techniques to quickly detect a utility failure. The first method is RMS voltage detection. Every fifth cycle, the RMS value of the input voltage is calculated from the 334 samples taken over one complete cycle of the input voltage. If the RMS value of the input voltage deviates from nominal by more than the limit programmed into the UPS, the UPS will disconnect from the input and enter discharge mode. RMS voltage detection is effective for relatively slow changes in input voltage.

The UPS also detects input voltage transients by sampling the input voltage every 50 microseconds and comparing it to the corresponding point of a stored sine wave that has a RAM value equal to the previous RMS input voltage measurement. If the sample deviates from the stored sine wave by more than the amount programmed into the UPS, the UPS disconnects from the input source and enters discharge mode. Transient detection occurs very quickly. The total delay between sampling the input voltage and discharging the flywheel is about 500 microseconds.

The third method of detecting a utility failure is variation in DC bus voltage. In some cases, the input voltage appears to remain nominal, but current cannot be supplied to the UPS by the input source. In these cases, the DC bus voltage will immediately begin to decay. A reduction in DC voltage greater than a preprogrammed threshold triggers a transfer to discharge mode.

The final method of detecting input failure is to compare input frequency to nominal frequency. A frequency measurement and comparison is made every cycle by comparing the period between positive slope zero crossings to the period at nominal frequency. This combination of methods ensures the UPS will always detect an input power failure and discharge the flywheel before the output voltage is affected.

Recharge mode

When input power is restored to acceptable limits, the UPS synchronizes the output and input voltages, closes the input contactor and turns on the static disconnect switch. The utility converter then transfers power from the flywheel to the input source by linearly increasing the real input current. The ramping time is programmable from one second to 15 seconds. As soon as the load power is completely walked-in, the utility converter and flywheel converter start to recharge the flywheel and return to normal operation. The recharge power is programmable with a default value of 75kW. Recharging is accomplished by controlling the utility and flywheel converters in a similar way to that used to maintain full charge in normal operation, but the IGBT gating points are changed to increase current into the flywheel.

CONCLUSION

The Cat Flywheel UPS supplies superior, fast-responding UPS performance using high efficiency line-interactive UPS technology. The UPS:

- Maintains excellent output power quality for highly non-linear and conventional loads, and at the same time assures low input current harmonics
- Eliminates the need for input filters
- Presents an input power factor that helps regulate upstream utility voltage
- Integrates easily with engine generators and recharges quickly

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