Replacement of saturable reactors with solid-state, SCR based valves, yields efficiency improvements and environmental benefits

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INTRODUCTION

For decades, Saturable Reactors provided a straightforward means to remotely and proportionally control the AC through a load, an indispensable control in the transformation of coated steel. Although simple to control, Saturable Reactor losses are high, old units are isolated/cooled with Polychlorinated biphenyls (PCBs), and they typically have a large footprint.

Advances in Power Semiconductor Technology like BCTs and Hi-Performance Aluminum Heatsinks allowed the use of a Medium Voltage Air Cooled Valve control. The bi-directional controlled thyristor (BCT) is a concept for high power phase control thyristors (PCTs) where two anti-parallel high power thyristors are integrated onto one single silicon wafer and are assembled into one housing. This article presents the design, installation, and benefits of the implementation, presenting advantages, such as size, efficiency, versatility, and coating quality, versus a traditional Saturable Reactor solution.

BACKGROUND

Steel Coating Processes

Several processes in the steel making industry require high amounts of electrical energy to transform steel to higher value finished products. The electrolytic tinplating process is a coating process that adds a layer of tin to steel plate, protecting it from rust and oxidation, producing tinplate to manufacture food or beverage cans.

Cold rolled strip steel is transported through a bath of tin and acid in solution. High current, low voltage, rectifiers are used to electrolytically deposit the tin, with the strip acting as a cathode and the bath as the anode. Process requirements such as target coating thickness and process variations such as line speed, strip thickness, and strip resistivity dictate that the voltage must be controlled. Hence controlled rectifiers or uncontrolled rectifiers fed from saturable reactors are used.

For improved corrosion resistance and bright surface appearance, a tin-iron alloy layer is produced by heating the coated strip to the melting point of tin (450 Degrees F), then quenching in water. Heating is accomplished by either induction heating, strip resistance heating, or a combination of both. For strip resistance heating, high power, variable voltage AC is indicated and historically, saturable reactors feeding transformers have been used.

Saturable Reactors

Saturable reactors have been used for decades because they are simple to control and can be used with a wide range of voltages and currents. A medium voltage saturable reactor feeding a medium voltage step down transformer can be used to deliver and control the low voltage, high current required for strip resistance heating:

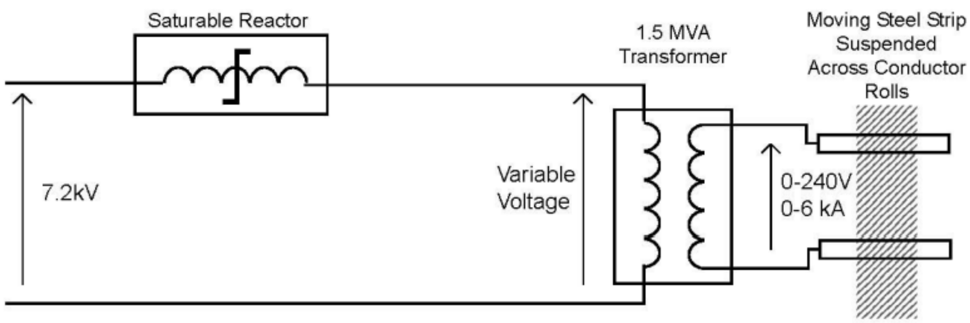

Fig. 1 – Steel coating process power supply using Saturable Reactor

Saturable reactors operate in the nonlinear zone of their reactance saturation curve, acting as commutating devices, which allows control of the current passing through the reactor with reasonable efficiency, versus linear behavior where it will have a considerable voltage drop, and high losses [1].

Construction of saturable reactors to withstand medium voltage levels requires good insulation materials and large footprints for the necessary clearances. At the same time, heat losses generated by the saturable reactors, require an efficient cooling method, and typically as with transformers, oil is used as a cooling fluid and dielectric isolator. For many years, when this technology was the most feasible and available one, the oil used often contained polychlorinated biphenyls (PCBs), in a period when they were not regulated as they are today, since their harmful effects were not well known.

PCBs are a group of chemicals with good electrical insulating properties, a high boiling point, chemical stability and are not flammable. They became commonplace in electrical equipment, like transformers, reactors and capacitors, for much of the 20th century until their use was banned in most countries: they are toxic and have been shown to cause cancer and other serious health problems when released to the environment. Today, PCBs are strictly regulated in many countries, in the US the EPA regulates their use under the CFR 40 Part 761 [2].

