ELECTRICAL ENERGY MANAGEMENT IN THE FERROALLOY BUSINESS

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ABSTRACT

Ferroalloy producers are large-scale users of electrical energy, which in many countries is in short supply and increasingly expensive. Preheating and/or pre-reduction using natural gas, recycled furnace gas or coal fines have lowered the specific use of electricity, but the high energy concentration necessary for most reduction processes can be achieved only by the use of high electric currents.

Most countries have insufficient electricity to supply the demands of industry and the domestic consumer, particularly during certain periods of the day and certain times of the year. The generation and distribution of electricity is a large-scale expensive business, which is financed and managed directly or indirectly by government bodies in most countries. Both economic and political imperatives determine how much electrical energy is made available to whom and at what price.

In South Africa demand is set to outstrip supply within the next few years, and the local supplier Eskom has moved from a traditional demand tariff pricing structure to a time-of-use tariff pricing so as to limit peak demand usage. This will mean a substantial increase in electricity cost to those users unable or unwilling to reduce consumption during peak periods.

The optimal use of the available electrical energy depends both on the process, the furnace size, the configuration and infrastructure of each plant and its cost structure. As the cost and availability of electricity is set to change dynamically, the management of the situation becomes a real time control and optimisation problem.

This paper discusses some the process and operational constraints associated with low- or no-load conditions and how to manage the situation. Electrode management will be one of the key issues.

1. INTRODUCTION

Energy management is of major concern for both developing and developed economies. Energy sources are scarce, and expensive to develop and exploit. Although the supply and distribution of electrical energy has been essential for growth of most economies, the incremental cost of providing additional capacity to service high demand periods has become prohibitive. Governments and utilities have developed creative strategies to manage the supply of available electricity based on socio-political-economic constraints. Thus non-essential industries could expect to be limited or shut down for certain times of the day or certain months of the year. Although this strategy works on average, it is not optimal as load fluctuations are random to a degree and vary according to conditions.

Traditionally, ferroalloy producers have been steady load users who cut back on production during peak demand periods. As the demand for electricity is set to outstrip supply within the next few years in South Africa, the local supplier Eskom has moved from a traditional demand tariff pricing structure to time-of-use (TOU) tariff pricing to limit peak demand usage. Once the infrastructure is in place, the time periods are likely to be more dynamic and the cost structure more demand-based. The present regulation structure is supplemented by an energy reserve market, which consists of large users who are in a position to shed load on short notice (seconds or minutes) in exchange for more favourable rates. As the cost differential between peak high-demand periods and off-peak low-demand periods becomes progressively greater, ferroalloy producers need to make techno-economic decisions on how best to manage the situation. Variables such as furnace conditions, production targets, contract prices and exchange rates will affect the decision of which furnaces to cut back, by how much, and for how long.

This paper will examine control structures and options available to ferroalloy producers depending on the process and plant infrastructure.

2. ELECTRICITY SUPPLY STRUCTURES AND TARIFFS

Traditionally, industries required power during weekdays, domestic consumers required power in the evening, while production plants required power 24 hours a day for the whole week. In contrast, the electricity supplier would like to see a steady high load. This usage pattern has not changed much except that the demand keeps increasing, which has necessitated restricting consumption for specific periods either by decree or price differential. Hence ferroalloy producers will have to change from steady load users to variable load users. Ultimately, users may have to bid for power during peak demand periods.

2.1 Maximum Demand Tariff Structures

Depending on the contract, the customer would elect to pay for the electricity consumed plus a demand charge for each kVA of the maximum consumed during the month or only during peak periods within the month. The demand charge was of a similar magnitude to the consumption charge. Hence it was in the users' interests to maintain a steady high load to make best use of the demand charge being paid. Except where there were a number of furnaces that could be regulated automatically, load factors were normally in the low nineties. Control of the plant load was often only based on an individual furnace to limit or shed load according to conditions. This could be managed by a PLC, an intelligent instrument or manually.

