

Harmonics in industrial power networks of aluminium smelters — A comprehensive mitigation approach

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Abstract

Large DC power requirements supplied through extensive use of rectifying equipment impose challenges on the electrical power network of Aluminium smelters to maintain power quality parameters within acceptable limits. Conventional methods of design considerations of transformer phase shifting alone may not be sufficient in view of expansions, complexity and other practical considerations of the smelters. A more comprehensive approach using passive harmonic filters which can provide an optimum techno-commercial solution along with reactive power compensation can be applied to network widely. This paper presents a case study of implementation of harmonic filters in a real network of Aluminium smelter based on harmonic simulations and filter parameters recommendations through software simulations. At the end, the estimations are compared with the actual results obtained through measurements.

Keywords: Aluminium smelters, converter, filters, harmonics, IPSA, power quality, rectifiers, simulation

1. Introduction

Aluminium smelters are high energy consuming units in the industries requiring huge amount of power to produce metal. In fact, apart from other raw materials, electrical energy is the main raw material to produce Aluminium through electrolysis process. Such processes work on direct current (DC) power inputs necessitating conversion of large electrical power from alternating current (AC) into DC. Present day's technology permits large Aluminium potlines to operate on DC current in excess of 400 kA. This calls for the need of large rectification devices. One of the prevailing methods to obtain large DC power outputs is using diode based rectifiers. As with any other power electronic devices, such rectification process is responsible for production of harmonics in the AC network polluting the quality of the power supply of the high voltage network which feeds such Aluminium smelters along with other important loads. The characteristic harmonics depend on the pulse number of the converter [1].

For new Aluminium smelters, generally, harmonic mitigation measures are considered during the design phase of the plant. However, the same does not hold for the plants operating and evolved over several years ago. Many changes such as increase in production capacity, plant expansion and supply network changes violates the designed operation mode and causes harmonics to penetrate into the network.

Hence, a system wide harmonic mitigation approach is recommended for the smelters which are already in operations. The criteria for such mitigation shall be such that the recommendations are implemented without disturbing the production process of the plant and remains valid for different operating conditions and possible future expansion of the power network. Accordingly, usage of passive filters at identified locations of the electrical network is discussed. A case study of high voltage power network of Dubai Aluminium (DUBAL) Company is presented in this paper. Harmonic analysis simulations are conducted using integrated power system analysis (IPSA) software and the analysis results are compared with actual measurements post installations of proposed harmonic mitigation

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measures [2].

2. Power Quality Issues in Aluminium Smelters

In most of the Aluminium smelters, almost 85% to 90% of the total load is a DC load. This means that extensive network infrastructure is required to transmit and convert the AC power into DC power. This is mainly done through rectifier transformers. The rectifier transformer (RT) circuit consists of regulating winding, rectifier winding along with diode circuits. One typical configuration of diode circuit is a 6 pulse rectification, with two secondary winding of the transformer to realize the same as 12 pulse rectification. The same is depicted in Fig. 1.

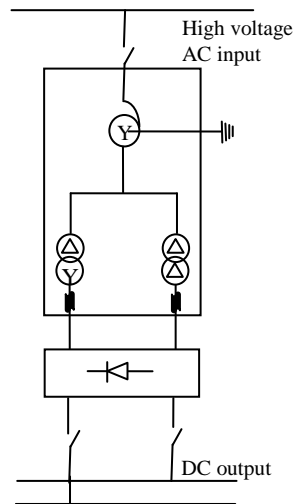


Fig. 1. Typical rectifier transformer circuit of Aluminium potline

Table 1. Harmonic limit guidelines

Voltage Level	IEC 61000-3-6 [3]	IEEE std. 519-1992 [4]	UK Engineering Recommendations G5/4 [5]	European Standard EN50160 [6]
400kV	3	1.5	3	NA
132kV	3	2.5	3	NA
33kV	6.5	5	3	8
11kV	6.5	5	3	8

