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Response Analysis of Saturable Reactors and Tap Changer in an Aluminium Smelting Plant

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Abstract—**Aluminium smelters are one of the peculiar loads, which typically represent a series of electrolytic cells supplied by a multi-pulse rectifier system. In order to address the complexity involved in the modelling of a smelting plant, the impact of multi-pulse configurations and its connection to HV networks and control aspects of load current should be considered. This paper addresses the issues related to the control of DC current using saturable reactors for different alumina feeding mechanisms in a typical smelter. The saturable reactors are modelled as variable inductors of which the magnitude is controlled using a proportional-integral control scheme. A smelting plant with a twelve pulse rectifier system and variable DC load has been modelled in PSCAD®/EMTDC©. The plant is connected to the AC network through 220 kV/110 kV transformer with tap changing facilities to control the secondary voltage and associated load current of the smelter. The simulation results are reported for the control of DC current under varying load conditions.**

Keywords-aluminium smelter; saturable reactors; alumina feeding process

I. INTRODUCTION

The aluminium smelting plant can be categorised as one of the bulk industrial loads. It typically demands for very high DC power. The multi-pulse rectifier configuration is commonly deployed in such cases, which consists of a number of series and parallel connected diode/thyristor bridges to supply series of electrolytic cells [1], [2]. The process control of a smelting plant is one of the complex activities due to inter-relationship between the different variables related to the process [3]. The heat balance of the electrolytic cells can be controlled by continuously monitoring the cell voltage and current. The DC current control (in case of smelting plant) typically constitutes of saturable reactors (for continuous control) and on load tap changer (OLTC) of the group transformer (for discontinuous control).

Rectifiers being nonlinear power system loads, they tend to distort the sinusoidal waveform thereby producing harmonics [4]. The behaviour of 11 MW, twelve pulse, half wave diode rectifier and the quantification of harmonic current components with and without delay angle variation have been discussed in [4]. The design and implementation of shunt connected passive reactive power compensation system comprising of harmonic filters has been described in [5] for a 12 pulse converter system in the ETI Aluminum Works, Turkey. The active filter control system and hybrid filter topology has been proposed in [6] for the harmonic compensation of 12 pulse converter system. The modelling of smelting plant distribution system and load including harmonic measurements at rectifier transformer have been used in conjunction in [7] to provide solutions to correct power factor and harmonic resonant conditions of 470 MW aluminium smelter load.

The load model corresponding to an electrolytic process of a typical aluminium smelting plant has been discussed in [8]. It also elaborates the statistical load behaviour for different scenarios and reports the outcome of field tests such as disconnection of rectifier groups and automatic load reduction for deciding effective load shedding strategy. The detailed rectifier load model, which includes the dynamic representation of DC load and abnormal modes of operation, have been investigated in [1] for transient stability studies. The intelligent controller based on the bath resistance process model has been outlined in [9] for aluminium smelter potlines. It uses multilevel intelligent control architecture, which has capability to control multistate distributed metallurgical process of smelting alumina. The nonlinear process model of a smelter has been developed in [10] to determine the feasibility of improving energy efficiency and electrical demand regulation possibilities in particular process.

This paper emphasises on practical current control strategy using tap changing transformer and saturable reactors for smelting plant with short time interval feeding. The P-I control strategy has been proposed to vary the inductance of saturable reactors so as to ensure smooth current control. The time domain simulations have been conducted in PSCAD®/EMTDC© to investigate the response of 12 pulse rectifier system depicting smelting plant. The paper has been organised as follows: Section II elaborates smelter system configuration. Section III outlines alumina feeding mechanisms. Section IV emphasises on coordinated control mechanism of smelting plant using saturable reactors and tap changer. Section V reports the simulation results and Section VI concludes the paper.

II. SMELTER SYSTEM CONFIGURATION

The aluminium production process involves four major process areas: anode area, rodding area, potrooms, and ingot mill. The anodes are manufactured in the anode area and the baked anodes are suspended in the pot in the rodding area. The

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molten aluminium from the potrooms gets transferred through to the ingot mill, which further cast it into ingots [11]. The simple flow sheet of the aluminium smelting process, interdependency of different variables and the process control aspects have been elaborated in detail in [12].