2.2 Time of Use Tariff Structures

Increasing demand necessitated restricting usage during periods when generating capacity was not readily available. Thus three pricing categories were introduced – high-, standard-, and low-demand periods, which are adjusted on a seasonal basis. Thus there are economic incentives for the consumer to manage total plant power usage based on criteria other than maximum demand, which now is only a small fraction of the total monthly bill. Currently, the high demand periods are no longer than three hours, which is fortunate for ferroalloy producers as discussed subsequently. A summary of the main components of the 2003 tariff structure as determined by Eskom in South Africa is summarised below. Full details of all the charges can be obtained from the Eskom website[1].

2.2.1 Defined time periods

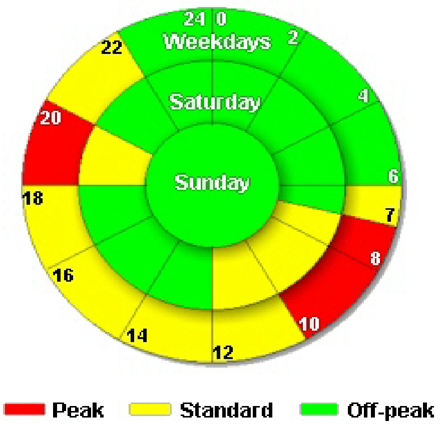


Figure 1. Eskom Time-of-Use Periods.

2.2.2 Demand charge

A charge payable for each *kW* of the *maximum chargeable demand* supplied during the month measured over *30 minutes integrating periods*, payable in peak or standard periods on weekdays and Saturdays. No demand charge is applicable during the off-peak periods. This charge is now a much smaller fraction of the total charge than the night-save tariffs.

2.2.3 Active energy charge

A time and seasonally differentiated charge linked to each unit of energy (kWh) consumed.

Table 1. Eskom Active Energy Charge Rates (January 2003).

High-demand season (June – August)		**Low-demand season (September – May)**
56,35c/kWh	**Peak**	**17,26c/kWh**
16,26c/kWh	**Standard**	**11,42c/kWh**
9,64c/kWh	**Off-peak**	**8,62c/kWh**

2.3 Real-Time Pricing

The logical extension of the fixed time of use structure would be a dynamic time-of-use structure with associated dynamic pricing structure[2]. A more sophisticated communication/management structure will need to be in place to manage such a system, and some pilot studies are in place. Whatever the eventual structure is, the end user will need to make decisions based on a number of criteria in a short time. Hence, more adaptive, configurable software control structures will need to be in place on most plants. Some options will be discussed in subsequent sections.

Table 2. Typical ferroalloy process characteristics [3].

Process	**Temperature, °C**	**MWh/t**	**Selling Price US$/t**
Ferromanganese	1500	2.5	516.2
Silicomanganese	1600	3.8	550.7
Ferrochromium	1800	3.8	378.0
Ferrosilicon	1900	9	759.9

