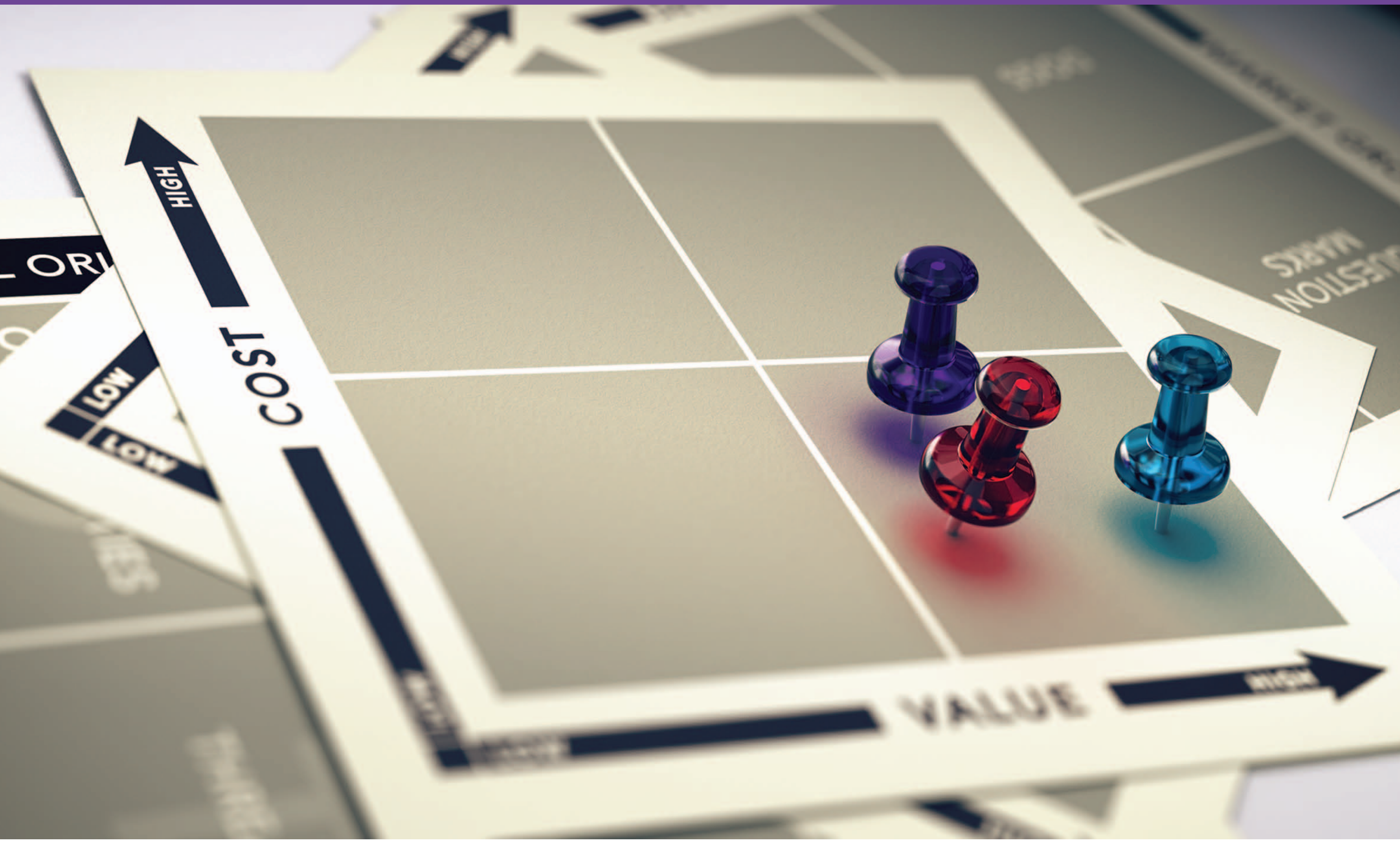
AN AFFORDABLE EVOLUTION USING VARIABLE VOLTAGE TRANSFORMERS



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Lower Cost Solution for Medium Voltage Heater Control

POWER ELECTRONIC DEVICES ARE THE STANDARD SOLUTION FOR LOW-voltage (LV) heater control; however, cost and harmonic issues are amplified for medium-voltage (MV) heater applications. To provide an MV alternative at a significantly lower cost, this article details modifications and testing that will evolve part-range and load-tap-changing voltage regulators into full-range

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Digital Object Identifier 10.1109/MIAS.2017.2740444
Date of publication: 3 January 2018

1077-2618/18©2018IEEE

variable voltage transformers (VVT) for MV heater control. From the initial minor modifications that converted autotransformers into 16-tap isolation transformers, the development moves on to the inclusion of secondary base windings that bring 32 taps into play for refined control. Three-phase solutions and the addition of MV interrupters from the utility industry provide an economical solution for a stand-alone MV heater operation that avoids the harmonic issues of other heater control technologies.

Voltage regulators are designed for reliable operation and ease of maintenance.

MV Heaters as the Majority of the Loads on Distribution Systems

The significant material and processing advances permit a mineral-insulated (MI) heater operation of up to 4,160 V [1]. While power electronic devices, i.e., silicon-controlled rectifiers (SCRs), are the standard for LV heater control, costs and the quantity of harmonic distortion increase significantly for MV devices. As illustrated in Figure 1, total harmonic distortion (THD) for a phase-angle-fired controller presents considerable issues when heaters are a significant portion of the system loads.