Aluminium production being an electrolytic process, the series connected electrolytic cells on the DC side forms the smelter system load. There are several pot lines (reduction lines), which supply different groups of electrolytic cells. The diagrammatic representation of multi-pulse rectifier system, derived from [2] and [8], is shown in Fig. 1. Each twelve pulse rectiformer unit typically comprises of rectifier transformer with tap changing capability, phase shifting transformers, and diode bridge rectifier with saturable reactors. The DC load constitutes of equivalent resistance, inductance and back emf of the series connected electrolytic cells. In the typical aluminium production process, the electrolytic cells are fed with alumina using short or long time interval feeding mechanism.

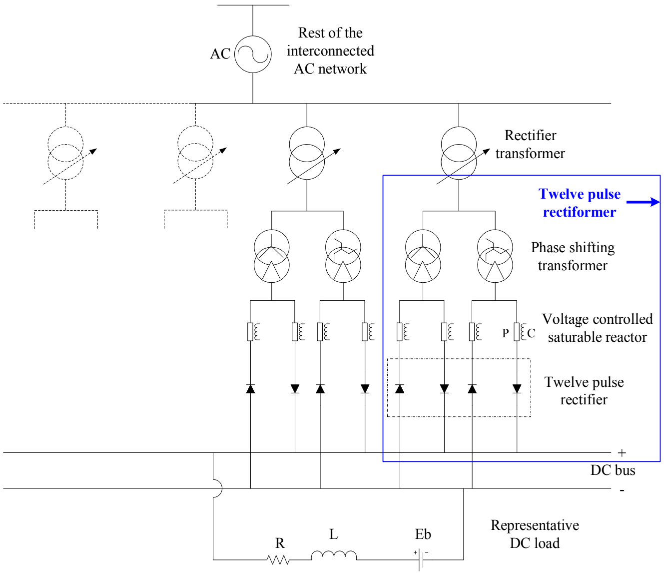

Figure 1. Smelter system configuration

III. ALUMINA FEEDING MECHANISM

In a typical aluminium smelter, there are certain alumina feeding mechanisms based on the frequency of alumina feeding into the pot. In case if the cells are fed typically more than 20 minute interval then it can be classified as long feed interval. The control strategy for long feed intervals can be derived from the slope of the resistance versus time curve and actual change in cell resistance [3].

The short time interval feeding mainly refers to the small time gap (such as around 2 minutes for a typical cell) between the intervals of alumina additions to the cell. It is applicable to alumina feeders, designed to discharge all the alumina in a small zone within the cell, wherein, the average time interval between the two feeds is very small. Since alumina may not dissolve completely within a small time and because of the slow process of mixing the electrolyte, the cells usually have several alumina feeders with small discharge zone within the cell. In case of a short time interval feeding, the control strategy is to maintain low alumina concentration. The cell resistance is dependent upon the inter-electrode spacing as well as the underfeeding and overfeeding of the cell. Fig. 2 shows the worst case scenario with continuous underfeeding and overfeeding of cells. The corresponding variation of cell resistance from lower value R_1 to higher values R_2 and vice versa with respect to time has been represented in terms of slope S_t and slope S_z respectively. This paper focuses on the time domain simulation study for response analysis of smelting plant under short time interval feeding scenario.

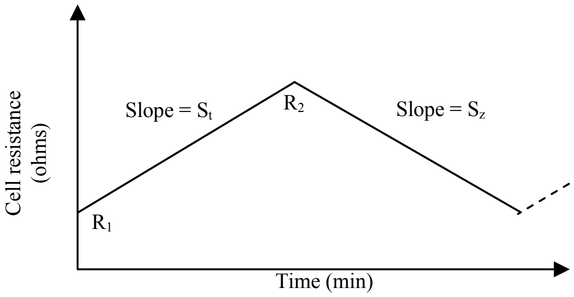

Figure 2. Underfeeding and overfeeding of cells [3]

IV. COORDINATED CONTROL MECHANISM OF SMELTING PLANT USING SATURABLE REACTORS AND TAP CHANGER

The voltage controlled saturable reactor typically controls the DC side voltage, thereby controlling the load current. It has power winding (P) in series with the AC supply and control winding (C) supplied by a separate DC source as indicated in Fig. 1. The rectifier output voltage 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]. A typical control characteristic for a voltage controlled reactor is as represented in Fig. 3. The increase in the reactor control current causes to decrease in the output DC voltage and also decrease in the corresponding DC side load current and vice versa. Realistically, the saturable reactor operates between certain range of the control current, which could be decided by the linear portion of the curve represented by the relationship of DC side voltage and control current as shown in Fig. 3. Normally, the tap changer operates outside the range of typical reactor in order to ensure effective control of the DC side voltage. Since the smelter current set-point is normally fixed, saturable reactors are used for fine control and tap changers for coarse control to operate continuously in a closed loop mode in order to achieve automatic DC side current control.

