NEW DEVELOPMENTS IN FURNACE POWER STABILIZATION WITH SPLC

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ABSTRACT

Today's high power ferronickel smelting furnaces operate from 65 MW to over 85 MW and at transformer tap voltages as high as 3000 V. Such operation imparts significant power swings. The Smart Predictive Line Controller (SPLC) is a technology to smooth out furnace MW fluctuations using predictive thyristor control of the supplementary furnace electrical reactance at a speed of up to 60 times a second. This paper describes, via analysis supported with field measurements, how the SPLC essentially flat-lines furnace power, enables increased furnace throughput, lowers electrical frequency fluctuations, and improves the energy efficiency of the captive power generation equipment. There are currently three high power furnaces equipped with SPLC installed at the main substation, and several more installations are in various stages of design and implementation. Different SPLC configurations are also compared from the standpoint of long versus short arc operation as well as installation and maintenance costs. The new trends in modularization of SPLC equipment and advances in the SPLC controls are discussed.

1. INTRODUCTION

High voltage smelting of nickel laterite ore to produce ferronickel is typically performed using shielding of the arc cavity below a deep calcine cover as shown in Figure 1. A photograph of a representative three-electrode furnace is included as Figure 2, which shows a furnace charge bank profile and electrode tips without the charge bank cover.

The importance of arc power versus bath power has been discussed before [1]. With shielded arc smelting, most of the power is transferred directly to the calcine from the arc. This increases the concentration of furnace power around the electrodes, and away from the sidewalls compared with immersed electrode smelting.

Arc power, however, is much more variable than the power liberated in the bath because arc length variations are not fully controllable or balanced. As the arc to bath power ratio increases and the arcs become longer, the furnace power fluctuates more. As a result shielded arc operation is generally associated with larger power fluctuations than the immersed electrode or brush arcing operations.

Arc power fluctuations lead to inefficiencies in furnace operation through unscheduled furnace power downs due to trips caused by the furnace power supply protection system, frequent electrode movements, and lowered furnace utilization. In some cases, a series reactor of a fixed size is used in the furnace power supply to control the arc power variations and to stabilize the furnace. However, while large reactor sizes provide more stability, they can limit the furnace operating power. Therefore, the size of these reactors has to be a compromise between the arc stability requirements and desired range of furnace operating power. As a result, often a fixed size series reactor alone is not capable of reducing these fluctuations adequately and more advanced power stabilization is required.

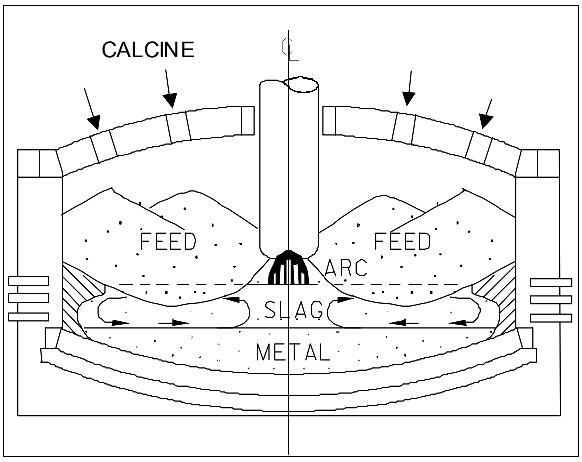

Figure 1: Shielded Arc

Figure 2: Three Electrode Furnace (open arc during start-up)

Moreover, the introduction of high-voltage shielded-arc smelting places an increasingly fluctuating load demand on the power systems. Many of the world's ore bodies and electric smelting furnaces are in remote locations distant from power generation facilities. As a result, local islanded (independent) electric power generation stations ranging in size from 100 MW to 400 MW are often constructed near the mine site to power the smelter and mine site. In some cases, these generating stations are connected to the utility grid to allow power imports under contingency conditions or power exports when metal production targets are reduced. Even when tied into the utility grid, the power system may not be sufficiently strong. Therefore, furnace power variations lead to variations in the electrical frequency. Excessive power frequency variations are not acceptable to other customers on a utility grid and are harmful to electrical equipment [2], [3]. In addition, furnace power fluctuations lead to inefficiencies and heightened maintenance in generation system operation.

This paper describes how the Smart Predictive Line Controller (SPLC) technology compensates arc power fluctuations to a near flat-line profile and how it affects the efficiency, utilization, and maintenance requirements of furnace and power generation equipment. In particular, the SPLC allows the average furnace power, and therefore furnace production, to be increased by as much as 20%, to near the peak power rating of the generation equipment, without causing power plant trips. Alternatively, locally generated excess power that is made available through SPLC application can be sold (exported) to the local utility grid without causing adverse effects on the grid.