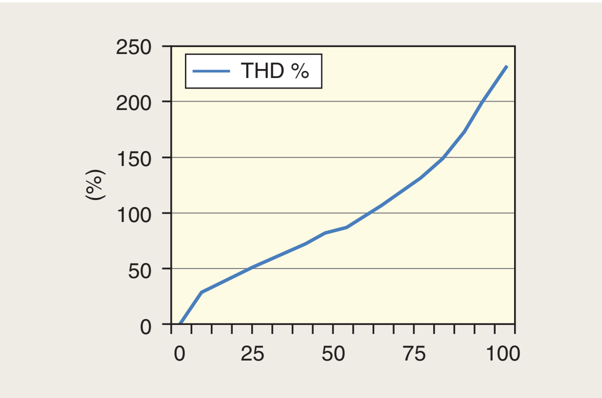

FIGURE 1. The phase-angle-fired SCR THD percentage versus the voltage turndown percentage.

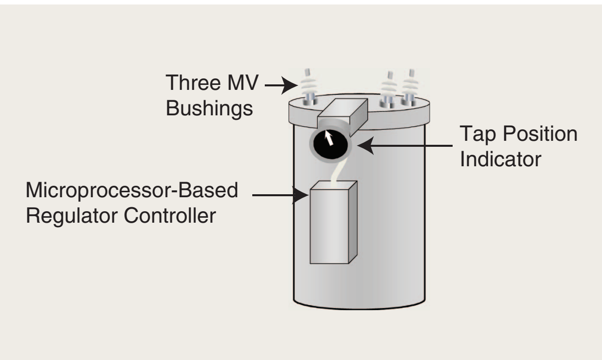

FIGURE 2. A typical pole-mount voltage regulator.

Per IEEE 519 [2], THD is expressed as a percentage of the fundamental frequency. Therefore, THD can be greater than 100%. The quantities of harmonics are surprising to IEEE-519-certified equipment users who expect a THD of less than 5%, but testing may be done at a 100% load and zero turndown where the SCR THD is 0%. IEEE 519 compliance is a distribution system issue. An individual device that has high harmonic distortion levels is IEEE 519 compliant if that device is a limited portion of overall system load.

The goal of the MV heaters, however, was for them to be the majority of the loads on distribution systems and multiple gigawatt generation stations. One suggestion to control heaters without the harmonics typical of electronic controllers was a load-tap-changing voltage regulator, as illustrated in Figure 2.

Voltage regulators are load-tap-changing autotransformers with a range of ±10%. First developed in the 1930s, voltage regulators are designed for reliable operation and ease of maintenance [3]. Tasked with adjusting the voltage at the end of long utility runs, regulators withstand weather extremes between recommended inspection intervals of four-to-ten years, depending on the load and operations [4].

Figure 3 shows both the base and tap-changer windings of an autotransformer. Two fingers of the tap-changer contacts are split by a balance winding with at least one of the fingers in contact with one of the eight 1.25% taps at all times. When the fingers span two taps, the step size is halved to 0.625% with the effective number of taps doubled to 16. At the neutral position, the M-K switch reverses the tap winding polarity in relation to the base winding to either buck for voltage reduction or boost to add to the regulator output for a total of 32 steps. The unit's three bushings, in the gray circle that represents a top-down view of the tank, are labeled *source* (*S*) for the nominal input voltage and *load* (*L*) for the adjusted output, and *SL*, the normally grounded SL bushing.

The voltage regulator was rejected for heater control because of the limited 20% adjustment range and the lack of secondary isolation. However, the 1,247-V travel range of the tap changer was a near match for the 1,200-V operating voltage of a proposed heater application. Discussions with a voltage regulator manufacturer revealed that the units incorrectly installed with the S bushing grounded had resulted in a 0–1,247-V output.

Modifications for Heater Control

An autotransformer, also called a *step transformer*, is a two-winding transformer connected in a special way [5]. In the voltage regulator, what was the secondary winding is now a step winding sharing a common point with the base winding at the S bushing. Connected as intended, the SL bushing is the ground point for both the source and load. The source voltage at the S bushing is added to the number of taps selected for the step winding to provide an increased load voltage at the L bushing if the winding polarities are the same. However, if the step winding is reversed, it becomes a step-down arrangement [6]. If the S bushing common point is grounded, the L and SL bushings have separate winding output voltages like a traditional transformer except with a shared ground. Because early heaters required isolation from utility systems, the common ground of the autotransformer was unacceptable for heater control, but standard equipment within the regulator still showed promise for control applications. The VT and current transformer (CT) provide the operating feedback for heater power flow. The control power transformer (CPT) enables the remote standalone operation without the need for auxiliary power supplies.

In theory, solving the autotransformer isolation issue was a simple matter of separating the 1,247-V-tap-changer winding section from the 12,470-V-base winding of the autotransformer to create the variable output transformer shown in Figure 4.

The initial VVT schematic differed from a standard voltage regulator only by a missing wire connecting the tap changer to the base winding and the addition of a fourth bushing. In this configuration, the output from 0–1,247 V is divided between 16 steps of 6.25%. For operational clarity, the voltage regulator bushing naming convention was replaced with standard transformer terminology. As shown in the gray circle representing the top of the device tank in Figure 4, the SL became H1, S became H2, L became X2, and the new bushing is the X1 of the now-isolated secondary winding.