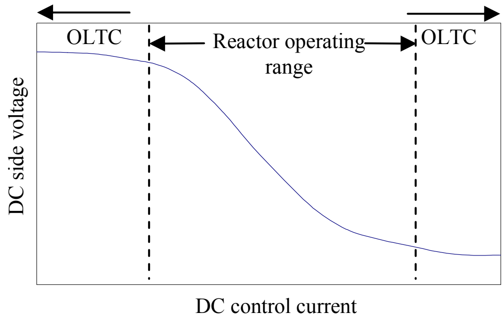

Figure 3. Control characteristic for a voltage controlled reactor

A. DC current control using saturable reactor and on-load tap changer

In a typical rectiformer, the tap changer operates in accordance with the upper and lower limit of a control current for a saturable reactor. A coordinated approach for reactor and tap changer is essential to control rectiformer output current. The tap changing transformer has multiple taps in order to adjust the DC side output voltage. Each rectiformer has a unit reference current, which is compared with the measured current in a closed loop current control. The current control loop for a rectiformer is shown in Fig. 4. The output measured current of twelve pulse rectifier is compared with the reference current and a proportional-integral (P-I) controller adjusts the control current of the respective reactor, thereby maintaining the output current at the desired value. The OLTC operates outside the controlled current range of reactors.

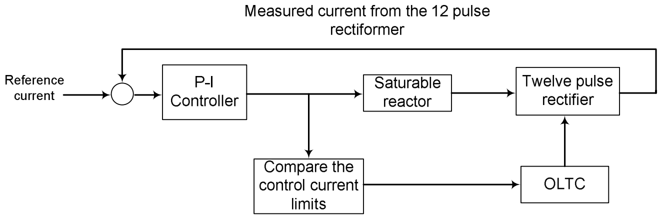

Figure 4. Control characteristic for a voltage controlled reactor

In this paper, a P-I controller is designed for the reactors. The proportional gain and the integral time constant of the controller have been selected based on the trial and error method. The control current of the reactors is initially kept constant at the specified value (as an initial operating point) and a time delay logic has been incorporated to vary the control current based on the error signal being fed to the P-I controller. The error signal has been generated by evaluating the difference between the rated DC current and the measured DC current. The rated DC load current (I_{dc}) for a smelter can be evaluated based on the following equation:

$$I_{dc} = \frac{V_{dc} - E_b}{R_{fixed}} \tag{1}$$

Where V_{dc} is the rated DC voltage, E_b is the fixed value of back emf, and R_{fixed} is the constant DC resistance corresponding to the rated capacity of the DC load.

The change in reactor control current results into a subsequent change in the inductance values so as to keep the load current constant. The tap changer operates on the line drop compensation principle to mitigate the voltage drop on the AC side of the rectifier. The coordinated current control philosophy adopted in this paper has been elaborated in Fig. 5