2. SPLC FUNDAMENTALS

The SPLC technology uses dynamic control of the supplementary reactance in the furnace power supply to counter arcing fluctuations. The concept can be explained using the diagrams in Figure 3 representing a simplified model of the SPLC on a two-electrode furnace supplied by single phase power.

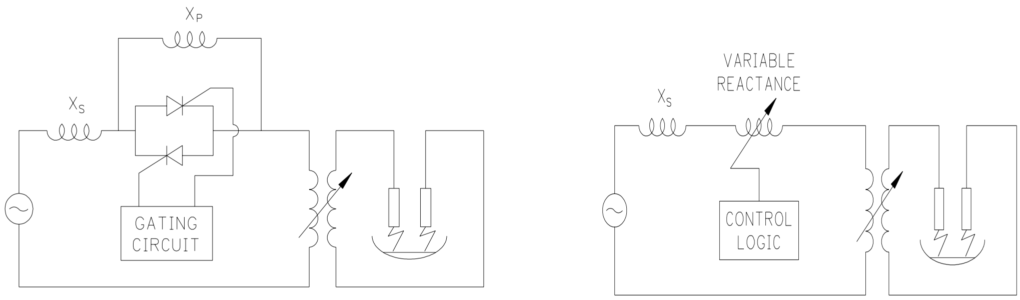

Figure 3: Simplified circuit diagram of the SPLC (left) and its equivalent model (right)

The SPLC variable reactance is created using a combination of a series reactor (X_S), a thyristor valve, and a reactor parallel to the valve (X_P). In Figure 3 the SPLC is shown to be placed on the primary of the furnace transformer. By varying the firing angle of the thyristor valve the effective equivalent reactance in the circuit changes. The variable reactance can then be dynamically changed to keep power constant based on Equation 1.

$$X_{SPLC} = \left(\sqrt{\frac{R_L V^2}{P_{SP}} - R_L^2} \right) - X_L \quad (1)$$

Where, P_{SP} is the setpoint power, V is the supply voltage, and R_L and X_L are the circuit resistance and reactance (excluding the SPLC reactance).

The plots in Figure 4 show a simulated power profile using measured data from a ferronickel shielded-arc smelting furnace equipped with a series reactor. The top plot shows the change in the furnace electrode resistance that is primarily due to variations in the arc resistance. For example, the electrode resistance increases when an unusually large amount of feed slides into the arc cavity between the electrode tip and slag bath and increases the arc resistance. In a worst case this charge cave-in can completely obstruct the arcing path leading to a loss of arc. The middle plot shows the furnace power profile with the series reactor and the bottom plot shows the corresponding power profile with the SPLC.

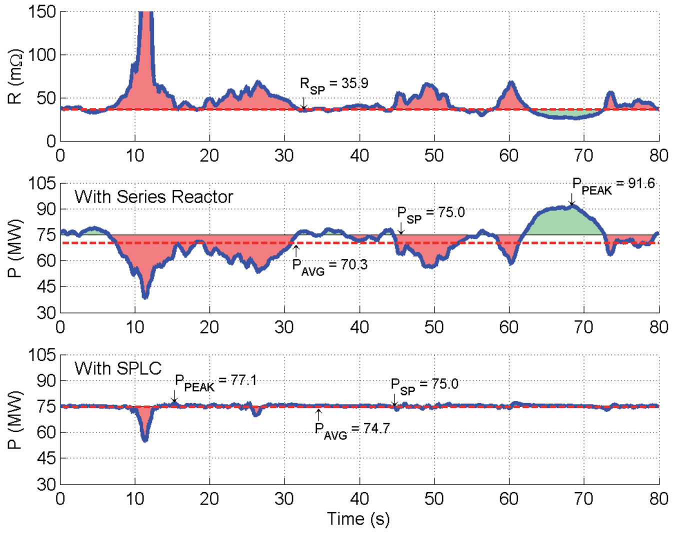

Figure 4: Furnace power with a fixed series reactor versus SPLC

From Figure 4, the impact of the SPLC on furnace power for operation at a setpoint power of 75 MW can be summarized as follows:

1. SPLC nearly completely eliminates the power excursions above the furnace power setpoint. Note that the peak furnace power with the SPLC is clamped down to about 77.1 MW compared to 91.6 MW with the Series reactor. This allows a higher furnace power setpoints relative to the size of the power plant to be used.
2. SPLC boosts the furnace power during power dips that can be caused by high electrode resistance or losses of arc. Minimizing the power dips increases the furnace average power to the power setpoint level. Figure 4 shows that the furnace average power is increased from 70.3 MW to 74.7 MW with the SPLC.
3. With the SPLC, the overall furnace power deviations from the setpoint are greatly reduced in extent and duration and the power profile is nearly flat-lined.

Furnace power stabilization with the SPLC affects the power plant and furnace utilization, electrical frequency variations, power plant efficiency and furnace productivity as explained below.