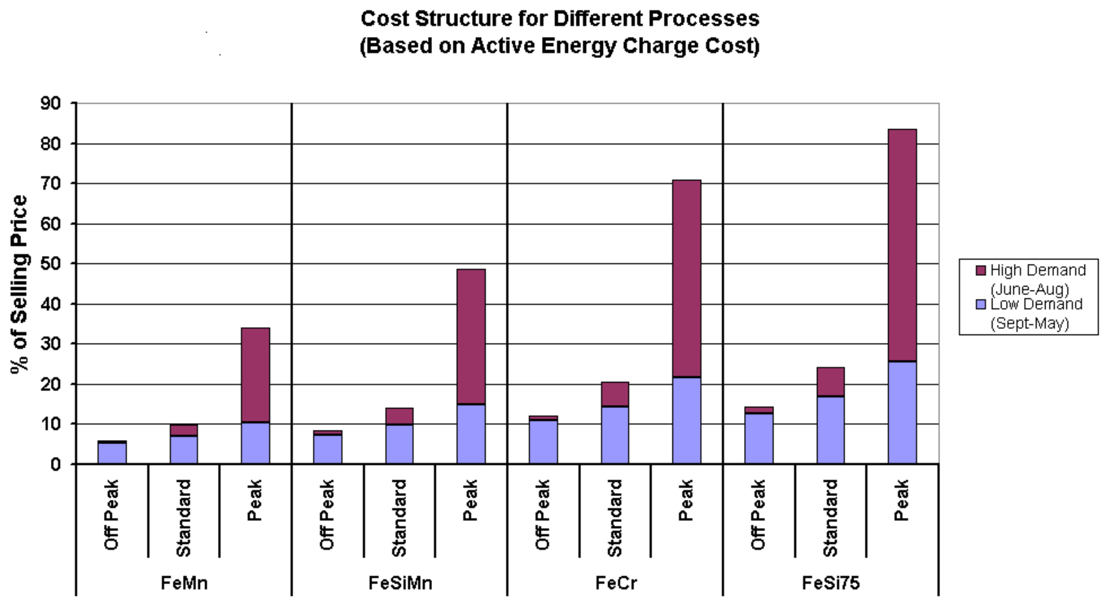


Figure 2. Cost structure for different ferroalloy processes.

2.4 Economic Implications

If the producer were to operate continuously during the high and low demand seasons, the average cost of electricity would almost double during the high season. However, the difference between the high season peak and the low season off-peak is very much greater than that. As a percentage of the alloy selling price, the cost of electricity varies with the seasonal charges, the process energy consumption, and the exchange rate (as prices are fixed in United States dollars). Assuming an approximate energy consumption and selling price (Table 2), one can draw a series of graphs showing how the cost structure varies with the electricity price for the different time-of-use tariffs (Figure 2). The premium paid during peak periods is quite clear.

3. FERROALLOY FURNACES

The trend in the ferroalloy industry is to build increasingly larger, more efficient units to optimise the considerable capital investment required and reduce running costs. These units are usually closed in order to utilise the energy in the off-gas both directly and indirectly. Hence they require preconditioned feed materials of uniform size and minimal fines. Large furnaces use large electrodes, which are subject to considerable thermal and mechanical stress. These stresses increase considerably during periods of rapid heating and cooling. Small furnaces use smaller electrodes, which can handle more stress, and the furnaces are able to process a greater variety of feed materials. More than any other factor, the size of the electrodes will dictate how long a furnace may be switched off and subsequently how long it will take to bring that furnace up to full load without risking an electrode break. The options for the producer are either to lower the power during the peak periods or to switch off. These options are considered for the different processes.

3.1 Ferroalloy Processes

Table 2 lists the common ferroalloy processes and the different temperature and energy requirements of these processes. Temperature determines the reaction rates and the equilibrium products of the process reactions. Different feed materials may require different temperatures or operating conditions. Most ferroalloy processes can be classified either in terms of operating resistances or currents for specific power levels[3][4]. Electrode penetration and arcing will determine the energy densities under the electrodes necessary for the particular process. At lower power levels, the electrode resistances should be decreased to maintain current densities necessary to achieve the temperatures required for the reduction reactions, for baking electrodes, and to limit the inflow of material into the reaction zone. By maintaining the energy balance, idling these furnaces should not be a problem.

3.1.1 (Ferro)silicon processes

Slagless (ferro)silicon processes, although having the highest temperature and energy requirements, are predominantly batch processes. The reaction zone expands progressively outwards until it collapses and fresh feed material falls or is stoked in. (Ferro)silicon furnaces should operate at full power or close to the maximum current limit to ensure high process temperatures. There will be a power level below which the temperatures will drop and the silicon reactions will not go to completion. Switching off the furnaces becomes a better option below this minimum power level.

3.1.2 Chromium processes

The chromium process depends very much on the type and preconditioning of the feed materials. Processing fine feed material appears to require high temperatures and powers to ensure the even flow of material to prevent sintering or hanging of the feed materials. High temperatures are also required for smooth tapping conditions. Preconditioned materials are easier to manage, but it is important that the metal is not allowed to solidify within the furnace. Therefore idling the furnace is probably the best option.

