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Open Loop Response Characterisation of an Aluminium Smelting Plant for Short Time Interval Feeding

A. P. Agalgaonkar, K. M. Muttaqi, *Senior Member, IEEE*, and S. Perera, *Member, IEEE*

Abstract--An Aluminium smelter is one of the peculiar loads, which typically represents a series of electrolytic cells supplied by a multipulse rectifier system. From the perspective of modelling a smelting plant for load modelling purposes, the multipulse configurations and its connection to HV networks and control aspects of load current must be considered. This paper presents the results of preliminary simulation work carried out covering the open loop behaviour of a smelter load under some varying system conditions. A typical smelting plant with a twelve pulse rectifier system has been modelled in PSCAD®/EMTDC®. The plant is connected to the AC network through a 220 kV/110 kV transformer with tap changing facilities to maintain the DC voltage. The saturable reactors are also included on AC side in order to control the load current of the smelter. Investigations have been carried out to characterise the behaviour of the smelter load under varying feeding conditions and determine the voltage and frequency dependency of the smelter load under small disturbances.

Index Terms--AC-DC power conversion, Inductors, Load modelling, Metals industry, Rectifiers, Time domain analysis

I. INTRODUCTION

THE importance of load modelling has been very well acknowledged in the literature. The voltage dependency of real and reactive power loads from stability perspective has been addressed in 1945 by Crary [1]. The basic load modelling aspects and the need for improved load representation have been discussed in [2], [3]. It also highlights the static load characteristics in terms of voltage and frequency dependency for various loads. Some of the practical aspects of load modelling have been addressed by EPRI [4]. The exhaustive bibliography (till year 1994) on load models for power flow and dynamic performance simulation is available in [5]. It is evident that the representation of peculiar loads such as aluminium smelter, arc furnace, and

paper mill is a challenging task and needs to be dealt with thoroughly. The intricacies involved in the modelling of various physical processes associated with each load further complicate the load behaviour under varying system conditions.

The aluminium smelting industry is one of the energy intensive industries. The molten aluminium is typically produced directly from alumina in reduction plants or smelters by the use of electrometallurgical process [6]. The development and validation of a nonlinear model to represent the electrical demand behaviour in a typical smelting plant is discussed in [7]. The possibility for improving the energy efficiency and exploring various demand management possibilities is also discussed. The smelting plant is normally supplied through diode rectifier systems with multi-pulse configurations [8]. The multi-pulse configuration is an effective way to eliminate characteristic low order current harmonics. The detailed investigation justifying the requirements for power factor correction and mitigation of harmonic resonant conditions at the substation supplying a sole smelting load is discussed in [9]. Authors in [6] discuss the structure and design of harmonic filters in order to address the power quality problems arising from the 12-pulse rectifier system in the ETI Aluminum Works, Turkey.

The transient stability studies associated with the aluminium production plant are elaborated in [10]. It also highlights the development of electrolytic process load model based on different tests and simulations. Moreover, the statistical behaviour of the plant load variations is examined for estimating the spinning reserve in the system. An improved rectifier load model including the dynamics of DC load in case of a typical smelter application is proposed in [11]. Moreover, the effect of three different rectifier load models on transient stability is analysed using a sequential and unified algorithm.

This paper mainly focuses on the time domain simulation studies related to the voltage and frequency dependency of the aluminium smelter under varying load (feed) conditions. PSCAD®/EMTDC® is used as a software tool for analysing the response characteristics of a smelter plant with short time interval feeding. The paper is organised as follows: Section II illustrates the multi-pulse rectifier system. Section III elaborates aluminium smelter type load. Section IV discusses

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short time interval feeding scenario. The smelting plant and its operation is described in Section V and Section VI presents the simulation results obtained under varying system conditions. Section VII concludes the important outcomes of the paper.

II. MULTI-PULSE RECTIFIER SYSTEM

Large rectifier loads such as a smelter usually consist of a number of series and parallel connected diode/thyristor bridges. In such cases, the low order harmonics can be eliminated by using multi-pulse configuration. Normally, the phase shifting transformers with appropriate phase shift are used to achieve 96 or 192 pulse operation [12]. It ensures minimum distortion of the supply voltage. The diagrammatic representation of a multi-pulse configuration is shown in Fig. 1.