Each Aluminium potline (PL) is generally fed through either 4 or 5 such transformers connected at different phase shifts, making the effective pulses as either 48 or 60 respectively. This means that the AC power feeding this DC load shall be fairly sinusoidal. However, this is always not the case, since:

- Loading and rating of each of the RT may not be uniform.
- Outage of one of the RT may reduce the total number of pulses to 36 from 48.
- Unbalance between loading of the two secondary windings of the same RT.
- Usage of standby RTs for normal operations (due to production demands), make the effective pulses to 12 from designed pulses of 48 or 60.
- Grouped tap position change of one PL can change system impedance significantly shifting the resonance coinciding with one of the prevailing order of harmonics.
- Interactions of other PL's rectifier transformers deteriorate the ideal phase shifting.
- Changes in the high voltage network configuration can shift the resonance frequency (due to changes in system impedance).

Due to one or more of the above reasons, it is not unusual to witness total voltage harmonic distortions

(V_{thd}) at the point of common coupling (PCC) or on important nodes of the network to be in access of limits defined in international standards. Summary of important total voltage harmonic distortion limits is presented in Table 1.

3. Harmonic Simulations—Case Study

A simplified sketch of high voltage power network of DUBAL is presented in Fig. 2. As evident from the sketch, there are three nodes of 132kV voltage levels feeding two PLs (each of around 300 MW) at each node through equivalent generation. These nodes are interconnected through current limiting reactors. While the entire load of the Aluminium smelter is being supplied through in-house generation of combinations of combined cycle and co-generation power stations, there are two interconnections with the 400kV Gulf cooperation council (GCC) grid through two inter connecting transformers (ICTs) to cater the emergency power flow requirements. In total there are more than 40 RTs spread across different voltage levels, majority at 132kV, while small numbers of RTs are supplied through 33kV and 11kV voltage levels. A typical supply arrangement of one such PL is presented in Fig. 3. Each RT has a specific phase shift with respect to other RTs. 6° phase shift from -12° to $+12^\circ$ with a 12 pulse output effectively produces 60 pulses together with 5 RTs.

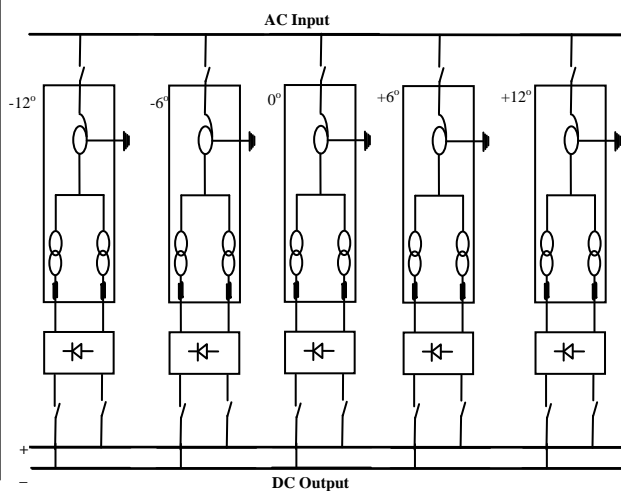
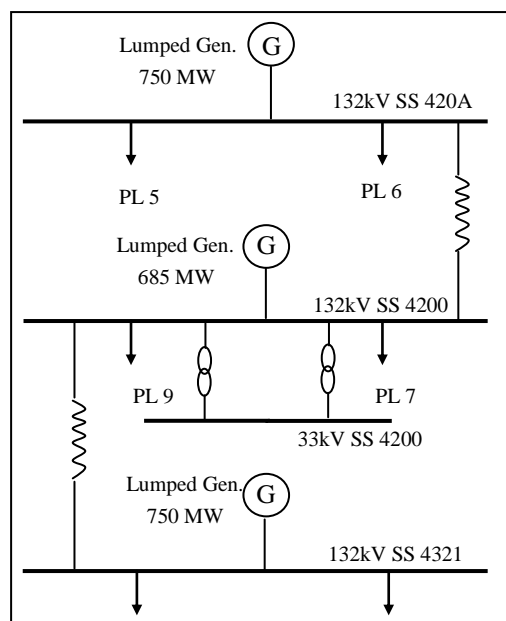