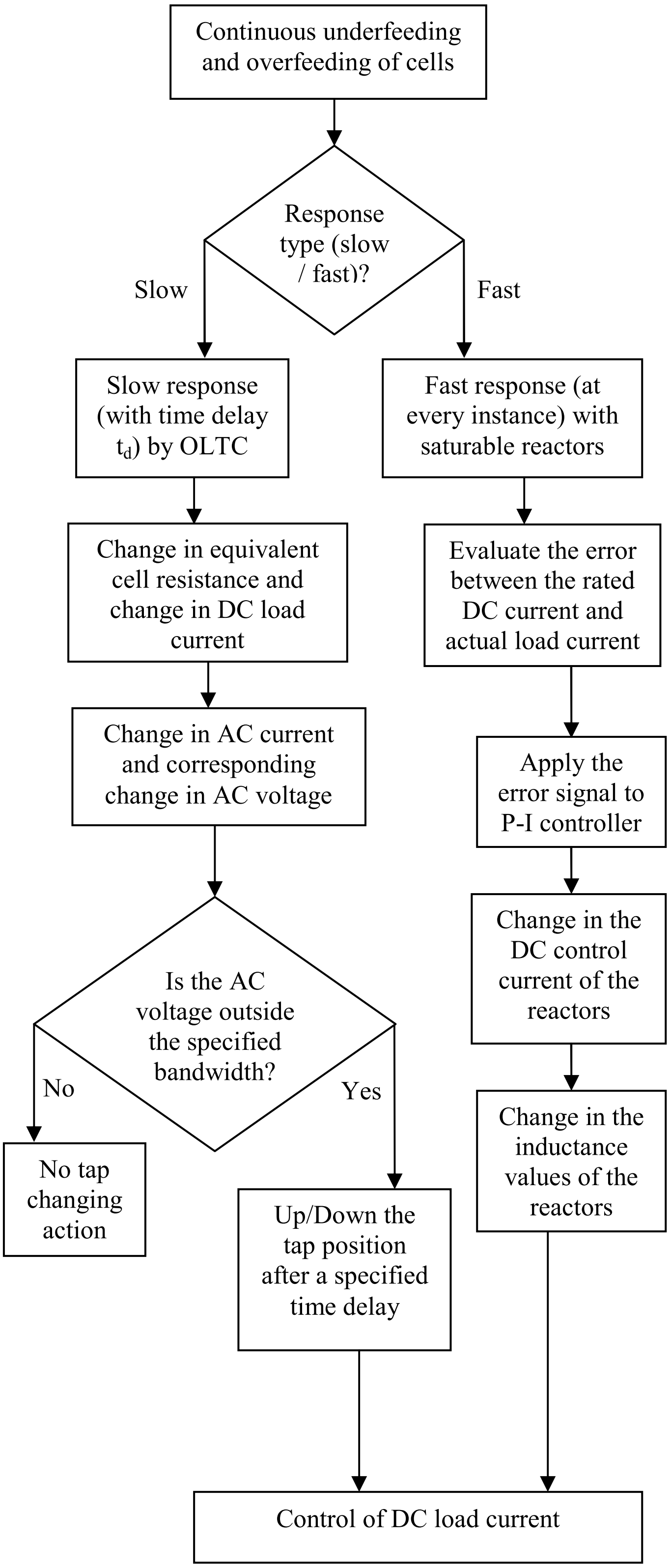

Figure 5. Flow chart for DC current control

V. SIMULATION RESULTS

The time domain simulation studies will be conducted using PSCAD®/EMTDC© for a typical aluminium smelting plant involving 12 pulse rectifier system. Fig. 6 shows the pictorial representation of the system under study.

The plant response is investigated for fixed supply conditions and varying DC load. The DC load can be typically represented in terms of series connected electrolytic cells with an equivalent back emf and a DC resistance to emulate the simultaneous alumina feeding. The back emf for each cell is assumed to be 1.6 V in accordance with the typical cell data [3]; effectively, the series connected 50 electrolytic cells (as a sample case) are modelled in terms of the fixed DC voltage source of 0.080 kV. The DC resistance is varied between 0.7 Ω to 0.8 Ω to depict the underfeeding and overfeeding of the cells.

The 12 pulse rectifier system is constituted of parallel connected bridge rectifiers and each bridge is supplied from 110 MVA, 110 kV/1 kV delta-star and star-star transformer respectively. The entire smelter system is supplied from a fixed 3 phase, 50 Hz, 220 kV voltage source (infinite bus), 220 kV transmission line with a line length of 90 metres, and 250 MVA, 220kV/110kV tap changing transformer (tap changing facilities on 110 kV side). The smoothing inductor of 0.01 H is included on the DC side to reduce the ripple content of the DC voltage as well as DC current. The saturable reactors are included in series with each diode to ensure the fine current control as discussed earlier. It is assumed that there will be 12 saturable reactors for 12 pulse configuration as shown in Fig. 6. 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 and based on the varying control current generated by the P-I controller. The design parameters for each saturable reactor are obtained from [14] and subsequently, these parameters are modified in order to conform to the control characteristics of voltage controlled reactor.