3.1.3 Manganese processes

In general the manganese process requires lower temperatures to minimise manganese losses, and longer residence times to optimise preheating/pre-reduction and equilibrium reactions. Hence idling these furnaces may even be beneficial as the reactions have more time to reach completion. Lower resistances will be necessary to reduce the flow of unreduced material into the reaction zone.

3.2 Global Experiences

Until recent times, most ferroalloy plants in South Africa elected to manage their load only during peak periods. The user would be charged for the contracted MVA limit, or the peak value over the month if greater, whether or not the user was able to maintain the load. An intelligent meter or PLC normally managed load shedding with pre-configured shed settings. A load factor around 0.9 was common and only on those plants with a number of furnaces was some form of economic optimisation possible[5].

In colder countries where there was a shortage of electrical energy during the winter months, furnaces were shut out for months at a time depending on the severity of the season. While this is simple to manage and is beneficial for maintenance, it is not a good economic solution during favourable market conditions.

In most regions of Brazil, the standard practice has been to switch off all furnaces for the three peak hours each evening. The start-up and shutdown times were short, and the problems experienced were minimal and could be managed. The Brazilian furnaces are mostly smaller (ferro)silicon furnaces, with some larger manganese furnaces.

Three hours is the optimal time for maintenance shutdowns on most plants, since shutdowns longer than these require an electrode reheating schedule to be followed. If furnaces will either be shut down or run at reduced power for extended periods, more sophisticated software/hardware tools will be required to manage the “state” of the electrodes. These tools will need to reflect the position of the baking zone, paste levels and temperatures, and will need to consider slipping and consumption rates.

4. ELECTRODE MANAGEMENT

Economic constraints and the large diameter of the electrodes required for high currents dictate that most ferroalloy furnaces use self-baking Soderberg electrodes. Electrode current will determine the baking rate, temperature distribution within the electrode, and the rate of erosion at the tip. Most of the current leaves from the tip of the electrode, either in the form of an arc or directly to a carbon/slag layer. Both mechanisms ensure a highly variable rate of electrode consumption depending on temperature, carbon concentration, thermal and mechanical stress. These stresses increase each time the electrode is subjected to cooling and heating cycles. Thus severe tip breaks often occur hours or days after a shut-down period. A ferroalloy producer will not want to subject his furnace to variable load fluctuations, but economic criteria will dictate otherwise. Some of the factors that will influence how much and for how long the furnace power may be reduced are briefly discussed below.

4.1 Temperature Distribution

The temperature distribution within an electrode will depend primarily on the current and electrode diameter, but boundary conditions, particularly at the water-cooled contact clamps, will have a considerable effect. Below the contact clamps, the current is carried mainly by the steel casing, the melting temperature of which will depend on carbide formation. The steel casing must also carry the full weight of the electrode; hence it is critical that the Soderberg paste be completely baked well before the casing melts. The baking zone is between the 450 and 500°C isotherms; the iron carbide (casing) melting temperature is around 1200°C.

