

Novel Advancements in Solid-State Magnet Control Technology

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INTRODUCTION

Significant advancements have been made in magnet controller technology that improve the performance and reliability of magnets and reduce the failures and maintenance associated with contactor-resistor controllers. New magnet control technology also eliminates the damaging magnet discharge voltage spikes.

PROOF OF TECHNOLOGY INSTALLATION AND RESULTS

These significant advancements are a result of Cableform's Solid-State Optimizer™ magnet controller, first installed on a proof of technology trial basis in February of 2004. With no contactors to wear or fail, utilizing current control rather than voltage control, and eliminating damaging magnet discharge voltage spikes into the power supply line, the Optimizer has shown the following results since it was installed in a 24/7 scrap handling application:

- ✓ Magnet operating temperature reduced
- ✓ Magnet lifting capacity increased by 17%
- ✓ Scrap handling cycle time reduced
- ✓ Zero down time associated with the solid-state magnet controller
- ✓ Zero maintenance required on the solid-state magnet controller
- ✓ Magnet controller maintenance cost savings in excess of \$15,000 since the solid-state magnet controller was installed
- ✓ Zero magnet failures, changes or replacements have occurred
- ✓ Cut and/or shorted magnet cables have had no effect on the solid-state magnet controller
- ✓ Magnet discharge voltage spikes have been eliminated
- ✓ Power consumption has been reduced

The areas in which the Optimizer™ Solid-State Magnet Control improves efficiencies, increases throughput and reduces costs include:

- Control of Magnet Current and Minimization of Magnet Temperature
- Elimination of Magnet Discharge Voltage Spikes
- Elimination of Contactors, Timers and other wear parts
- Reduction of Magnet Charge Time & Increase of Magnet Lifting Capacity
- Reduced Power Consumption
- Additional Features
 - Power loss ride through
 - Ground fault detection
 - Cut cable detection
 - Battery back-up
- Opportunity for Magnet Manufacturers to Design Magnets Specifically for Use With Current Control

WHY CONTROL MAGNET CURRENT?

Traditional magnet controls are constructed of contactors and resistors configured to apply a voltage across the magnet. The applied voltage induces current through the magnet and the strength of the magnetic field is then proportional to the magnet's ampere-turns¹. For any given lifting magnet where the number of turns (N_m) is constant, the work that can be accomplished by the magnet is then proportional to the current through the magnet (I_m).

$$(1) F = k * I_m * N_m$$

Where F = Force, k is a constant, I_m = Magnet Current, and N_m = Number of turns within the magnet

The steady state magnitude of the Magnet Current (I_m), using Ohm's Law, is then equal to the applied voltage (V_a) divided by the internal resistance of the magnet (R_m).²

$$(2) I_m = V_a / R_m$$

The internal resistance of a magnet, wound with copper or aluminum, is then proportional to the magnet temperature³ (T_m) so that as the temperature of the magnet windings increases, magnet resistance (R_m) increases, and for a constant applied voltage, the magnet current (I_m) decreases resulting in a decrease in the work that a magnet can perform.

$$(3) R_m = k * T_m$$

Where R_m = Magnet Resistance, k is the temperature coefficient of resistivity of the magnet windings, and T_m = Magnet Temperature

The Magnet Temperature (T_m) is then proportional to the $I_m^2 R_m$ electrical heat losses within the magnet. Therefore the internal heating of the magnet through normal use⁴ is proportional to the square of the magnet current and directly proportional to the magnet resistance.

$$(4) T_m = k * I_m^2 * R_m$$

Where k is a constant, I_m = Magnet Current, and R_m = Magnet Resistance

During use, with contactor resistor controls, the applied magnet voltage remains constant, the magnet temperature increases, the magnet resistance increases, the magnet current decreases, and the lifting capacity of the magnet is reduced.