These changes appear simple on paper, but a great deal of lobbying was required to get manufacturers to believe this would work. Of the four regulator manufacturers in the United States, only two responded to a quote request for a prototype, with one placing a significant premium on the "removal of a wire and addition of a bushing." Beyond the mechanical revisions, modifications were required to make the voltage regulator's microprocessor-based tap-changer controller suitable for the new application.

An autotransformer, also called a *step transformer*, is a two-winding transformer connected in a special way.

Tap-Changer Controller

The control of modern-day voltage regulators is performed by microprocessor-based digital controllers with a schematic similar to that seen in Figure 5. Like the mechanical portion of the regulator, the controller must operate in extreme conditions with typical operational ratings between –40 °C (–40 °F) and 85 °C (185 °F). The regulator operation involves the setting of high- and LV band limits along with delay times. Voltage sensed below the low limit for the specified time causes a raise tap, with a lower tap issued when the high limit is surpassed.

The operating parameters for heater control are current or power. With the current sense as the standard for the regulator controller, a modification to the operating firmware provided an option for current-based

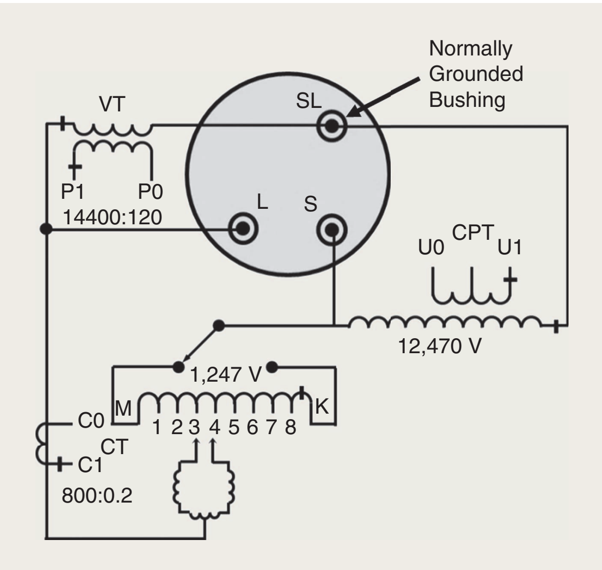

FIGURE 3. A typical voltage regulator schematic.

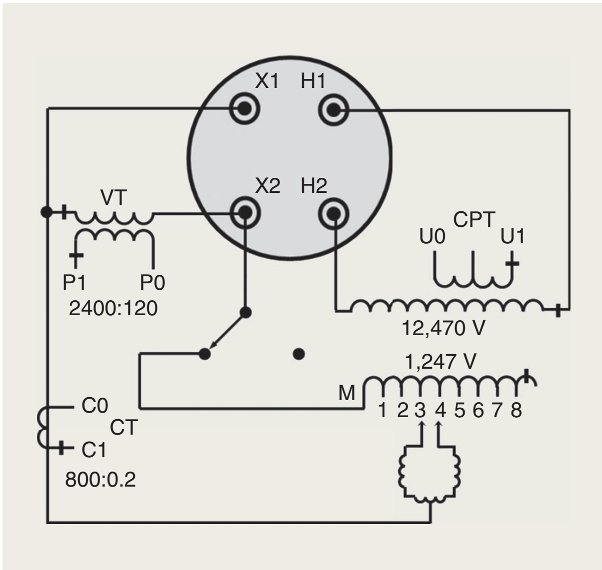

FIGURE 4. A proposed four bushing schematic modification.

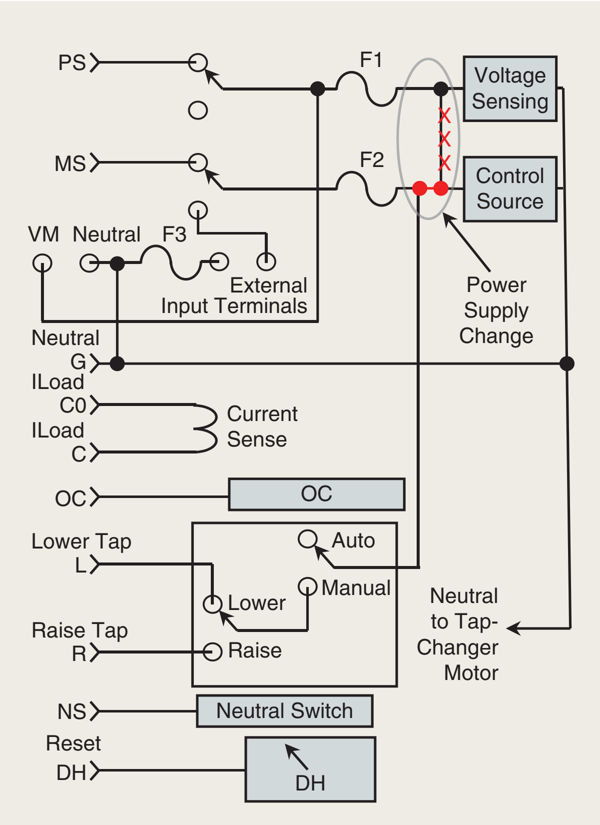

FIGURE 5. The voltage regulator controller schematic. PS: panel source; MS: motor source; OC: operation count; NS: neutral switch; DH: drag hand.