Control of saturable reactors is usually via bias (DC) field coils which have significant losses, limit control response, and require a field exciter with appropriate protection, isolation, and control circuits. Coil variations and ageing affect repeatability and so performance can vary or degrade over time. Hence maintenance requirements are somewhat more than that required for a transformer of similar power.

Operating as nonlinear devices, switching between high impedance and saturated states, saturable reactors create a pulsed current waveform, generating harmonic currents in both the supply and load. Current flows in the steel strip to heat up both the steel and the applied tin coating to the melting point of tin. Heat is distributed slightly differently depending on the harmonic content/waveform, so process changes are sometimes made to compensate.

Therefore, the US Steel (UPI) plant in Pittsburg, California, decided to upgrade the saturable reactors on electro-tinning line #3 melter for new, highly efficient and environmentally friendly MV AC single phase power converters, with modern digital controls, high reliability, and low maintenance.

SOLID STATE, SCR BASED, MV AC VALVE

Design

The proposed solution was to design a new power converter based on solid state devices which have been broadly used in recent decades - devices with a fast response, repeatability, high efficiency, a small footprint, simple cooling requirements, and no moving parts - improving reliability, operation, and maintainability.

This application is in the medium voltage range, specifically controlling the power to two 1500KVA (7.2kV, 208A primary) single phase transformers, whose secondaries supply up to 240VAC, 12.5kA required by the process.

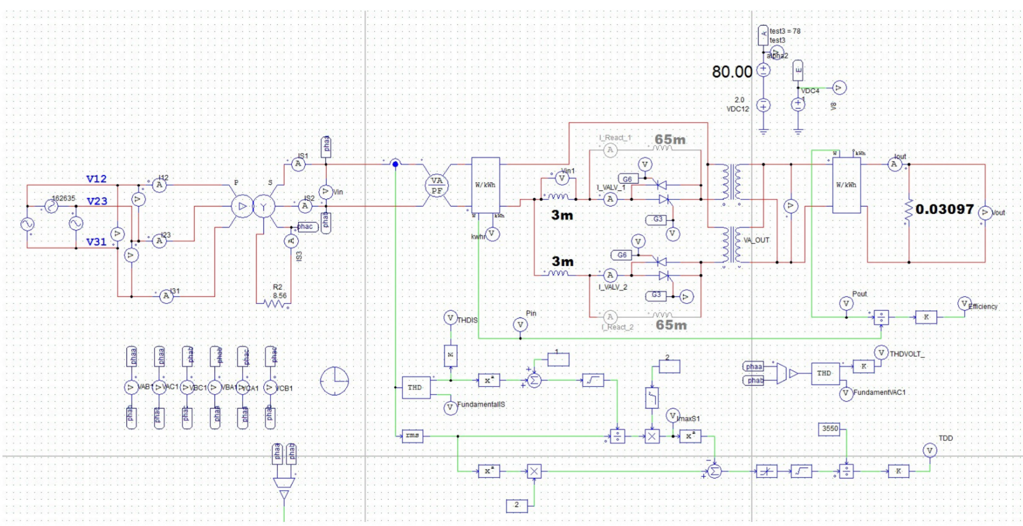

Fig. 2 – MV AC Valve Electrical Diagram

BCTs for medium voltage

Several solid-state devices are available for different power, current and voltage levels, offering various responses and requiring different control methods. The AC supply, AC load, and response requirements indicated natural commutation devices such as thyristors (SCRs) – their robustness and availability at the necessary voltage/current levels meant they were a good choice.

To control the AC power from the supply to the transformer (to function as an "AC valve"), an antiparallel SCR topology is required. The BCT (bi-directional controlled thyristor) is two high power thyristors integrated onto one single silicon wafer providing forward and reverse function in a single encapsulated device, hence this very attractive option was chosen.