2.2 SPLC Effect on Power Plant and Furnace Utilization

The power plant load factor is defined as the ratio of the power plant average power to power plant peak power demand. SPLC eliminates furnace power demand peaks above the furnace power set point. This feature allows the furnace average power to be set close to the maximum power available from the generation, without risk of causing system trips by exceeding maximum power. That is, with SPLC in the system, the set point power and hence average furnace power can be safely increased to very near the peak power available from the generation.

For a green-field installation, the SPLC application increases the power plant load factor and allows the power plant MW rating to be not much larger than the maximum furnace power setpoint plus auxiliaries. Without the SPLC, the power plant must be about 20%-30% larger than the maximum furnace power setpoint plus auxiliary power to account for furnace power load swings around the power setpoint. Installing SPLC in a Greenfield plant, therefore, leads to significant savings in the power plant capital cost.

For a brown-field installation, the SPLC can be retrofitted in the furnace power supply system to allow an increase in the power plant load factor by allowing the power plant average power to be higher and closer to the power plant peak rating. The extra power made available can be used for increased production at minimum incremental cost through increases in the furnace power setpoint to its maximum capacity or can be exported to the utility grid.

2.3 SPLC Effect on Electrical Frequency

Generally, furnace power is the largest component of the process plant power demand from the captive power generation system. For a thermal power plant, generated power is adjusted continually via main steam valve throttling. In a hydro power plant short-term power changes are handled by controlling the turbine wicket gates. However, the mechanical action of steam valves or wicket gates is relatively slow. Therefore, any changes in furnace power cause a momentary difference between the power demand and the power generated before the steam valves or wicket gates can fully adapt to the new demand. In extreme cases, even after opening of the steam valve to the rated Valve Wide Open (VWO) capability level, there is not enough steam available to meet the demand and the power difference persists.

Momentary power differences are handled by variations in the kinetic energy of the rotors of the turbine-generator set before they can be met by more steam/water flow. The change in the kinetic energy requires a variation in rotational speed that is equivalent to changes in the electrical frequency. The relationship between this power difference and the electrical frequency is expressed by Equation 2.

$$\Delta P = \frac{2H}{f_n}\frac{df}{dt} \tag{2}$$

Where f is the electrical frequency, H is a constant related to the mechanical inertia of the turbine generator rotors, f_n is the nominal system frequency and ΔP is the power difference as per unit of the size of the operating power plant. Therefore, a step change in power causes a linear change in electrical frequency. As an example, on a 200 MW power plant supplying power at 60 Hz, a step load change of 50 MW causes a frequency change at a rate of 1.5 Hz/seconds.

Figure 5 shows the measured frequency roll at a ferronickel smelter site caused by furnace power variations ending in the trip of one of the two furnaces. The direct correlation between the frequency and furnace power variations can be seen from this graph. Large variations in frequency are harmful to electrical equipment. There are limits on steam turbine operation at off-nominal frequencies, as described in IEEE standard C37.106 [4]. As a result, power stations are equipped with under frequency relays to prevent excessive frequency drops and system frequency collapse by removing excess load (load shedding). The furnace trip shown on the graph is because of the operation of such an under frequency relay.

The SPLC controls the power variations to a large degree and therefore reduces the electrical frequency variations and their negative impacts.

2.4 SPLC Effect on Power Plant Efficiency and Maintenance

For a thermal power plant, the thermal efficiency has a direct relationship with the power plant load factor. Figure 6 shows the efficiency of a thermal power plant installed in a ferronickel smelter. As shown, an increase in load factor from 75% to 90% increases power plant efficiency by about 1%.

With less power fluctuations, the power plant operation also becomes more efficient requiring less maintenance because of reduced throttling of the steam valves or wicket gates.