Fig. 2. Sketch of high voltage network of DUBAL Fig. 3. Typical arrangement of potline

Harmonics measured in the network before application of mitigation measures are presented in Fig. 4 while the distorted voltage waveform recorded in the network before mitigation measures is presented in Fig. 5. [7]

Apart from above, several instances of large voltage harmonics in high voltage network are recorded, which are attributed to shift in resonance points due to either change in network configurations or due to change in the system impedance through a grouped change in tap positions of multiple transformers per PL. One such record of observed resonance peak is presented in Fig. 6.

It is evident that the harmonics presented in the network consist of wide range of harmonics starting from 3rd order till 35th order harmonics, 11th, 13th, 17th, 19th, 23rd, 25th being the predominant ones. Some of the frequent ill effects related to harmonics observed in DUBAL at certain network operating configurations are:

- High total harmonics (due to resonance) of the order of 12% at 132kV and 20% on 33kV during

specific operating conditions (short time).

- Rise in total harmonic distortion to double the magnitude during daytime as compared to night periods – especially due to shift in PL group RT tap changes – effectively changing the system impedance.
- Sudden increase in harmonics while taking outage of one of the RTs of the PLs.
- Frequent operations of transformer tap positions due to transformer Automatic Voltage Regulator (AVR) relays mal operation.
- Unwarranted auxiliary supply changeovers without actual problems with the healthy circuits.
- Mal-operations of the protective relays (not having inherent filters) operating on true root mean square (RMS) signals.
- Cables and transformers insulation deterioration/ bushing failures and so on.