Fig. 1. Multi-pulse rectifier system

For a typical aluminium smelter consisting of a diode bridge rectifier scheme, tap changer and saturable reactors are commonly used as part of current control technique [11]. The voltage controlled saturable reactor has power winding (P) in series with the AC supply and control winding (C) supplied by a separate DC source. The rectifier output voltage (and thereby the DC current) changes in accordance with the change in control current. The relationship between control current and output voltage can be represented in terms of a control characteristic for a specific reactor [13]. Moreover, the tap changer operates depending on the upper and lower limit of a control current. Since the smelter current set-point is normally fixed, saturable reactors are used for fine control and tap changers for course control to operate continuously in a closed loop mode in order to achieve automatic current control. This paper highlights a twelve pulse rectifier system as a representative of a multi-pulse configuration.

A. Twelve-Pulse Rectifier

Single phase diode rectifiers typically demand for large transformer rating for a given DC power. Hence, three-phase

or poly-phase rectifiers are preferred in case if the power requirement is above 15 kW [14]. A typical 12 pulse uncontrolled rectifier circuit is shown in Fig. 2. It consists of two six pulse groups fed from two three-phase transformers, which are connected in parallel with their fundamental voltage equal and phase shifted by 30 degrees. The bridge rectifiers are connected in parallel on the DC side. The bridge rectifiers can be connected in series or in parallel depending upon particular application. The parallel connected bridge rectifiers are normally used for high output current applications while the series connected bridge rectifiers are commonly used for high output voltage applications [14].

The combined output voltage for 12 pulse configuration will have 12 times the ripple frequency as that of mains. Moreover, the ripple of the output voltage will be less than that of the individual bridge rectifier [14].

Fig. 2. Twelve pulse rectifier system

In Fig. 2, the peak voltage for delta connected secondary (E_m) is the same as that of the peak line-line voltage for star connected secondary. Since there is a phase displacement of 30° between the two secondaries, the peak voltage across the load can be given as [14]:

$$V_{peak} = E_m \cdot \cos\left(\frac{\pi}{12}\right) = 0.96592E_m \quad (1)$$

The average value of the output DC voltage can be given as:

$$V_{dc} = \frac{12}{2\pi} \int_{5\pi/12}^{7\pi/12} V_{peak} \cdot \sin\phi \cdot d\phi = 0.98862V_{peak} \quad (2)$$

The rms value of the output voltage can be obtained as

$$V_{rms} = 0.98867V_{peak} \quad (3)$$

The inductor-input or capacitor-input filters are normally used on the DC side in order to smooth out the DC output voltage. The typical application of inductor-input DC filter is shown in Fig. 2. The smoothing reactor (L_s) can reduce the output ripple by the following factor [14]:

$$\frac{V_{load}}{V_{rms}} = \frac{R}{\sqrt{R^2 + (2\pi f_p L_s)^2}} \quad (4)$$

where, V_{load} is the voltage across the resistive load 'R' and f_{rp} is the ripple frequency.

It is expected that the rectifier switching action should provide a constant, ripple free, dc output to the load. The resulting ac side current is a non-sinusoidal step like waveform. The input power taken from the ac side will be the output real power plus real power losses and reactive power required to produce the step like waveform. This reactive power normally gets dissipated by producing higher order harmonics, which are transmitted back into the ac system. Thus, rectifiers are typically labelled as harmonic generators and non linear power system loads [15].

For a twelve pulse rectifier system of Fig. 2, the resultant AC side current (I_a) is given by the sum of the two Fourier series of the star-star and delta-star transformers [16], i.e.

$$I_a = \frac{4 \cdot \sqrt{3}}{\pi} \cdot I_d \left(\cos \omega t - \frac{1}{11} \cos 11 \omega t + \frac{1}{13} \cos 13 \omega t - \frac{1}{23} \cos 23 \omega t + \dots \right) \quad (5)$$

where, I_d is diode current. The above expression contains harmonics of the order of 11th, 13th, 23rd, 25th, etc. The idealised harmonic response for a rectifier can be given by the generalised equation [15]:

$$h = kq \pm 1 \quad (6)$$

where, h is the harmonic order, k is an integer and q is the pulse number of the rectifier. Thus, the harmonic order will be one lower and one higher around multiples of the pulse number. The aluminium smelter type load prefers multi-pulse configuration in order to minimise supply side distortions.

III. ALUMINIUM SMELTER TYPE LOAD

The aluminium production process (typically Hall-Heroult process), can be subdivided into four major process areas namely: anode area, rodding area, potrooms, and ingot mill. In the anode area, the raw materials are taken into the plant and the anodes are manufactured. The rodding area has two main activities. The first is to attach a rod to the baked anode in order to suspend it in the pot. The second activity is to remove the remains of the baked anode. The potrooms contain reduction cells (pot), which contain anodes, cathodes, and bath (liquid electrolyte). The molten aluminium from the potrooms will be sent through to ingot mill, which further cast it into ingots [17]. The simple flow sheet of the aluminium smelting process is shown in Fig. 3.