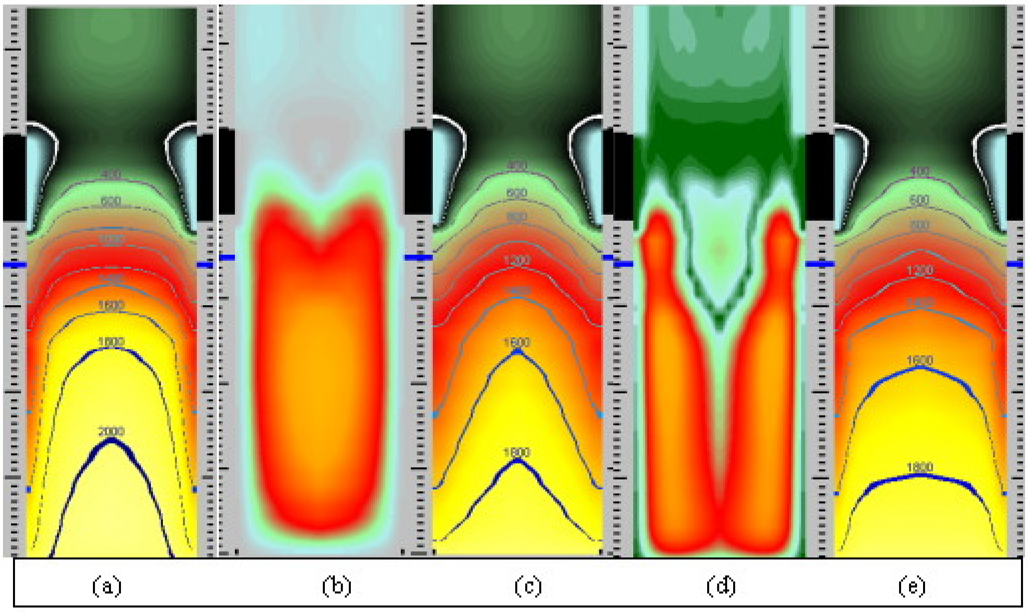
The introduction of time-of-use tariffs, and the likelihood of dynamic time-of-use structures in future, indicates that increasing levels of furnace load fluctuation can be expected in future. These may be in the form of furnace outages, furnace idling, or tracking of a dynamic power setpoint. These load fluctuations will inevitably result in large electrode current and power fluctuations, resulting in increased electrode thermal stresses.

The advent of powerful desktop computers has facilitated the development of real-time electrode temperature profile simulators.

These dynamic on-line simulators can provide a number of powerful electrode management features to handle the variable current and power conditions:

- Provide visual indication of stress levels
- Warn the operators if stresses reach danger levels
- Display the electrode baking and case melting isotherms
- Provide diagnostic capabilities such as play-back and fast-forward scenarios

Figure 3 shows comparisons between the temperature distribution and rates of temperature change developed in a 2-meter diameter electrode.



(a) (b) (c) (d) (e)

Figure 3. Simulations of temperature distributions and rates of change.

Figure 3a shows the steady state simulation of the temperature distribution of an electrode that has a constant current of 120 kA passing through it. Figure 3b shows the simulated temperature rate of change (°C/s) 3 hours after the furnace has been switched off. This figure gives an indication of the rate of cooling of the electrode. The light green coloured area (white in the black and white picture) represents the region of highest temperature rate of change. Figure 3c shows the corresponding temperature distribution within this electrode. After the furnace is restarted and 120 kA current is once again passed through the electrode, the rate of temperature change after 1 hour is shown in figure 3d. One can see that the amount of white/light green area has increased which implies that there is an increase in the thermal gradient. Excessive thermal gradients need to be avoided since these may lead to vertical electrode cracks and tip breakages. One can minimise thermal stresses by idling at only slightly lower currents, but much lower resistances to reduce the load. An accurate estimation of electrode resistance is essential to avoid overheating the hearth. Figure 3e shows the corresponding temperature distribution.

4.2 Electrode Slipping and Consumption

Ideally, the slipping rate of an electrode should equal the consumption rate to maintain electrode length and penetration. For a number of reasons, these rates are seldom equal, and the electrode will either increase or decrease in length until corrective action is taken. Maintaining the required electrode length will be even more difficult with the fluctuating loads imposed by demand schedules.

Since the baking rate is closely associated with the electrode current, and electrode consumption with the current and power, fixed slipping schedules will no longer be effective for maintaining electrode length and ensuring adequate baking of the electrodes as load fluctuations are imposed by demand schedules. As an illustration, consider an example of a furnace that is idled during peak hours. As indicated previously, in order to maintain the current density necessary for achieving the temperatures required for the reduction reactions during idling, the electrodes have to be lowered, reducing their tip-to-bath resistances.

The result is a situation where the electrodes have currents of similar magnitude to normal operation but powers that are significantly less. Since the current is similar to normal operation, the rate at which the electrode bakes will be similar, but the consumption of the electrode is likely to be much less than during normal operation. These variable conditions are extremely difficult for furnace operators to manage. The actual electrode current, power, and temperatures have to be continuously monitored to enable informed decisions to be taken regarding the control of slipping rates.