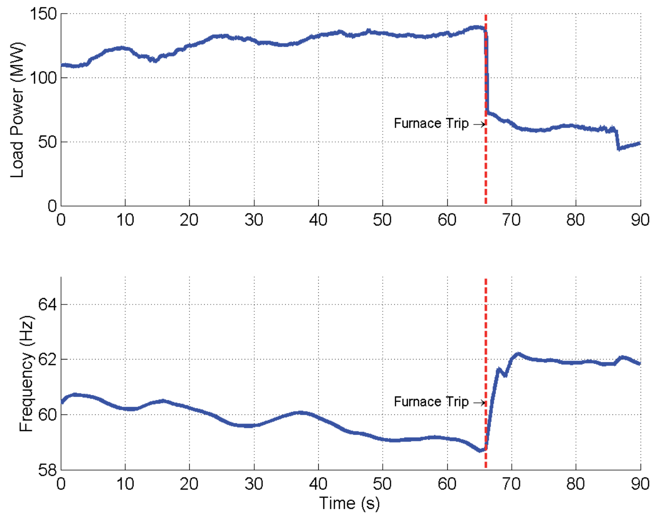

Figure 5: Measured trends of Electrical Frequency and Power Demand

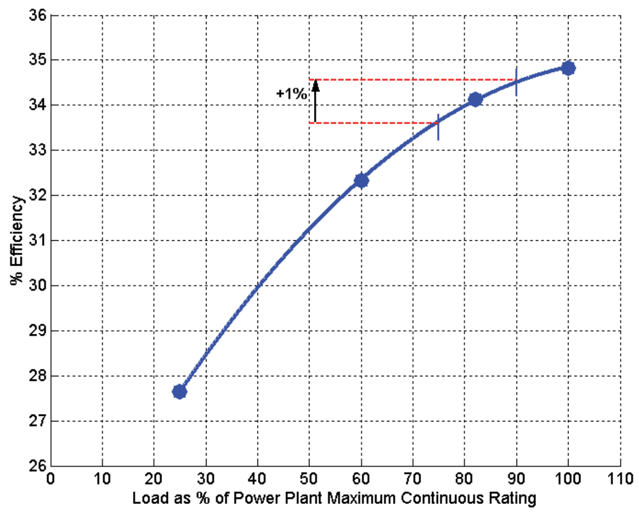

Figure 6: Efficiency vs load factor for a typical thermal power plant

Application of the SPLC also reduces the furnace sudden shutdowns caused by under frequency trips (by precise control of furnace power) and overcurrent trips (by limiting furnace current). Each time the furnace trips, a large volume of steam is released to the atmosphere. In a hydro power plant, excess water is diverted to the spillways. In either case, the available energy is not converted to electricity; therefore, with fewer trips the power plant efficiency is increased.

Finally, steam turbine load changes modify the steam temperature within the turbine. These temperature variations can lead to additional stresses in the turbine components [3]. Therefore there are limits to the magnitude of the load changes for a given number of load cycles during a turbine lifetime in order to limit the thermal stresses. By reducing the furnace power variations, the thermal stresses are reduced and the turbine life is expected to increase.

2.5 SPLC Effect on Furnace Productivity

Due to the power dips caused by periods of high electrode resistance, the average furnace power is typically less than the setpoint power. By boosting the furnace power during the period of high electrode resistance, the flow of electrical energy to the furnace continues at the same rate and furnace productivity is improved with the SPLC. Figure 4 shows an increase in the average furnace power by about 4.4 MW.

SPLC effect on reducing the number of furnace trips, also affects furnace productivity by reducing the amount of time that is used to investigate and correct the causes of a trip, restart the furnace, and ramp up the power.

Additionally, power control via the SPLC offers the potential to lower electrode movements that otherwise are required in the attempt to control the furnace power in response to arcing fluctuations. As a result, the charge banks are less disturbed, the charge cover is maintained more consistently and the instances of charge cave-ins are reduced.

3. SPLC AT FALCONDO XSTRATA NICKEL

Falcondo Xstrata Nickel (Falcondo) operates a two-furnace ferronickel smelter with captive power generation in the Dominican Republic. Commissioned in 1971, Falcondo notably was the world's first smelter to include the sidewall copper cooling technology and higher voltage shielded arcs [5]. Starting in 1998, the furnaces moved toward very high voltage arcs and Falcondo's capacity to either sell or buy energy was reduced because of the disturbing effects of the smelter power fluctuations on the grid. Two SPLC units were fully commissioned in 2004 [6] and the utility subsequently granted Falcondo permission to reconnect their facility to the grid Figure 7 shows the thermal power station at Falcondo and Figure 8 shows the SPLC system installed at Falcondo.

Figure 7: Falcondo Power Station

Figure 8: Falcondo SPLC

Recordings of the furnace power fluctuations before and after commissioning of the Furnace 3 SPLC are shown in Figure 9. The 'before' data was recorded during the feasibility assessment of SPLC at Falcondo in 2000. The 'After' data was obtained after commissioning of the SPLC for Furnace 3. It is easy to see the improvement is the power fluctuations, the near elimination of furnace power upswings and the significant reduction in power downswings.

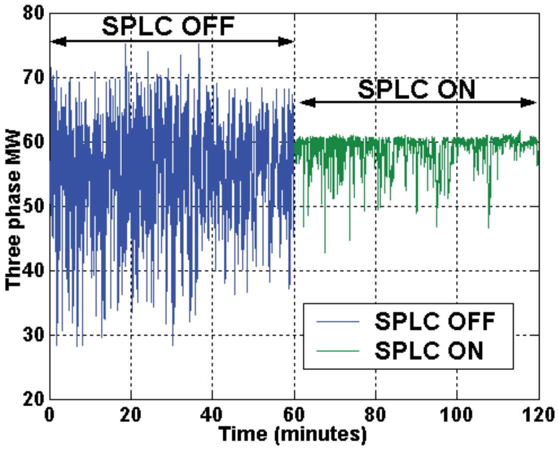

Figure 9: Measured power at Falcondo

The key measured observations attributed to the SPLC and the Hatch Electrode Regulator as identified in a benchmarking study [7] were:

- Utility permission to permanently reconnect to the grid, ability to buy power during generator maintenance with no reduction in production or sell excess power when required.
- An average increase in tapped metal throughput of 5%.
- A reduction in furnace trips by a factor of 10 to 1.
- 0.91% reduction in the oil to MWH (BBL/MWH) conversion.