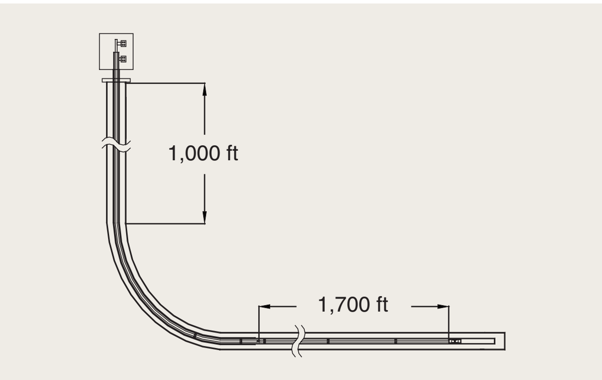

FIGURE 6. The HZ4 long heater configuration. (In this article, values in historical drawings or actual test data my be in U.S. customary units only.)

control or, for long heaters, watt-per-length control. To provide a true-start and walkaway operation of long heaters, a ramp-over-time function was included to match the previous heater process controller capabilities and operating experience.

A controller hardware issue was the control power for the microprocessor and was supplied by the voltage-sensing VT rather than from the CPT used for the motor source. For regulators operating at ±10% of the voltage, the nominal 120 V on the VT-sensing circuit is well within the margins for controller operation. For the VVT operating at 0–100% of the nominal control power, another solution was needed. In the prototype controller, as shown in Figure 5, the panel source (F1) and motor source (F2) fuse outputs were juxtaposed, enabling easy redirection of the CPT power. Careful inventory control was needed to clearly identify the custom controllers. Though custom units would work on a voltage regulator, a regulator controller would not work on a VVT.

Horizontal 4 Test with SCR Supply

The first long heater demonstration was in Houston, Texas. In a well called *Horizontal 4* (*HZ4*), a 518-m (1,700 ft)-long pipe-in-pipe heater was installed horizontally 450 m (1,500 ft) below the surface, as shown in Figure 6. With a resistance of approximately 2 Ω, the device required nearly 630 A to achieve 1,100 W/m (350 W/ft) on the heater. Including overburden losses, the 1,100-V power supply total load approached 700 kW. Following the precedence of shorter heater tests, an SCR fed by an isolation transformer was chosen as the power supply. This quickly led to a case of MV sticker shock.

In addition to the cost increase associated with MV components, the equipment's size required an air-conditioned building rather than an enclosure. The addition of a custom isolation transformer and programmable logic controller (PLC) increased costs to nearly US$250,000. While the controller successfully operated HZ4 for 90 days to prove the viability of a long horizontal heater, tests amplified concerns regarding the controller cost and the observed harmonics.

The idea for a modified regulator as a replacement controller for HZ4 was revisited and given approval for testing. The 833-kVA unit shown in Figure 7 was produced at a cost of US$35,000. Because of an aggressive schedule, there was no time to program a supervisory PLC, and the test was run with a modified regulator controller alone.

VVT Prototype Test

Once the target set point and heater parameters were set in the controller, the VVT automatically ramped power over a four-day period. Even though the unit remained energized for weeks while the heater temperature continued to increase and the test site's nonoil-bearing shale formation slowly heated, the transformer oil temperature was well below the rated 55-°C (130 °F) rise. Figure 8 shows the voltage, heater temperature in degrees Fahrenheit, and power in watts per foot as recorded for corresponding test start-up periods for the two power supplies. The top curves display the voltage, the middle ones show the temperature, and the bottom lines present the power for both VVT and SCR in the units of the actual tests.

The difference at the start-up is that the SCR voltage is taken immediately to 50% to limit the harmonics. A further voltage step is shown in the chart a few hours into the SCR-driven test. This was done to address flickering lights in an office building served by the same 12.47k-V feeder as the SCR controller. Having no harmonics issues, the VVT starts at 0 V with the time in step increasing to give the voltage plot an exponential curve to provide a straight line increase of the power steps. Though lower power is seen initially from the VVT, the higher initial temperature is shown because of residual heat from the earlier test, even though that ended three months earlier. The VVT test heater temperature remains higher throughout the test with the curve showing slight waves with each tap change. Power levels for both control devices were slightly off the 1,100-W/m (350 W/ft) target with the SCR operating at 100% output on a slightly low isolation transformer tap, while the VVT had tap choices of 1,033 W/m or 1,246 W/m (315 or 380 W/ft).

Once at the target temperature, the gap control was programed with a 15-min tap change delay. The current overshot on the high tap and was below the setting on the lower tap, resulting in tap cycling to provide an average power of 1,100 W/m (350 W/ft) that enabled temperature control within a narrow window centered on the 570-°C (1,050 °F) target. Unfortunately, when the heater specialist saw the results the next day, he explained that the 518-m (1,700-ft) heater was expanding or contracting approximately 2 ft during every tap cycle. To avoid heater damage, an immediate stop to the tap cycling was ordered. Considerably smaller percentage steps were deemed necessary if the cycled taps were to be used for long heater control.

FIGURE 7. A VVT prototype connected to HZ4.

First Field Test in Alberta

A test facility located approximately 500 km (300 mi) north of Edmonton, Alberta, Canada, had operated 18 heater wells for more than three years with a subsurface conversion of kerogen, producing thousands of barrels of low-viscosity product. While a relatively low quantity, the facility product provided a significant benefit by acting as a diluent for the heavier output of larger nearby installations. Two heaters previously under SCR control were transferred to VVTs specifically designed for the 180-m (600-ft)-long horizontal heaters located 450 m (1,500 ft) beneath the surface. Given a length nearly one-third of HZ4, the new design output was 480 V. Based on discoveries from the first VVT test, the desire for smaller tap steps was addressed in three ways.