The tap changer on 110 kV side has been modelled with the incorporation of Line Drop Compensator (LDC) wherein, the tap changer is expected to mitigate the voltage drop between regulating transformer and the AC side of the rectifier. OLTC has been coordinated with the saturable reactors using an intentional time delay of 3 s to ensure coarse control strategy.

The tap changer operation for a test system is shown in Fig. 7. It is seen that the tap changer operates after the intentional time delay of 3 s to guarantee the slow response. The tap changer exhibits the capability to operate for +/- 16 taps with a corresponding +/- 5% change in the rated voltage. It can be observed in Fig. 7 that the tap changer responses with executing 6 steps consecutively to ensure the necessary improvement in the AC as well as DC voltage and the load current. The corresponding RMS value of the AC voltage on the 110 kV side and the DC voltage response over a simulation time of 5 seconds can be seen in Fig. 8.

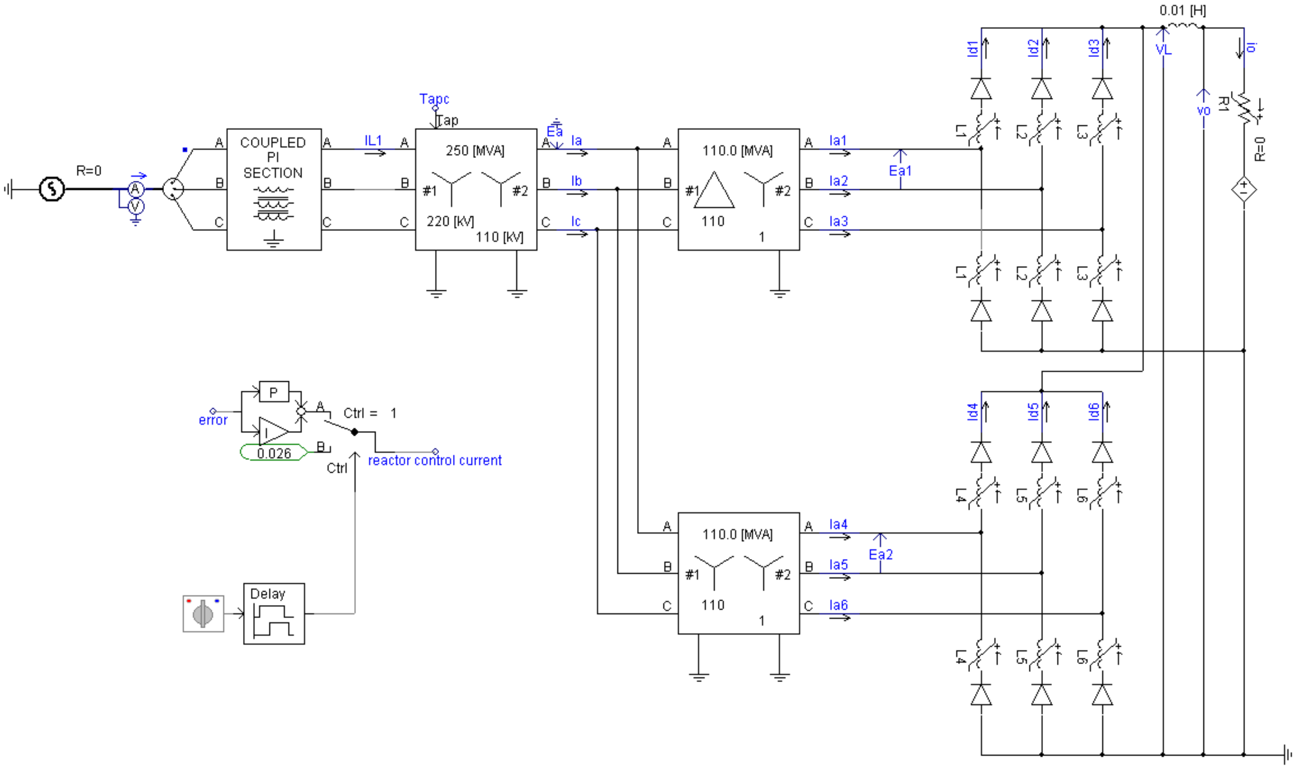

Figure 6. PSCAD®/EMTDC© simulated smelter system under study

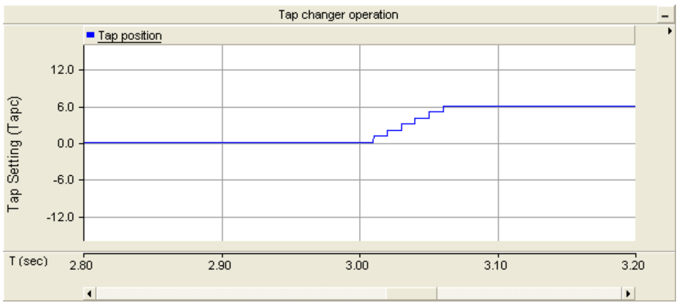

Figure 7. Tap changer operation

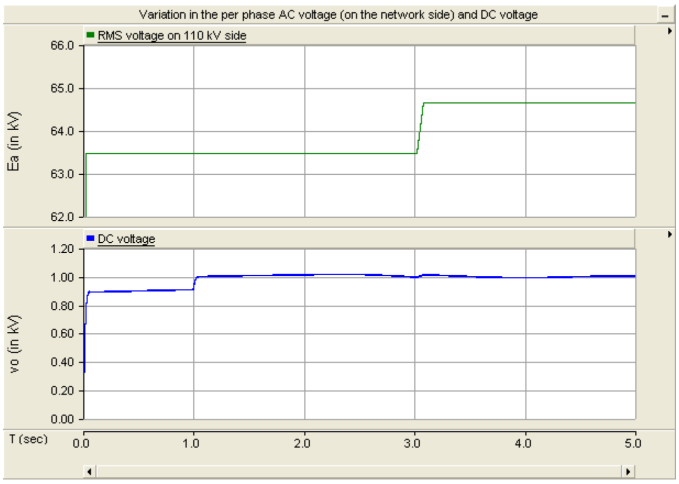

Figure 8. Variation in AC-DC voltage