4. RECENT DEVELOPMENTS IN SPLC DESIGN

The SPLC has also been installed on a three-electrode, 85 MW steel scrap melting furnace (Gerdau Whitby, Canada) which has been fully operational since 1997.

At the present time, there are two projects underway where one SPLC will be installed on a three-electrode 85 MW smelting furnace and another on a three-electrode 55 MW smelting furnace at another site.

The most recent evolution of Hatch's patented SPLC technology employs a water-cooled thyristor valve system, factory installed and tested in a prefabricated modular building. Following the factory integration testing, the prefabricated building is shipped with equipment in place. Site work is then limited to the installation of the modular building on a platform or foundation and making the electrical and cooling water connections and high voltage tie-in's outside the modular building. For P.T. Inco, SIEMENS Germany was selected as the equipment supplier for the SPLC project underway for the first of P.T. Inco's furnaces at their Indonesian nickel smelting plant [8]. A typical High Voltage SPLC modular building and reactor layout is shown in Figure 10.

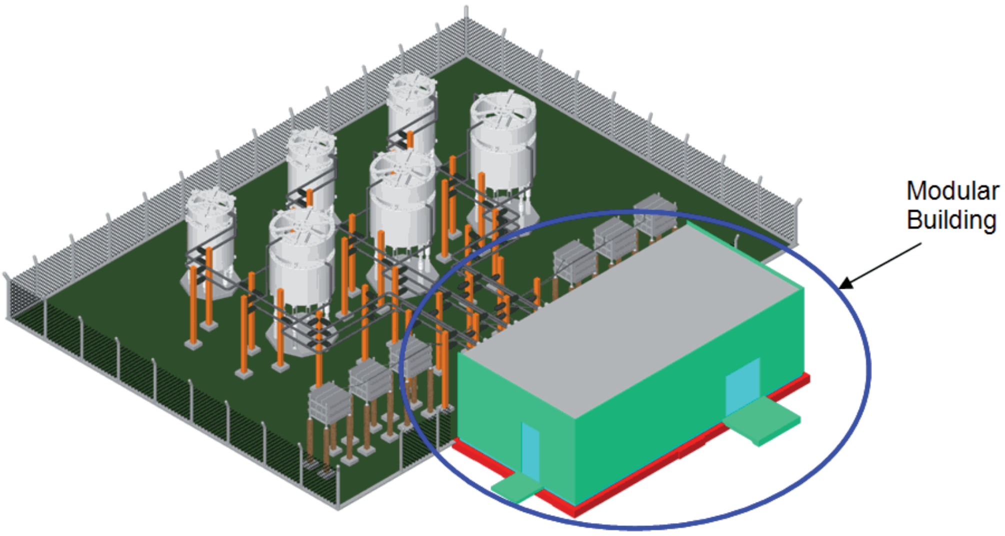

Figure 10: SPLC Equipment Arrangement

4.1 SPLC Control Advancements

In the design of the SPLC at Falcondo, the control objective was to stabilize power to each pair of electrodes and to preferentially clip the power peaks so that Falcondo could export and sell the remaining generation capacity to the power grid. This performance criterion dovetailed well with operating the SPLC within the existing furnace transformer ratings.

Utilizing recent developments in SPLC control and slightly larger MVA furnace transformers, a wider control range with essentially equal power peak clipping and power dip filling control is achievable. The simulated results are shown in Figure 11 for a recent three-electrode smelting furnace application.

The SPLC power control achieved in Figure 11 requires the precise coordination of a large quantity of control parameters. Furnace transformers utilize a tap changer to select a voltage tap to deliver the required power to the arcs at the required arc to bath power ratio. The electrodes, shown in Figure 1 and Figure 2, are mechanically raised and lowered by hydraulic cylinders, to control the arc length and thereby arc resistance. These parameters relate to the required arc to bath power ratio and the required arc lengths. The determination of these variables requires a unique combination of electrical and thermal equations as well as a balancing of time constants for the SPLC gating control and electrode column hydraulics, furnace transformer tap changing needs, and power station protection and control system settings. Careful consideration of all of these factors is required to avoid control oscillations while delivering flat line power and to ensure optimal operation of the power station. While a discussion of these equations is outside the scope of this paper, those familiar with this equipment will appreciate the inherent complexity of this task.