A 300-V base winding was added to the secondary winding so the 16 taps could now buck and boost like a standard regulator to provide 32 taps, as shown in Figure 9.

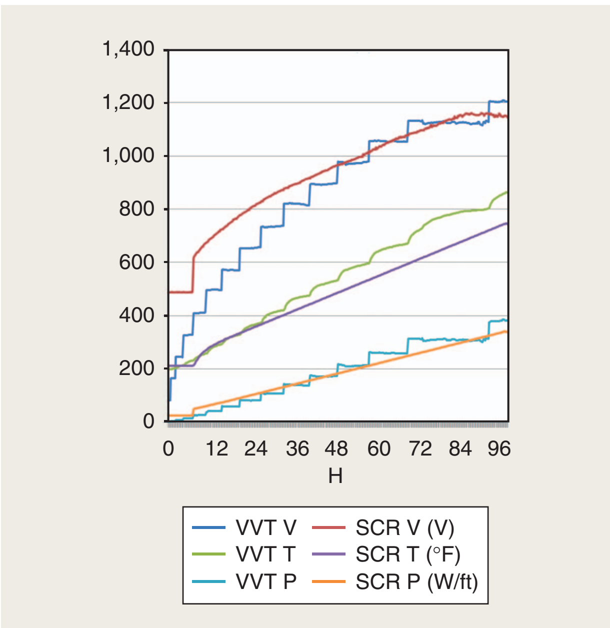

FIGURE 8. The HZ4 operating results.

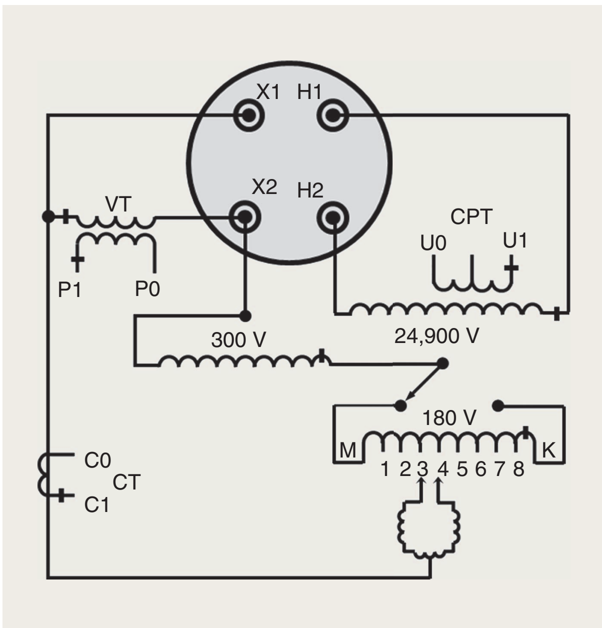

FIGURE 9. A 32-tap VVT configuration.

Bucking at 100% was deemed impossible, so the minimum voltage was now 25%, with the base winding sized at 62.5% of the device rating. The reduced control span dropped the tap size to 2.3% rather than the 6.25% taps of VVT1. Also, an increase of tap size at half the operating range was implemented to drop the step size at the operating target. With four 20-V taps at the midrange and 10-V taps throughout the remainder, the finer tap step sizes were less than 2.1%.

The VT and current transformer provide the operating feedback for heater power flow.

With the VVT configuration determined, the Canadian site provided a wealth of learning opportunities.

1) *PLC interface*: For reliable operation as well as access to the wealth of data within the VVT controller, the VVT was successfully tied to the existing PLC via distributed network protocol 3 (DNP3). A slightly modified version of the SCR human-machine interface ensured that minimal operator retraining was needed for VVT operation.
2) *Cold weather operation*: The manufacturer of the VVT offered only lower-48 oil as an option, which meant the tap changer could only operate at oil temperatures above –30 °C (–22 °F). Device thermal losses proved to maintain an internal temperature for encountered ambient temperatures as low as –50 °C (–58 °F), but, as a precaution, a resistance temperature detector replaced the standard tank temperature gauge to block the tap changes for oil temperatures below –30 °C (–22 °F). For the controller with a –40-°C (–40 °F) temperature limit, a space heater was included in the control box. In actual operation, the heat given off by the controller itself was sufficient to maintain the required operating temperature for all conditions.
3) *Harmonics*: In addition to affecting power quality, harmonics also cause instrumentation distortion. Figure 10 shows the relative noise levels for the SCR operation with three filter capacitors added, the SCR without capacitors, and the VVT without capacitors. Replacing the SCR power supply by the VVT avoided high noise levels that previously made transmitter feedback unintelligible without capacitors.

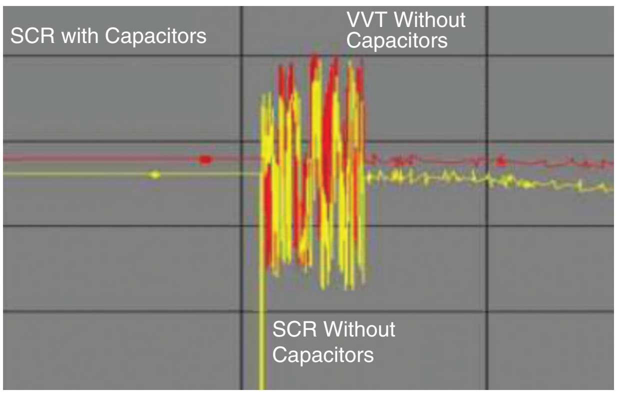

FIGURE 10. A temperature transmitter distortion comparison.