On large closed furnaces, the situation is even more difficult to manage. As an electrode break can have disastrous consequences, most large modern furnaces limit electrode movement to reduce mechanical stresses. Hence, the furnaces are balanced electrically only to a degree by differential transformer tapping, and fluctuations in current and power are inevitable. Imposing fluctuating loads from demand schedules on these furnaces will further aggravate the situation.

The first step towards managing the situation is obtaining a reliable measurement of slip. This is to detect and account for under- and over-slipping, and uncontrolled slipping through the slip rings. Logging the frequency and lengths of the slips is also important to ensure that slipping schedules are being carried out correctly and not merely accelerated to catch up towards the end of a shift. The second step is to accurately integrate current and power inputs which, coupled to electrode temperature profiles, can set the slipping schedules dynamically.

4.3 Electrode Baking and Recovery

In the event of an electrode break, typically a long slip needs to be taken to re-establish electrode penetration. The portion of unbaked electrode within the casing needs to be baked before operating at full current again. The importance of baking electrodes properly, particularly those for large closed furnaces, has been emphasised already. There are well-defined baking schedules according to slip lengths developed by paste suppliers and modified according to specific furnace conditions such as casing design. The challenge lies in following the applicable baking schedule.

Operators often find themselves in the unfortunate situation where a second and maybe third electrode breaks while the first electrode is partly through its baking schedule. This will typically happen after periods of frequent or prolonged furnace outages. The more recently broken electrode(s) then restrict the baking current of the original electrode. A variable load setpoint from a maximum demand controller and other aspects, such as unstable furnace conditions, can also adversely affect the operators' ability to follow the baking schedule correctly. Dynamic compensation for the deviation from the fixed baking schedule needs to be made in order to achieve acceptable baking of the electrode in these situations. Advanced computer-based baking programs are able to monitor the deviation of the baking current from the required value and dynamically adjust the schedule to compensate, and hence ensure correct baking of the electrode.

With the potential increase in furnace shutdowns and restarts introduced by electricity supply restrictions, the use of recovery schedules to limit the thermal stresses experienced by electrodes will become more important. Once an electrode has been baked, stress-relieving cracks are likely to form on cooling. When the electrode is reheated, its baked strength is lower and hence it should be subjected to low stress levels if possible. The larger electrodes are more at risk, as not only do they heat up more in the centre, but current distribution and hence heat generation is more to the outside, creating high stress regions. Any additional stoppages will exacerbate the problem.

4.4 Electrode Management Structures

Any form of on-line electrical energy control system will need to take the requirements of Soderberg electrode management into consideration either directly or indirectly. The power and integrity of networked computer systems has increased dramatically over the past few years, and dynamic simulation systems can be linked to real-time control systems to provide powerful decision-making tools. Previously, such capability was available only in high-end workstations. The following section describes some of the control structures.

5. ENERGY MANAGEMENT

The trend away from maximum-demand-based electricity tariff structures towards TOU-based structures complicates the issue of electrical energy management. With the TOU tariffs currently in place in South Africa, there is the potential for having three different electrical energy usage levels, one for each of the three defined time periods. During weekdays, this means up to six changes in the electrical energy usage targets per day. In addition, since the majority of the charge is based on actual usage of electrical energy, unlike with the demand tariffs where a significant portion of the charge was based on a maximum for the month, it is likely that the energy usage targets for the defined time periods will be changed frequently during the month for logistical and production reasons. Therefore a flexible, customisable system to control and manage the use of electrical energy is essential.

The unpredictable variations in the furnace operating conditions further complicate the management of the electrical energy usage of a ferroalloy plant. Electrode breaks, electrode length problems, metallurgical imbalances, and tapping problems are some of the unforeseeable issues that can cause low loads or high load imbalances. These conditions in turn affect the ability of a furnace to maintain, increase or decrease power usage, as may be specified by a centralised electrical energy control system. It is therefore vital that the electrical energy management system be able to assess a particular furnace's ability to vary its power usage in order to allocate load effectively. Effective electrical energy management systems should also take foreseeable conditions, such as the position of the furnace in the tapping cycle, into account when allocating power.