The initial value of the DC control current has been assigned to 0.026 kA as one of the initial operating points, derived from the saturable reactor model. The P-I control strategy for the sample system has been designed in such a way that the control current of the saturable reactors has been varied continuously based on the error signal of the load current with an intentional time delay of 1 sec. The DC control current of the reactors is shown in Fig. 9.

The error signal for controlling the DC side load current has been obtained based on the difference between rated output current and the measured current. The rated output current is derived based on the DC resistance of 0.75 Ω and the back emf of 0.08 kV. The error signal for controlling the load current by adjusting the inductance value is shown in Fig. 10.

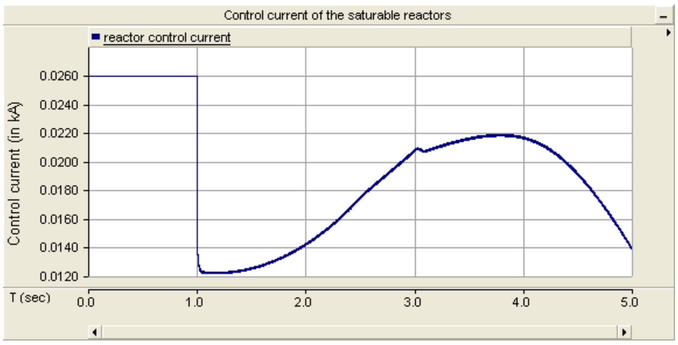

Figure 9. Control current of the saturable reactors

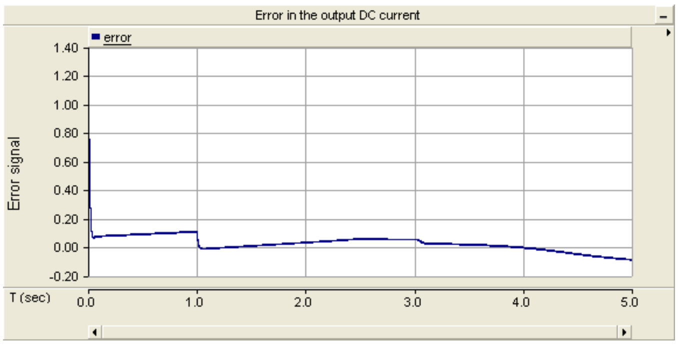

Figure 10. Error in the output DC current

The DC side load current response for short time interval feeding has been presented in Fig. 11. The continuous variation in the DC resistance (to replicate short time interval feeding) and the subsequent DC side load current response indicate that the coordinated operation of reactors and tap changer facilitate the DC side current control for varying load conditions.