Controller Wish List

After the field test in Canada, a roundtable operational discussion led to the creation of a controller wish list for future VVTs.

1) *Power supply isolation*: The power supply circuit of regulator controllers resembles a residential service drop with a single neutral ground point that is also tied to the controller case. When an external uninterruptible power supply was connected to the controller, much like a grounded back-up generator connected to a house, circulating ground currents are seen. Circuits equipped with ground-fault circuit interrupters would trip, leading to the need for a controller with an isolated power input.
2) *Distributed control systems (DCSs)-compatible communication*: DCSs seldom have utility communications protocols such as DNP3 or International Electrotechnical Commision 61850. Attempts to communicate with a DCS via a DNP3-to-Modbus converter resulted in command turnaround times that were frequently in the 15-s range. With the added frustration of a translator lockup, the communications interface could not be trusted for critical control functions. A typical DCS communication protocol, such as Modbus or Profibus, was, therefore, desired.
3) *System protection*: Early tests included the VVT controller, a meter to transfer data to the site historian, and a protective relay. When 500–1,000 heaters would be installed per year, combining the three devices into one could easily save millions of dollars.
4) *Waveform capture*: During testing, waveform capture is invaluable for estimating fault locations in long heaters.
5) *Adaptability*: For adjustment to site variations, the ability to make field programing changes was desired.

MI Long-Term Tests

Economic indicators steering heaters toward longer lengths than the pipe-in-pipe could support redirected research toward MI heaters. Near-term plans for the field deployment of 610-m (2,000-ft) horizontal heaters ran parallel with the testing of 4,160-V samples targeted for future 1,200-m (4,000-ft) heaters. Though a common VVT could, theoretically, adapt to either case, test-specific units were developed with single-phase secondary ratings of 1,300 V and 2,400 V, respectively.

The first set of 32-tap, 1,300-V VVTs supported HZ4 with a new, three-phase 518-m (1,700-ft) MI heater. The VVTs were configured as a wye power supply with a low resistance ground and physically arranged in a triangular formation to fit in the existing power platform bay. Figure 11 overlays the prototype operation of HZ4 with the smoother temperature control enabled by the 32-tap VVT.

Finer control of the 32-tap VVT is clearly evident with the lower tap power showing a nearly straight line increase. The heater temperature, again, initially higher because of thermal carryover from the previous operation, shows much less of the tap-induced ripple seen with the prototype. Tap steps would have been even less noticeable had the heater allowed the use of all 32 taps seen at 1,300 V rather than the 800-V maximum shown. In fact, the larger steps expected to be the midrange landed at the heater long-term operating voltage, which prevented a precise adjustment to the desired 1,100-W/m (350-W/ft) heater power level. Based on this experience, subsequent designs utilized equal voltage taps throughout the VVT adjustment range.

While combining heater development testing with power supply verification, long-term operations included two aboveground 4,160-V installations, two 1,300-V three-phase heaters, and two single-phase down-hole units at more than 1,000 V. As heaters completed test goals or failed extreme temperature testing, power supplies were shifted, at times requiring firm voltage limitations below the device maximum ratings. An unintended benefit from the device's voltage regulator heritage was the tap limit feature on the tap indicator. For voltage regulator applications, the tap travel may be limited for increased supplementary continuous-current ratings [7]. On one of the VVTs, a maximum 1,200-V output was guaranteed where the full tap range voltage was 2,000 V.

An unintended benefit from the device's voltage regulator heritage was the tap limit feature on the tap indicator.

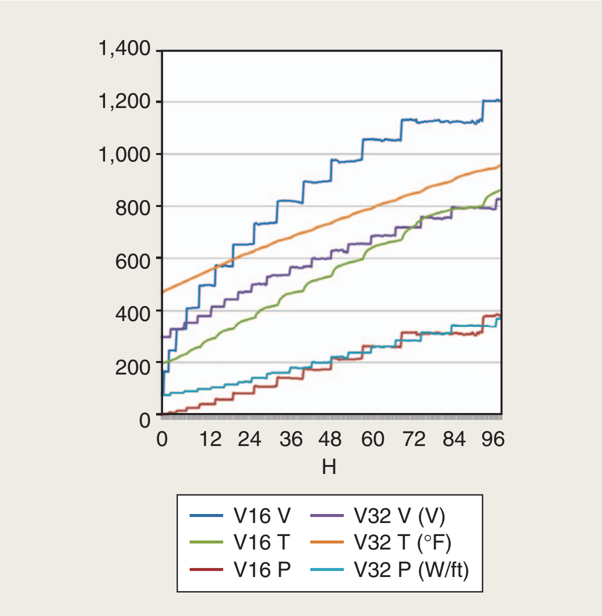

FIGURE 11. A 16 tap versus 32 tap for HZ4.

Long Heater Test

After several years of heater testing and improvements at the development site in Houston, a 610-m (2,000-ft)-long three-phase MI heater was deemed ready for field trials. This was the first downhole installation and field test of a high-power, long-length, MI heater cable assembly. It was conducted at the north field test site located in Northern Alberta, Canada. The purpose of the project, the long heater test (LHT), was to demonstrate mechanical integrity, heater/subsurface interactions, heater assembly deployment, and operational learnings for the long heater. The control room used at the previous Alberta test was relocated, and the PLC programing was updated for the operation of three units with 1,300-V outputs connected in the resistance grounded three-phase wye configuration shown in Figure 12.