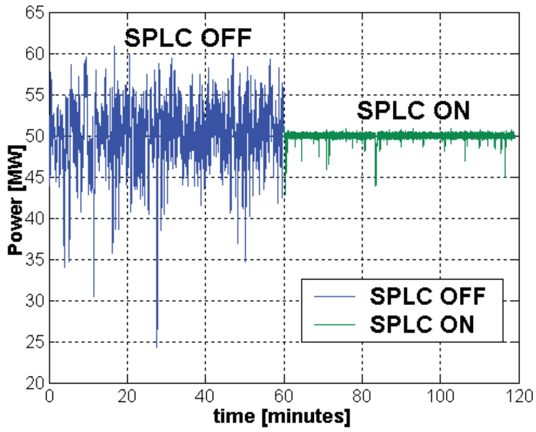

Figure 11: Simulated power for wider control range

5. COMPARISON OF HIGH VOLTAGE AND HIGH CURRENT SPLC

Thyristor valves have been an integral component of steel electric arc furnace [EAF] flicker control for more than 35 years. The Static VAR Compensator [SVC], a well known technology for steel arc furnace flicker control, employs high voltage thyristor valves and reactors connected in series [8]. The SVC is connected in parallel with the load and is typically located at the plant main substation. Thyristor valve stacks rated at 34.5 kV and 2500 A are standard in the industry. High current thyristor valves are traditionally employed in DC arc furnaces to rectify currents over 100 kA and are equally well proven.

Similar to SVCs, the SPLC can be applied on the high voltage side of the furnace transformer as in the cases described in Sections 3 and 4. Alternately, the SPLC can be applied on the low voltage side of the furnace transformer, in which case the thyristor valve equipment is not unlike those in high current rectifiers.

5.1 Electric Circuits

The electric circuits for High Voltage SPLC and High Current SPLC are shown in Figure 12 for a six-electrode furnace. The High Voltage SPLC uses a thyristor valve system with series connected high voltage thyristors. The High Current SPLC uses parallel connected thyristors rated for the required electrode currents, generally 15 kA to 40 kA for long arc operation at 35 MW to 90 MW. Similar configurations can be applied for three-electrode furnaces.

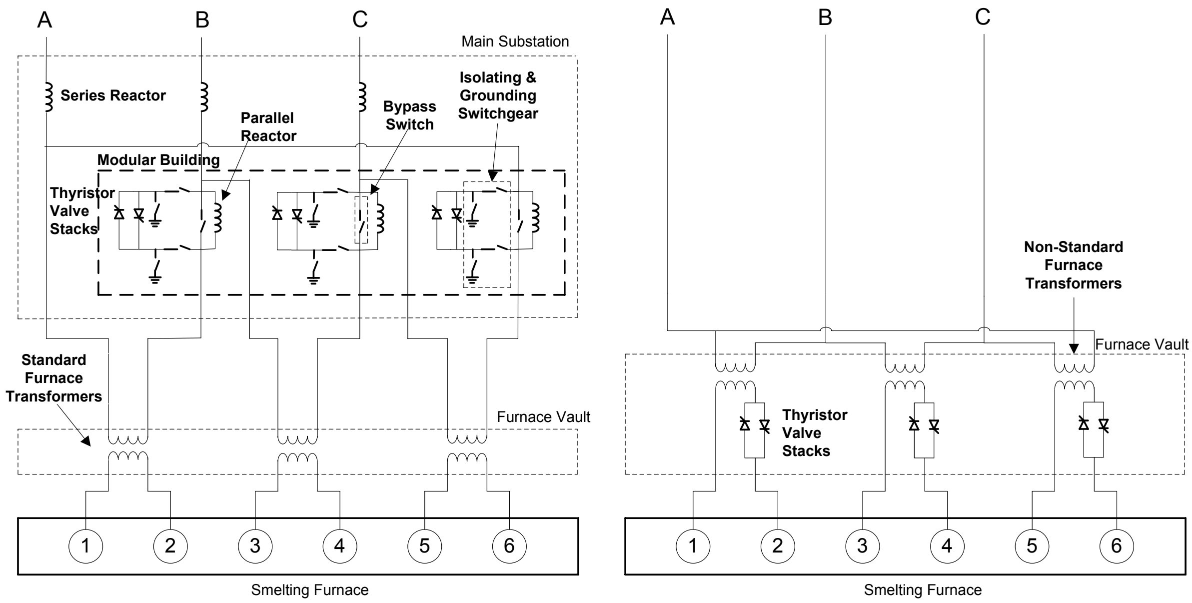

Figure 12: Electrical circuits for High Voltage SPLC and High Current SPLC on a six electrode furnace

5.2 Equipment Differences

The High Voltage SPLC incorporates standard substation switchgear to isolate and ground the thyristor valve for maintenance, and provides a bypass switch so that the furnace may continue to run during maintenance. These switches are shown in Figure 12, and are installed inside the Modular Building shown in Figure 10. The High Current SPLC does not include isolation and bypass switchgear due to the high cost, layout issues, and reliability issues surrounding multiple high kA switches or bus links.