The process control in case of an aluminium smelter is one of the complex problems due to the interrelationships between the variables such as alumina concentration, cell temperature, inter-electrode spacing, and cell voltage [18]. Most of the process control systems rely heavily on the measurements of cell voltage, since it is very difficult to sense the cell temperature as well as alumina concentration. The rate of change in voltage is another important aspect. Typically anode effect may lead to voltage abnormality, wherein there will be a fluctuation and sudden increase in the cell voltage due to the depletion of alumina in an electrolyte. The common control measures could be the variation of inter-electrode

spacing, breaking the crust of the cell and feeding it with alumina, or buzzing/squelching the anodes. Buzzing or squelching is raising and lowering the anode superstructure electro-mechanically in a repetitive manner.

Fig. 3. Simple flow sheet of the smelting process

Normally, the DC load in case of a smelter can be represented in terms of electrolytic cells. Each cell can be characterised by cell voltage, cell counter voltage, and cell resistance. This DC load may exhibit dynamic characteristics with significant time constant [11]. In this paper, it is assumed that all electrolytic cells are connected in series with each other and they can be modelled by using equivalent cell resistance (R) and equivalent cell counter voltage (back emf E_b) [11]. Thus, the DC current (I_{dc}) and DC side power (P_{dc}) can be represented as:

$$I_{dc} = \frac{V_{load} - E_b}{R} \quad (7)$$

$$P_{dc} = V_d \cdot I_d \quad (8)$$

where, V_{load} is the DC voltage across the load.

There are different process control strategies depending upon the specific requirements associated with the frequency of alumina feeding such as long interval feeding (for delayed feeding) and short time interval feeding (for frequent feeding). This paper highlights short time interval feeding with an extreme scenario of continuous variation in the cell resistance.

IV. SHORT TIME INTERVAL FEEDING

The short time interval feeding is more relevant to the point feeder systems, wherein the alumina is discharged in a small zone within the cell [18]. In such case, the cell resistance depends on the alumina feeding rate, the consumption rate, and the Anode to Cathode distance (ACD). Typically, the cell resistance remains constant with respect to time for constant ACD but, the resistance changes for the change in alumina feeding strategy. Practically, the cell

resistance varies between two limits depending on the underfeeding (increasing the time interval between feed) and overfeeding of cell. The slope of the resistance-time curve changes as per the change in ACD. The variation of cell resistance with respect to time is as shown in Fig. 4.

Fig. 4. Variation of cell resistance

In the underfeeding cycle, the resistance increases from R_L to R_U with a slope $S1$ (as dictated by ACD). Similarly, in the overfeeding cycle, the resistance decreases from R_U to R_L with a slope of $S2$. The DC current changes instantaneously with the change in cell resistance. The proper control mechanism needs to be devised in order to keep the DC side current constant. The main advantage of short time interval feeding could be the possible elimination of anode effects. Practically, this control strategy may be useful with the prior information about change in cell resistance with respect to time and alumina concentration. In this paper, the alumina concentration considerations have been neglected and typical resistance versus time characteristic has been considered. The saturable reactors and On Load Tap Changer (OLTC) are modelled for effective DC current control.

V. DESCRIPTION OF THE SMELTING LOAD AND ITS OPERATION

The twelve pulse rectifier system is modelled using PSCAD®/EMTDC® in order to depict the time domain response of smelting plant. The diagrammatic representation of the test system is shown in the Fig. 5.

The realistic network parameters for the test system are used in order to study the plant response under varying system conditions. The two parallel connected three phase bridges are supplied through 110 MVA, 110 kV/1 kV delta-star and star-star transformer respectively. Moreover, the entire system (representing smelting plant) is supplied by externally controlled 3 phase, 50 Hz, 220 kV voltage source (typically represented by an infinite bus), 220 kV transmission line with a line length of 100 metres, and the corresponding 250 MVA, 220kV/110kV tap changing transformer (with a tap changer on 110 kV side). The DC load can be typically represented in terms of an equivalent DC resistance (varying continuously over time 't') and a back emf for series connected electrolytic cells. The back emf for each cell is assumed to be 1.6 V; effectively, the series connected 50 electrolytic cells are modelled in terms of the fixed DC voltage source of 0.080

kV. The smoothing inductor of 0.01 H is included on the DC side in order to reduce the ripple content in the DC voltage as well as DC current.