For this application, the primary voltage was 4.16 kV to match the output of the 2.8-MW diesel generator serving the site. Following set-point commands from the PLC, the VVTs reliably executed synchronized tap changes in ambient temperatures as low as –50 °C (–58 °F). With power injection rates of more than 1,000 W/m (300 W/ft), the subsurface temperature goals of 650 °C (1,200 °F) were achieved ahead of schedule [8].

Three-Phase VVT

The LHT VVT installation, while successful, clearly illustrated drawbacks of the standard regulator configuration. The three tanks required significant real estate, which is compounded by the exclusion zones needed for exposed MV bushings. A minimum vertical clearance of 3 m (10 ft) to the bushings required the units to be installed on an

FIGURE 12. A three-phase LHT VVT installation.

elevated stand. Not shown in Figure 12 is additional space for a pad-mounted MV switching device.

To address the issues, a three-phase solution with integral MV switching was sought. While a pad-mount configuration was thought to be the most economical solution, the vendor was unable to provide that option. As proof of the three-phase concept, the VVT configuration was incorporated into a substation class transformer enclosure.

A molded vacuum interrupter (MVI) was mounted in the output air terminal chamber. This compact device, which utilizes the same vacuum bottles as metal-clad vacuum circuit breakers, provided heater isolation from the 4,160-V VVTs at all tap voltage levels. Tripping for the interrupter was provided by a protective relay that also contained programing capabilities that enabled the functions of the original VVT controller to be duplicated. Complete with a Modbus communication and waveform capture, the relay provided the necessary functions for the controller wish list that could be carried forward for future iterations of the VVT.

To push technology deployment forward, heater and power supply information were shared with a small start-up company.

Pad-Mount VVT

To push technology deployment forward, heater and power supply information were shared with a small start-up company. Their search for an alternative to the exposed bushings of the single-phase units and the expense of the substation class three-phase unit was aided by a previous relationship with a traditional electrical utility equipment supplier. That supplier had a unique three-in-one (3-in-1) pad-mounted regulator option that utilizes the internal components of traditional MV regulators and packages them into the three-phase pad-mounted transformer design of Figure 13. Enhancing the design's capabilities can control each phase of the three-phase regulator independently or in unison with a single microprocessor controller.

The 3-in-1 pad-mount design has several advantages that traditional overhead regulators and SCRs are unable to offer. Where the SCR shown in the HZ4 illustrations had to be started at 50% voltage to avoid issues with harmonics, the three-phase VVT design allowed for a smooth ramp to the desired voltage utilizing 32 evenly spaced steps from 0 V to rated voltage, with fine control of each phase possible. The 3-in-1 pad mount can be designed to accommodate any MV input from 2.5 to 34.5 kV, 50 or 60 Hz, with an output of 0–4,330 V wye at up to 350 A. This range covers many of the possible applications globally that would use utility power feeds and the current design of MV heater cables. Using feedback from thermocouples, the subsurface temperature can be monitored, and the voltage can be remotely adjusted to allow for a smooth ramp up, reducing the mechanical burden on the heater elements.

The three-phase VVT design incorporates magnetic coupling of the primary and secondary circuits along with fully rated dielectric isolation, which is desirable from a through fault standpoint. It additionally incorporates a double set of LV windings per phase. As seen in Figure 14 [9], one of the windings is always in the circuit and rated at 50% of the desired single-phase LV. This winding provides a voltage to boost or buck against with respect to the second tapped winding. Through the combination of the two windings, it is possible for the minimum tap to be at 0 V at the turn on. The three-phase VVT is also equipped with protection CTs on the secondary bushings to provide a current-sensing capability for the protection scheme as well as metering CTs for input of the current into the control.

To round out the metering package, wye/wye-connected power transformers (PTs) are supplied to provide secondary output voltage to the protection scheme and control. An X0-connected full secondary voltage PT is available as an option to sense the X0 voltage rise over the ground resulting from the use of a neutral grounding resistor to limit

FIGURE 13. A 3-in-1 pad-mount VVT.

the fault current. To provide adaptability to various MV primary distribution circuits, the three-phase VVT is equipped with a primary winding deenergized tap changer (DETC). The primary taps, in addition to the nominal primary voltage accessible with the DETC, are ±2.5% and ±5%.

The 3-in-1 pad mount also solves some of the issues outlined in the controller wish list previously mentioned in this article:

1) *DCS-compatible communication*: The multiphase controller offered by Modbus natively to remove a protocol converter that was utilized on previous protection schemes. This allowed for faster communication and communication error reduction.
2) *System protection*: The 3-in-1 pad mount includes either an MVI integrated with the standard design or a more recent design comprising an integral vacuum fault interrupter. This device protects the system from faults but can also be utilized as a mechanism to remotely turn off the unit through the multiphase control.
3) *Adaptability*: The multiphase controller offers communication options and software for the remote control of the VVT. Based on the unit and control design, each individual phase can be controlled to allow for fine control of the heater elements.