The High Voltage SPLC requires three series reactors to protect the thyristor valve during a load side short circuit. These reactors are shown in Figure 10 and Figure 12. The High Current SPLC uses the furnace transformer to limit short circuit currents and does not require additional series reactance. However, the required furnace transformer reactance is typically not standard and may require a custom design.

The High Voltage SPLC also makes use of reactors in parallel to the thyristor valve. These reactors allow the current waveforms to be continuous without intervals within which currents are zero, thereby helping the arc stability that would be required for keeping long arcs. These reactors are not included in the High Current SPLC because of the high cost and layout issues associated with their application.

5.3 Brownfield Installation Differences

As the High Voltage SPLC is installed outdoors in spaces available in or around the main substation yard, all major components can be installed while the furnace is energized. The shutdown required to tie in, test, and cold commission the high voltage conductors is less than four days in duration. Since the thyristor valve and controls are factory assembled and factory tested, the hot commissioning time is less than 1 day.

The High Current SPLC is installed between the high current bus-work and the furnace transformer secondary bushings. The brown-field space available on the secondary side of furnace transformers is usually very limited. To install the High Current SPLC, the furnace transformer vault requires an extension of a few meters, and the furnace transformer must be moved away from the vault walls by several meters. The work to install a High Current SPLC typically requires approximately 20 weeks of shutdown time, including the civil, structural vault extension, 34.5 kV cabling splices, cooling water moves/extensions, high current bus work disconnect and extension.

5.4 Maintenance Differences

Smelting furnace operation is around the clock and, as such, unscheduled operational shutdowns are costly.

One unique feature of thyristors is that they fail to a short circuit. This feature enables redundancy to be included in High Voltage SPLC by adding one or more additional thyristors in a series string. In that way, any single failure enables the valve to continue operation until a scheduled maintenance shutdown. For a High Current SPLC, the thyristors are connected in parallel. In this situation, a thyristor failing to a short circuit cannot be made redundant in a parallel configuration, and therefore the system is to be shutdown when a failure occurs. In particular, an immediate shutdown is recommended to prevent operation with a high degree of unbalance.

The High Voltage SPLC maintenance, if required, can be done while the furnace is powered, through the bypass switchgear. Operation of switches to go into and out of bypass mode takes just a few minutes. The maintenance takes place inside a main substation building in a clean and air conditioned environment well suited for handling electronic equipment. The same maintenance environment is usual for those familiar with maintaining thyristor valves for SVCs on steel furnace systems. On the other hand the maintenance of the High Current SPLC requires a furnace shutdown and application of manually applied safety grounds. During maintenance the furnace cannot be powered and the furnace breaker must stay off.

5.5 Arc Performance Comparison of High Voltage and High Current SPLC Systems

Hatch utilized a 50 kW test furnace located at the University of Toronto for conducting measurements on both the High Voltage and High Current SPLC systems. The experimental set up was as in Figure 12, but on a single phase, two-electrode furnace. The furnace as shown in Figure 14 has two arcing electrodes complete with motor operated electrode masts, and melts scrap steel to a molten pool.

Long arc operation was recorded for both styles of SPLC systems (High Voltage and High Current). Waveform measurements were taken of the Electrode 1 to hearth voltage and the arc current. The measured waveforms for the High Voltage SPLC and High Current SPLC are shown in Figure 13 on the left and right, respectively. These tests were done with a fixed firing angle of approximately 115 degrees on each thyristor system.

The High Voltage SPLC current waveform shows that the arc current remains continuous with a long arc and has an acceptable harmonic content, which is not a concern for the furnace transformer or power system. In contrast, the High Current SPLC waveform shows that the current waveform is discontinuous and very high in harmonic content based on its departure from a sinusoidal shape. A continuous current waveform is very important to maintain a stable long arc such as required in shielded arc smelting.