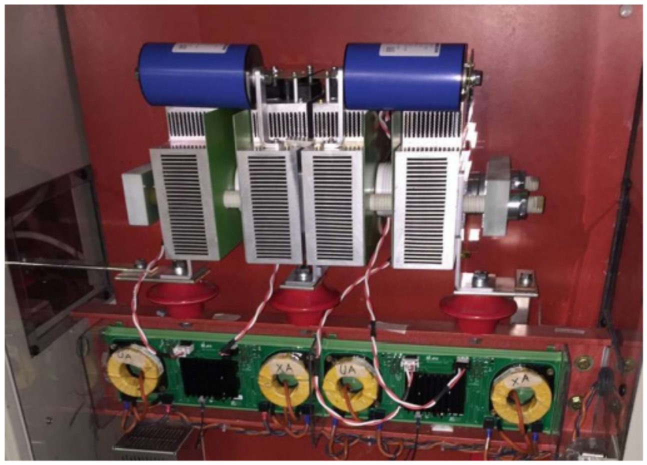
Fig. 3 – MV Cell Module

BCTs are available with blocking voltages up to 6kV and current ratings up to 400A rms. More than one single device is needed to withstand the 7.2 kV rms application voltage with appropriate safety margins, so multiple device in series are used. In this case 3 devices are needed, and a fourth device is added to increase reliability, a strategy which is referred to as N+1 redundancy.

For each BCT, a voltage detection circuit is used to detect short circuited devices – the valve can continue operating with a shorted device and BCT replacement scheduled at a convenient time.

Cooling Method

Although BCTs are very efficient devices, they can have heat losses in the order of hundreds of watts, including losses from their snubber circuits, so an efficient cooling method was required. Power modules, where the BCTs and related snubber circuits are mounted on an aluminum heatsink, were used - along with high flow, low noise, axial fan air cooling. This high efficiency cooling system proved preferable and more reliable than complex water cooling.

Firing circuit and power circuit considerations

As with thyristors, BCTs require gate pulses to start conducting. A firing circuit was designed to provide the necessary coordination and synchronization to trigger all the devices for reliable operation. Particular attention was given to the isolation between control and power circuit voltages as well as the energy required to trigger these devices.

The power circuit included fused disconnects and contactors at the input - to isolate the system for operation or maintenance activities and to disconnect the equipment on a fault. A series inductance, also on the input, limits harmonic currents caused by the non-sinusoidal current waveform.

This 7.2 kV rms application demanded close attention to wiring insulation levels, component clearances, isolation, grounding, protection devices and protective functions (both hardware and software).

Digital Controller

The digital controller provides control and sequencing functions, as well as advanced diagnostics such as high-speed trends, continuous trends, and alarm/event logging. A Profibus interface allows the controller to receive reference and command signals from a PLC and send feedback and status signals back to the PLC.

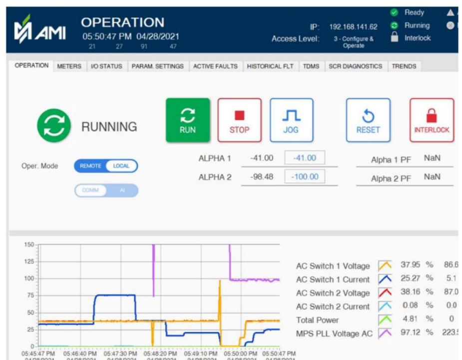

Fig. 4 – Digital Operation, Monitoring and Diagnostics Interface

IMPLEMENTATION

Implementation of the system involved gathering detailed data from the existing equipment and process so that it could be factored into the design. Simulations were done to validate design and performance criteria such as THD and response time requirements. Close cooperation and communication between engineering teams from AMI Automation as the OEM and USS UPI resulted in successful implementation and commissioning.

Engineering and construction took 16 weeks, which involved receiving equipment from several manufacturers. One of the major issues during project execution was the logistic problems created by Covid-19.

Fig. 5 – 7.2kV 3MVA MV AC Valve Cabinet

The equipment was subjected to rigorous factory testing before shipment, including UL 407 code applicable tests. AMI Automation performed routine tests for medium voltage power conversion equipment, and USS UPI requested tests. Tests included voltage withstand tests, partial discharge and tracking tests, hot run tests, and functional tests.

The system installation, commissioning and startup were done within a planned 5 day outage. During startup, the system was tested with a full range of products – different material compositions, gauges, width, and line speeds.