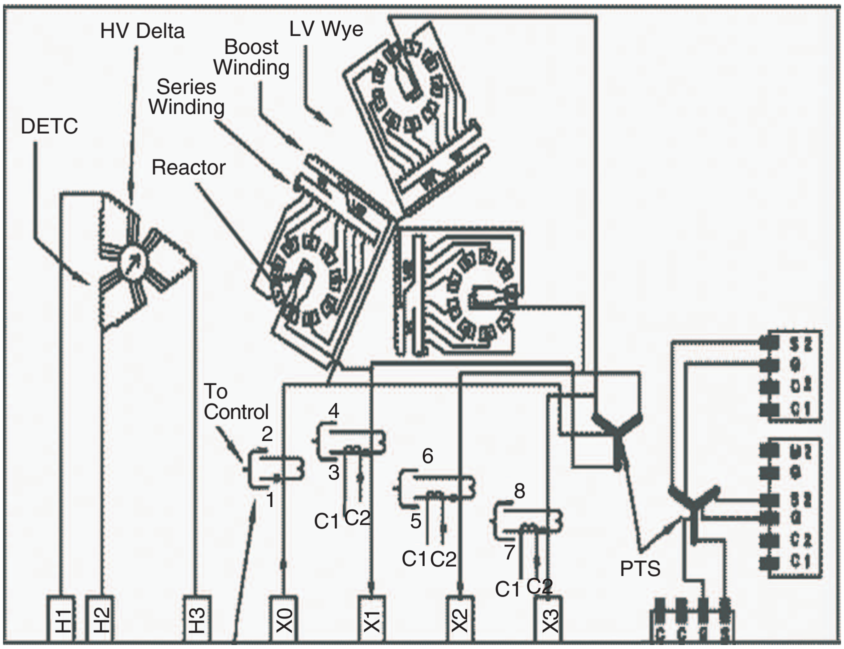

FIGURE 14. A three-phase VVT schematic. HV: high voltage.

Further options based on recent utility market trends include the capability to monitor gauges both remotely and locally while adhering to National Fire Protection Association 70E arc flash requirements. As seen in Figure 15, the gauges incorporated into the controller are placed to the side of the main tank and enclosed in a separate compartment to accommodate review of measurement conditions without exposing personnel to arc-flash hazards as might be the case with traditional pad-mount transformer designs. The gauges allow for the remote monitoring of the liquid level, temperature, pressure, and winding temperature to ensure that the device is operating properly.

Path Forward

Though creation of the VVT reduced the proposed in situ heater field development budget by US$1 billion, a decision review board's lack of confidence in the heater technology at the time put the project on hold. Reduced oil prices extended the pause in spite of tremendous strides in heater development. In the interim, there is still further potential for the reduction of heater deployment cost via compact drill rigs designed specifically for long horizontal heaters. While costs may still be too high to justify the large-scale projects that were once envisioned, 50- or 100-well installations may

FIGURE 15. The tank-mounted gauges.

Table 1. A summary of VVT benefits

Parameter	VVT	SCR
Cost 1 kW, 1 PH	US$35,000	US$250,000 with enclosure, heating, ventilation, and air conditioning isolation transformer, controls
Cost 2.5 kW, 3 PH	US$100,000 with MV breaker	US$173,000 without enclosure
Size 2.5 kW, 3 PH	72 in × 78 in × 78 in	210 in × 36 in × 90 in Needs enclosure minimum 282 in × 96 in × 126 in
Ambient temperature	–50 °C to 50 °C –58 °F to 122 °F	Indoor rated without enclosure
Auxiliary cooling needed	No	Yes
Needs stepdown transformer	No	Yes
Harmonics	No*	Yes
Losses	≈ 1%	1–3% + Transformer 1%

*Minimal VVT harmonics are typical of similar size distribution transformers that can be neglected in most study cases per IEEE 399 [11].

provide a light diluent to aid the pipeline transportation of heavier oil producers.

Beyond the in situ heater projects, some traditional LV process heater applications are turning to MV heating technology as a clean, efficient, and emissions-free [10] alternative for process heaters that may also benefit from reliable, harmonic-free control. Table 1 summarizes how VVTs can offer a lower cost, smaller footprint controller that can be installed in environmental extremes.

The higher voltage, longer lengths, and remote locations for which the VVT is suited are common for skin effect heat trace circuits. High temperature requirements and long circuit lengths are also found in molten sulfur pipeline applications, where the simplicity and durability of the online tap-changer concept might alleviate common maintenance issues.

Conclusions

When the first 16-tap VVT prototype was still on the drawing board, before the first order or operation, it was thought to be the perfect solution for MV heater control with plans for thousands in the field. The lack of awareness of ultimate needs was fortunate because it is unlikely any manufacturer would have agreed to more than the simple modifications that turned a regulator into the VVT prototype. Even with its simplicity, the first prototype worked well enough that management thought no formal development program was needed. New VVTs were purchased only as required to power heater tests. That led to this article's organization by heater tests. Each heater power supply addressed previous discoveries, like the need for 32 taps. Impractical ideas, like smaller-end range taps, were abandoned to lead to a three-phase pad-mount version that was not imagined when the first prototype was created.

From the simple idea of removing a wire and adding a bushing to a standard voltage regulator, the VVT concept was refined to become a compact drop-in-place MV heater controller. With multiple primary voltage options, the VVT serves as both a controller and utility step-down transformer. Onboard microprocessor control enables stand-alone operation or access by process control systems implemented via standard instrumentation communications protocols. Protection and control functions can be combined or separated as dictated by the owner or regulatory requirements. Power quality and instrumentation distortion issues related to SCR harmonics are avoided using a lower-cost technology that has proven reliable in environmental extremes for more than 80 years of utility service.

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