Daily electrical energy targets for the plant will depend on economic and production criteria. These criteria may vary during the month depending on actual production. A simple predictive economic model will provide these daily targets subject to fixed furnace constraints, such as primary current limitations or secondary voltage range, and variable constraints such as electrode length or maintenance problems.

5.1 Hardware

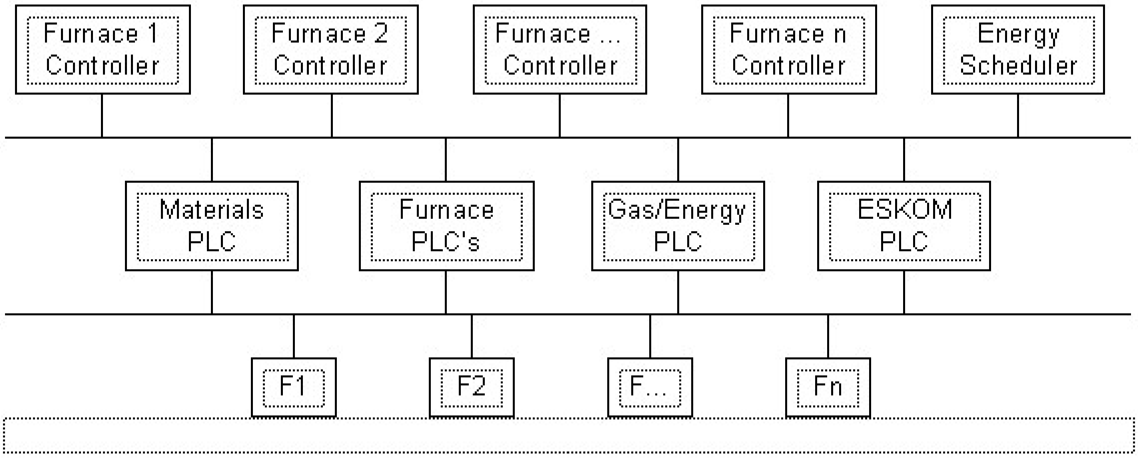


Figure 4. Automation Networking Structure.

The most likely structure will consist of a number of PC controllers networked to the plant PLC's, which will control the furnaces, raw materials section and gas cleaning/recycling. The Eskom PLC will receive regulation criteria from the national control centres. The energy scheduler will need to set limits based on Eskom, economic and furnace criteria.

5.2 Software

Microsoft Windows tends to be the default operating system for the control platforms, for reasons of ease of configuration, networking capability, security and cost. There are any number of PLC and independent SCADA systems available for monitoring, logging and control. These can be linked to the plant intranet system for management purposes. For system integrity, the plant control network should remain independent of the plant intranet system.

The success of OPC (OLE for Process Control) has paved the way for the large-scale utilisation of the computing power of desktop computers for advanced process control. OPC provides a hardware independent means of communication between control PCs and plant automation PLCs. Typically, PLC vendors will provide an OPC server application capable of communicating across their proprietary networks to their PLCs. OPC client applications can then communicate with the PLCs via the standard OPC client-server interface without concern for the underlying communications mediums and protocols. Together with the increased ease of integration, OPC has also improved the reliability of communications in this way since only the PLC vendor, who has an intimate knowledge of their specific communications protocols and mechanisms, is required to develop communications drivers for their networks.

6. CONCLUSIONS

As the demand for electricity exceeds generating capacity, the worldwide trend has been towards limiting usage during peak demand periods or charging a premium price. Ferroalloy producers will have increasing economic incentive to restrict their production during these periods. There are both process and maintenance constraints on high levels of load-shedding, but the greatest restriction will be the ability of the Soderberg electrodes to handle increasing stress levels. The inevitable dynamic nature of peak restriction periods will require networked configurable control structures that can monitor and model all the relevant processes to manage and optimise production and profits.

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