In order to control DC load current, the saturable reactors are included on the AC side of the rectifier. Thus, there will be 12 saturable reactors for 12 pulse configuration as shown in Fig. 5. Each saturable reactor is modelled as an externally controlled variable inductor and the value of this inductance changes depending on the magnitude of the diode current. The design parameters for each inductor are obtained from [19] and subsequently, these parameters were manipulated in order to rationalise the variation in DC current. Moreover, the AC side tap changer has been modelled with the inclusion of Line Drop Compensator (LDC) thereby; the tap changer has been made to operate in order to counteract the voltage drop between regulating transformer and the AC side of the rectifier.

The AC side voltage and frequency are independently varied in order to simulate the response characteristic of the smelter plant under variable supply conditions.

VI. SIMULATION RESULTS

The simulation results are obtained in order to investigate the effect of saturable reactors and tap changer for current control. Moreover, the behaviour of smelter plant under varying supply conditions will also be examined.

A. Application of Tap Changer and Saturable Reactors for Short Time Interval Feeding

The smelter plant typically represents short time interval feed scenario with underfeeding and overfeeding of cells (to represent the continuous change in equivalent cell resistance). It is assumed that the cell resistance varies between 0.7 Ω and 0.8 Ω over a total time period of 30 seconds in a saw-tooth pattern as depicted in Fig. 4. Practically, this time period is much higher (in minutes) hence, relative scaling is applied for time domain simulation studies. The corresponding DC current response obtained that corresponds to the change in the load is as shown in Fig. 6. It can be seen that the change in DC current typically follows (7), wherein the DC load current is inversely proportional to the load resistance.

The effect of saturable reactors can be seen in Fig. 6. The changes in DC current with and without saturable reactors indicate that the reactors can be useful in controlling the variable DC current. Moreover, the saturable reactors need to be coordinated properly with the OLTC in order to achieve effective current control. The tap changer operation for 220 kV/110 kV transformer can be represented diagrammatically in Fig. 7. The tap changer operates (after a specified time delay of 3 seconds) in order to maintain the rated valve side AC voltage and the corresponding DC voltage.

As the saturable reactors are included on the AC side (in series with each diode), they also contribute to control the AC current for each phase. The variation of AC current in A-phase for one typical cycle (of 20 ms) is shown in Fig. 8.

Fig. 5. Diagrammatic representation of the system under study

Fig. 6. DC current control with tap changer and saturable reactors

Fig. 7. Tap changer operation

The substantial reduction in the AC current with the inclusion of tap changer and saturable reactors can be distinctly observed in Fig. 8.

Fig. 8. Variation of AC current

B. Response of Smelter Load under Voltage and Frequency Variations

The changes in instantaneous real and reactive power (at the supply side) for 10% variation in input voltage and frequency are as shown in Fig. 9. The frequency is varied between 4.1 s to 4.9 s and the input voltage is varied between 5.1 s to 5.9 s for an overall simulation time of 30 s. The active and reactive power drawn by the load changes instantaneously

for a change in supply voltage but does not change significantly when the supply frequency is varied. Thus, it can be accentuated that the rectifier loads may be typically categorised as only voltage dependent loads for small frequency excursions.

Fig. 9. Change in active and reactive power for varying supply conditions

Moreover, it is also observed that the active and reactive power changes over a complete simulation time of 30 s usually follows the pattern of the load current. This is because of the minimal variation of DC voltage across the load barring the changes with respect to supply conditions. The variations in 110 kV side AC voltage and the load side DC voltage with respect to tap changer operation can be markedly seen in Fig. 10. The intermittent variations in supply frequency and voltage are also seen to reflect on the 110 kV side as well as on the DC side.

Fig. 10. AC/DC voltage variations

The supply side variation of frequency and voltage can be evidently observed in terms of the transient changes in the DC current waveform as shown in Fig 11.

Fig. 11. Change in DC current under varying supply conditions

VII. CONCLUSIONS

The modelling of an aluminium smelter load with short time interval feeding scenario has been emphasised in this study. The smelter response has been examined for small variations in supply side voltage and system frequency. The results indicate that the smelter load can be classified as a voltage dependent load with insignificant frequency dependence. The continuous variation of equivalent cell resistance and subsequent changes in the DC voltage and DC current have been highlighted. The effective open loop current control techniques have been successfully implemented for uncontrolled rectifier circuit. The line drop compensation technique is used for efficient tap changer operation. The saturable reactors are included in series with each diode for ensuring smooth current control. The studies carried out will be of significant use for future detailed investigations on practical smelter loads, which contain a range of closed loop control systems which govern their dynamic behaviour. Such studies are expected to assist in developing more realistic load models that can be used for power system studies.

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