The lifting capacity of the magnet can, therefore, be optimized if magnet current is controlled to generate the magnetic force required to perform the work and, excess current, which generates unwanted heat within the magnet, is minimized.

CONTROL OF MAGNET CURRENT

Optimizer Magnet Control Timing Diagram

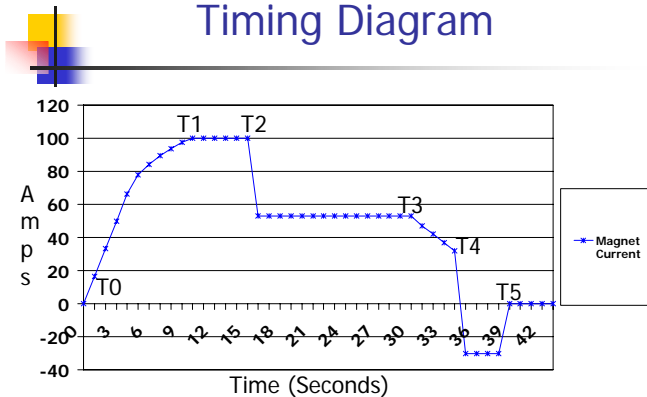



Figure 1



Optimizer™ Solid-State magnet Control

The Optimizer Timing Diagram details a typical magnet lift-drop current timing profile. At T0, the LIFT command is received from the operator, full voltage is applied across the magnet and the magnet current rises at a rate proportional to the magnet impedance. The programmed lift current is reached at T1 and is regulated until it is automatically lowered to the programmed holding current at

T2. The controller maintains the holding current level until the DROP command is received from the operator at T3. Upon receiving the DROP command, the programmed DRIBBLE (T3-T4), and DISCHARGE / CLEAN (T4-T5) operations take place.

- LIFT CURRENT - The maximum current programmed in initial lift) 100 amps in the diagram.
- LIFT TIME - The time from the lift current demand to the change to holding current. T0 to T2
- HOLDING CURRENT - The value of the holding current, 55 amps in the diagram. T2 to T3
- DRIBBLE - A controlled decrease in the applied magnet current. T3 to T4
- DROP - Rapid discharge of the magnet current and application of cleaning current. T4 to T5

The magnitude and duration of each of the operating segments may be adjusted by the user to shape the lift/drop current profile and optimize the performance of any given magnet application.

SHAPING THE MAGNET CURRENT PROFILE TO MINIMIZE MAGNET OPERATING TEMPERATURE

As described, the solid-state magnet control allows a magnet to operate at lower temperatures by reducing the excess heat dissipated within the magnet. Software parameters can be adjusted by the user to customize the 230 volt LIFT/DROP cycle as shown below.

Optimizer & Contactor Lift Cycle Current @ 230 VDC

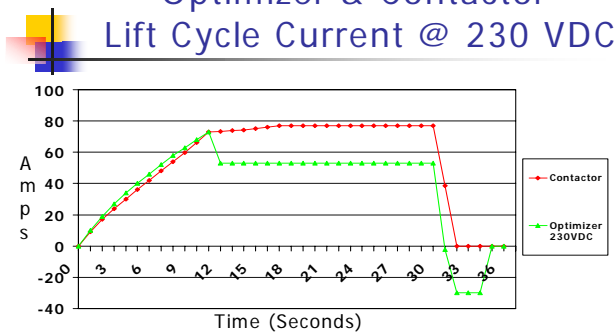



Figure 2

Magnet Operating Conditions with Optimizer™ @ 230 VDC

- Lifting Current 73 Amps
- Time to 73 amps 11 Seconds
- Holding Current 53 Amps


Figure 3

The current profile of a contactor control is shown in red and the current profile applying the solid-state magnet control to the same magnet is shown in green. As can be seen, using the solid-state control, the holding current is automatically reduced after 11 seconds and the load is maintained using approximately 24amps less than with the contactor control. The 24 amp reduction in magnet current equates to a reduction in the heat dissipated within the magnet by approximately 5KW during the load-carrying interval. This reduction in heat generated within the magnet results in a lower magnet operating temperature and a greater lifting capacity throughout the operating shift.