RESULTS

A power analyzer was used to monitor the incoming power Pin, the power delivered to the transformers (from either the saturable reactors or solid-state valves) Pxfmr, and the power delivered to the strip Pstrip from the secondary of the transformers. Two transformers and controllers were used. The next chart compares the efficiency of the new system, solidstate, versus previous results obtained with the saturable reactors, in similar conditions, also several product sizes were used, 0.0064" x 33" strip is shown in solid line and 0.0108" x 36.5" is shown in dashed line. This comparison considers the overall efficiency, including transformer losses.

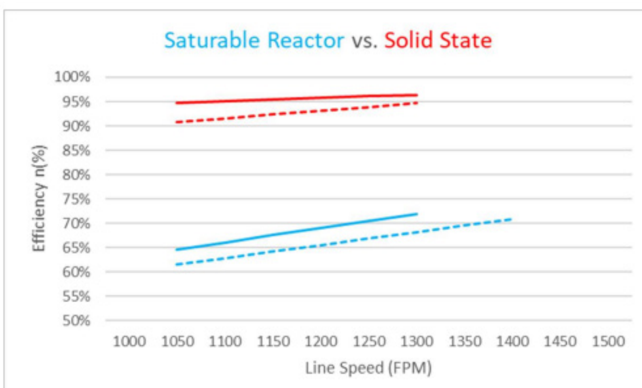

Fig. 6 – Efficiency Comparison

From this data we can observe that lighter material runs more efficient, and efficiency also increases with line speed. In general, solid-state valve achieved efficiencies greater than 24% versus his saturable reactor counterpart.

Also, the input harmonics were registered with the power analyzer, below data taken with 0.0108" x 36.5" strip running at 1050 FPM line speed is shown, for saturable reactor and solid-state ac valve.

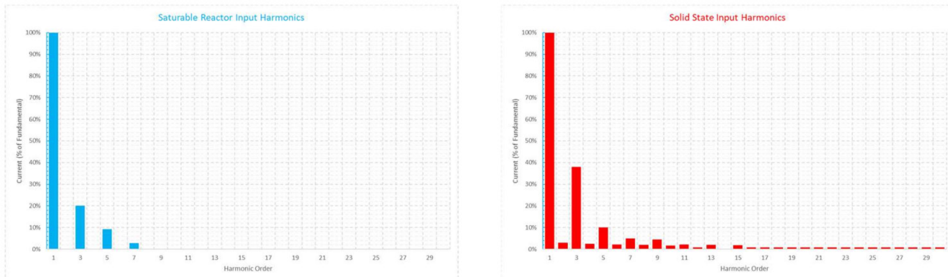

Fig. 7 – Input harmonic distortion

A comparison for THD between the two systems running with the two material sizes and different line speed is shown in the next chart.

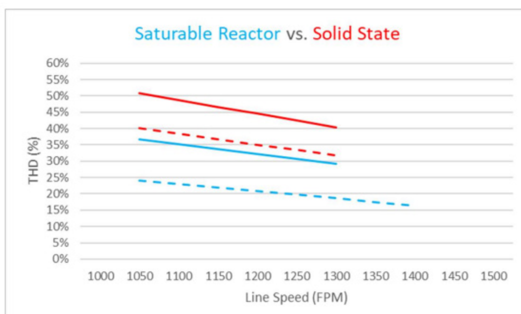

Fig. 8 – THD Comparison

CONCLUSIONS

The actual performance of the new system met the design criteria. The improved efficiency yielded significant electrical power savings (over $100,000 annually depending on product mix/electricity costs) and the decommissioning of the saturable reactors eliminated the PCB environmental liability.

The AC valve response time is faster than the original saturable reactor system allowing closer control of the process during line speed changes, order changes, and process disturbances – resulting in more consistent strip quality.

Strip quality is measured not only by the consistency of the tin coating but also by the visual appearance of the strip after tin coating. An unexpected benefit from this project was an improved visual appearance on lightly coated material.

As of May 2022, the equipment has been in successful operation for more than a year. There have been no BCT failures and no electronic board or component failures. There were some voltage isolator failures during commissioning which were due to a design problem which was resolved as part of the commissioning.

REFERENCES

CFR, Office of the Federal Register. CFR 40, Part 761, Protection of Environment, January 12 ,2022. CFR, 2022

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