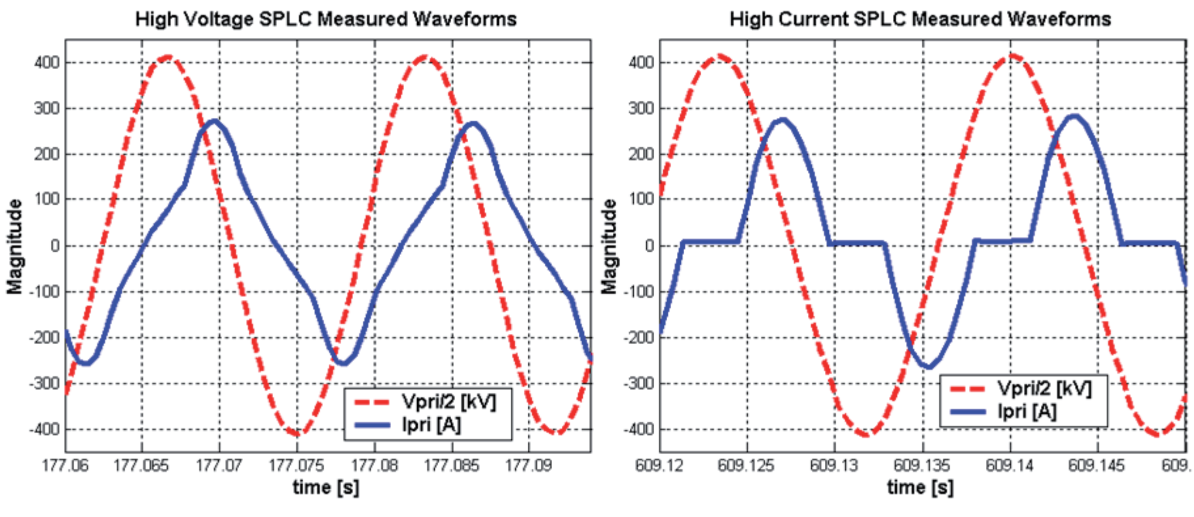

Figure 13: Measured waveforms for High Voltage SPLC and High Current SPLC

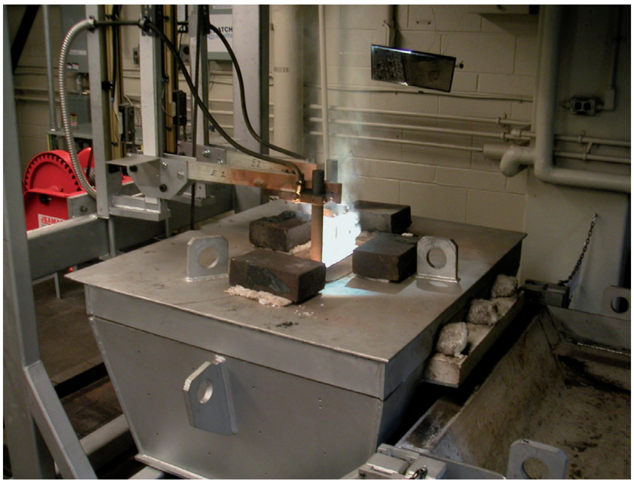

Figure 14: University of Toronto test furnace with SPLC

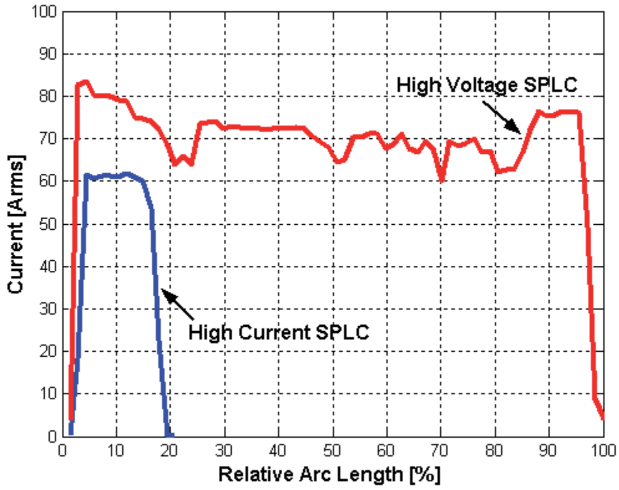

Figure 15: Achievable arc lengths for the test furnace with High Voltage and High Current SPLC systems

During the test, we observed that the High Current SPLC did not stabilize a long arc as well as the High Voltage SPLC system. In fact, the long arc operation with the High Current SPLC suffered frequent loss of arc where the electrodes needed to lower to touch the steel bath to re-ignite the arc. Figure 15 shows the achievable arc lengths for each of the SPLC systems. The maximum arc length that was achieved with the High Current SPLC was only 20% of the maximum arc length achieved with the High Voltage SPLC.

6. CONCLUSIONS

Shielded arc operation enables high power smelting furnaces to deliver higher productivity by focusing both the power and calcine feed into the middle of the furnace, thereby protecting the furnace walls. The SPLC is a technology to smooth out furnace power (MW) fluctuations using a continuously variable thyristor controlled reactor, as proven at Falcondo Xstrata Nickel. Without the need to increase the size of the power plant, the SPLC can increase the furnace average power by as much as 20% to enable commensurately increased production. The SPLC also improves the energy efficiency of the power generation equipment. The SPLC design is applicable to both three-electrode round furnaces and six-electrode rectangular furnaces. The modular nature of the latest High Voltage SPLC equipment design lowers installation cost in brown-field locations when compared to a High Current SPLC. The redundant design and ease of isolation of the High Voltage SPLC provides maintenance benefits. The High Voltage SPLC provides enhanced arc stabilization through primary current control resulting in a continuous current waveform.

7. ACKNOWLEDGEMENTS

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