SHAPING THE MAGNET CURRENT PROFILE TO REDUCE CYCLE TIME AND LIFT MORE MATERIAL

The solid-state magnet control allows an increased load to be lifted without increasing the magnet temperature by operating from a higher line supply voltage. See the 285 volt cycle diagram, Figures 4 and 5, applied to the same magnet and notice the increased current available in the same time.

Optimizer Magnet Lift Cycle Current @ 285 VDC

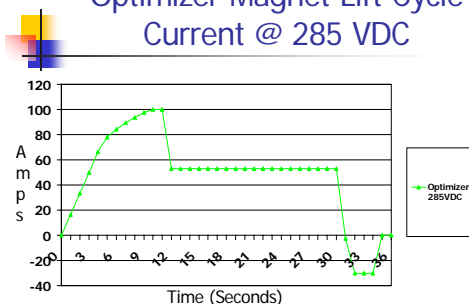



Figure 4

Magnet Operating Conditions with Optimizer™ @ 285 VDC

- Lifting Current 100 Amps
- Time to 73 amps 4.4 Seconds
- Holding Current 60 Amps


Figure 5

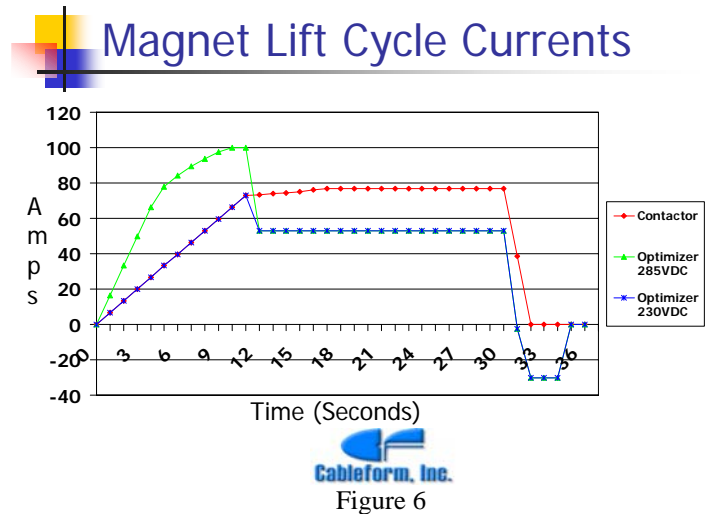
Comparing the 230 volt current profile with the 285 volt current profile in Figure 6, it is noted that the 11 second time to reach the 73 amp current at 230 volts is reduced to 4.4 seconds when using 285 volts. The 73 amp load is lifted much faster allowing reduced cycle times and the lifting current is increased to 100 amps allowing for increased lifting capacity. The holding current is raised slightly to hold the extra load but the thermal economy is substantially maintained and dual voltage rectifiers are not required.

ELIMINATION OF MAGNET DISCHARGE VOLTAGE SPIKES

Conventional magnet controllers discharge the energy stored within the magnet by switching a discharge load across the magnet. Common discharge loads utilized are resistors or varistors. The problem with conventional magnet controllers is that the rapid change in magnet current (di/dt), caused when the load is switched across the magnet, induces a very high magnitude voltage spike into the supply. These discharge voltage spikes can range from around 800 VDC to greater than 1,500 VDC depending on the discharge load utilized.

Discharge voltage spikes can cause damage to, and deterioration of, the magnet, magnet controller, and any other equipment connected to the magnet or crane power supply.