The change in 110 kV side line current for a typical cycle of 20 ms is shown in Fig. 12 that clearly indicates the significant improvement in AC current by applying the proposed control strategy. Fig. 12 shows the AC currents at the terminal of the smelting plant with and without proposed control strategy for tap changer and saturable reactors.

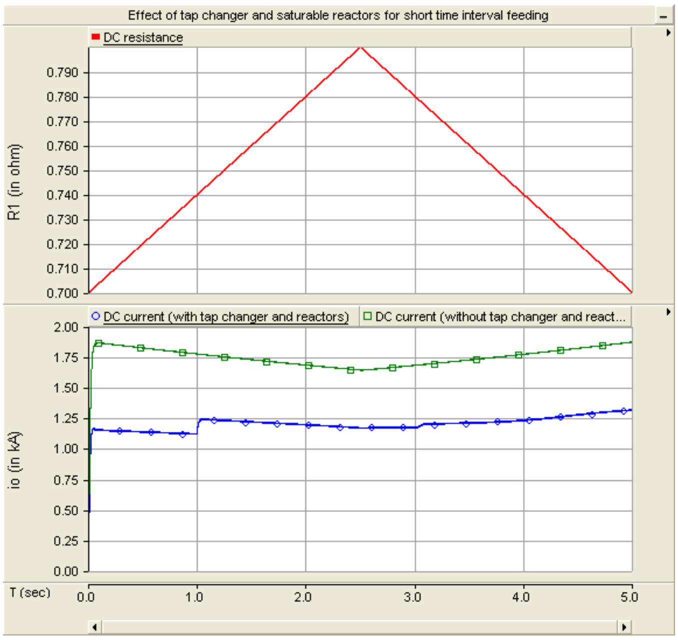

Figure 11. DC current control with tap changer and saturable reactors

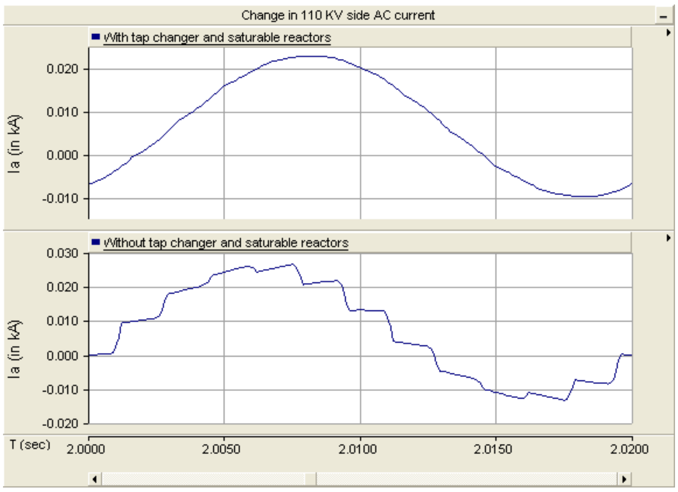

Figure 12. Variation of 110 kV side AC current

VI. CONCLUSIONS

This paper presents the response analysis of saturable reactors and tap changer for an aluminium smelting plant. The typical supply system including phase shifting transformers and twelve pulse rectifier system has been modelled in PSCAD®/EMTDC© to simulate the representative smelter load. The short time interval feeding mechanism has been depicted in terms of continuous variation of DC resistance. The closed loop current control scheme in terms of well tuned P-I controller has been proposed to change the value of inductance for a saturable reactor, connected in series with the diode. The OLTC with line drop compensation has been implemented to alleviate the AC side voltage drop thereby contributing to the current control. A coordinated approach has been developed considering fast response by saturable reactors and slow response by OLTC to ascertain the refined DC current control strategy. The proposed approach has been tested through simulations and the results show significant improvement in the AC current at the terminal of the smelting plant as well as in the DC side load current.

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