The solid-state magnet controller utilizes Discharge Voltage Control circuitry which detects the rise in supply voltage which occurs when the magnet is turned off and reacts quickly enough to switch a low impedance discharge load across the magnet, as required, to maintain the voltage at a user programmable level, typically 320vdc. Rapid cycling, on and off, of the low impedance discharge load while monitoring line voltage during magnet discharge, regulates the discharge voltage within a few volts. The magnet is rapidly discharged, the discharge voltage spikes are eliminated, and the entire crane electrical system is now not subjected to the traditional discharge transients.



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Figure 6



Solid-State Magnet Control



Magnet with Scrap Load

POWER LOSS RIDE THROUGH

Traditional contactor controls drop their load immediately upon loss of line voltage. When the line voltage falls below that required for the contactor coils to hold in the contactors, the control is configured to its normally de-energized condition, the magnet discharge load is switched across the magnet, and the load is dropped.

Power loss ride through is initiated in the solid-state magnet control when input power to the magnet control is lost while in LIFT mode. When a reduction in supply voltage is detected, the magnet control circuitry can be re-configured and controlled to hold the load for a period of time utilizing the energy stored within the magnet to provide both control power to the magnet control and holding power for the

load. This power loss ride through, or low voltage ride through, is accomplished by reconfiguring the Optimizer magnet control's IGBT's to allow the magnet current to circulate around a low impedance current path while periodically redirecting the magnet current to charge-up the capacitor bank of the controller which supplies control power to the magnet control.

The period of time that a load can be maintained is dependant upon the energy stored within the magnet, the energy required to hold the load, and the self-discharge characteristics of the magnet. The essential difference between a contactor based control and the solid-state control being that a contactor control switches a discharge load across the magnet whereas the solid-state control allows circulation of the magnet current around a low impedance path such that the decay of current within the magnet is dependant upon the self-discharge characteristics of the magnet. This power loss ride through feature of the solid-state control allows for recovery from momentary losses of input voltage without dropping the load.

POWER SAVINGS

Power savings are realized by two different means when utilizing the solid-state control. The first savings are attained by the user programmable automatic reduction in the magnet current from lifting current to holding current. As seen in the previous examples, the holding current required is approximately two thirds of the lifting current which results in a reduction of power consumption by approximately on third.

The second means of power savings is a result of current multiplication which takes place when magnet current is being regulated by the solid-state control.

Current multiplication is the factor by which the current generated within the magnet is greater than that which is drawn from the supply. In the trial installation, it was shown that only 15 amps were drawn from the supply to generate the magnet's holding current of 57 amps.

Current multiplication is best explained as follows: The total current within a magnet is equal to the current drawn from the supply when the controlling IGBT is ON, plus the current which flows through the magnet and the flywheel current path when the controlling IGBT is OFF. Thus, as the controlling IGBT is switched ON and OFF to regulate the magnet current, the total current flowing through the magnet is greater than the current being drawn from the supply. Using current multiplication, the current through the magnet can be as high as seven times the magnitude of the current drawn from the line and the magnitude of the multiplication is somewhat proportional to the IGBT OFF period divided by the IGBT ON period as it is switched to maintain the target magnet current.

The effect of current multiplication takes place whether the magnet is being supplied from the normal line or from a battery back-up system. The solid-state control can, therefore, supply holding current to a magnet from a battery bank while drawing only the power required to hold the load from the battery bank. This operation translates into longer hold times for a given battery bank or the ability to install a smaller and lighter battery bank to provide the required hold time.

SUMMARY

Solid-state controls have shown to be durable and reliable in the high vibration environment of a scrap crane installation. Control of magnets using solid-state circuitry and current control has been shown to increase operating efficiencies, decrease maintenance, and reduce costs. Furthermore, elimination of discharge voltage spikes, reduced magnet temperatures and reduced power consumption have added to the direct efficiencies gained as well as reduced the electrical wear and tear on the magnets, rectifiers, and all other electrical equipment connected to the crane supply.

The solid-state microprocessor based current controller also will allow magnet designers and manufacturers to design and build more efficient magnets specifically for use with current control.