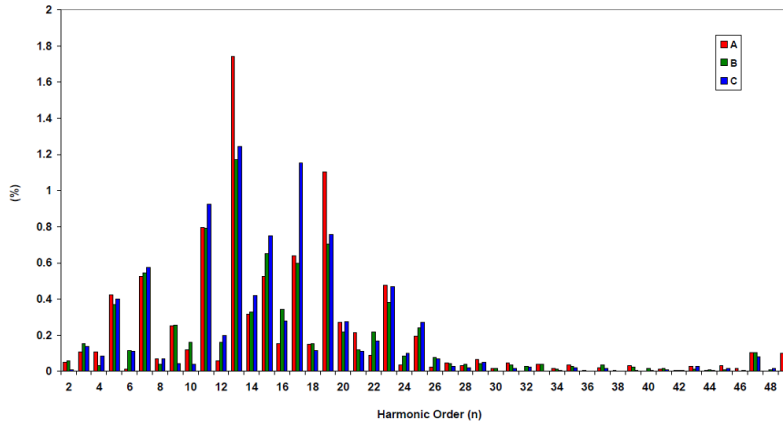


Fig. 4. Measured harmonic distortion before harmonic mitigation

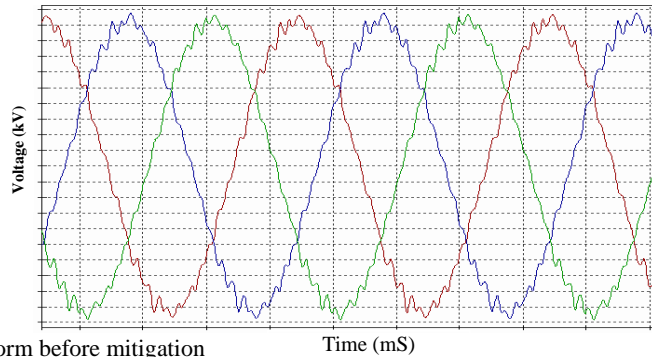


Fig. 5. Voltage waveform before mitigation

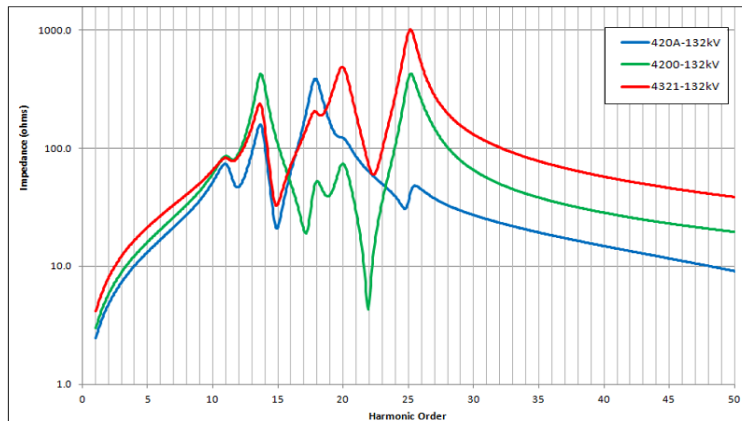


Fig. 6. Resonance peak observed in the network before mitigation

4. Mitigation Measures—Considerations and Recommendations

Due to the wide spread of the harmonics throughout the network and due to large band of order of harmonics, a comprehensive approach is necessary which can reduce the total voltage harmonics well within the limits at all the nodes of the high voltage network. The solution shall be such that apart from total voltage harmonic distortion, all the individual order of harmonic distortions is also within the limits, removing potential of any resonance issues. Apart from harmonic mitigations, the additional benefit of reactive power compensation to such energy intensive industry is an important consideration to arrive at a comprehensive solution. The mitigation shall be such that the network harmonics remain within the limits not only during normal operating conditions, but also during:

- Outage of network components.
- Different operating configurations.
- Future expansions (minor).
- Different time of the days and ambient conditions throughout the year.

Further, simplicity of the solutions and cost effectiveness are other criteria, which can decide the choice of the mitigation measures. Installation of passive filters fits into all the above requirements, while active filters may have disadvantages of complex control system and very high cost. Moreover, provision of a dedicated harmonic filter per RT will be impractical in case if the installations are already in operations without RT having a tertiary winding to allow connecting a filter. (Changing of all the RTs only for connecting a harmonic filter is commercially unviable and impractical option for the smelters already in operation). This leaves the option of putting busbar connected (network wide) passive filters. Accordingly, extensive simulations of various combinations of passive harmonic filters based on IEEE guidelines [8], [9] are performed in IPSA software to arrive at an optimum solution. The selection approach of the filter is to mitigate different predominant harmonics at different nodes of the network such that the overall effect will eliminate all the dominating order of harmonics. With these criteria, the recommended tuning frequency and other main parameters of various filters at different nodes of the network are presented in Table 2.

Table 2. Recommended tuning frequency of the filters [10]

Parameters	Network Nodes					Unit	
	4321	420A	4200	4200			
System voltage	132kV	132kV	132kV	33kV			
Harmonic filter order	5 th	11 th	13 th	3 rd			
Type of filter	C-type	High Pass	High Pass	C-type			
Nominal filter tuning Frequency	249	550	650	146.55		Hz	
MVAr output	35	35	30	10		MVAr	
Nominal bank capacitance / phase	6.394 (Main)	152.179 (Tuning)	6.341	5.448	29.23 (Main)	221.87 (Tuning)	μF
Reactor inductance	66.58	13.205	11.004	45.67		mH	
Resistor	0.26	0.083	0.086	0.18		Ohm	

The scheme of individual filter circuit is presented in Fig. 7. In view of reduction in losses during normal operations of the filters and to optimize the initial cost of the project, a techno-commercial optimization is kept in consideration. Accordingly, lower order (3rd and 5th order) tuned filters are recommended to be C-type while higher order tuned filters (11th and 13th order) are recommended to be normal high-pass filters.

Software simulations to estimate the impact of the proposed harmonic filters are performed and the simulation results are presented in Fig. 8.

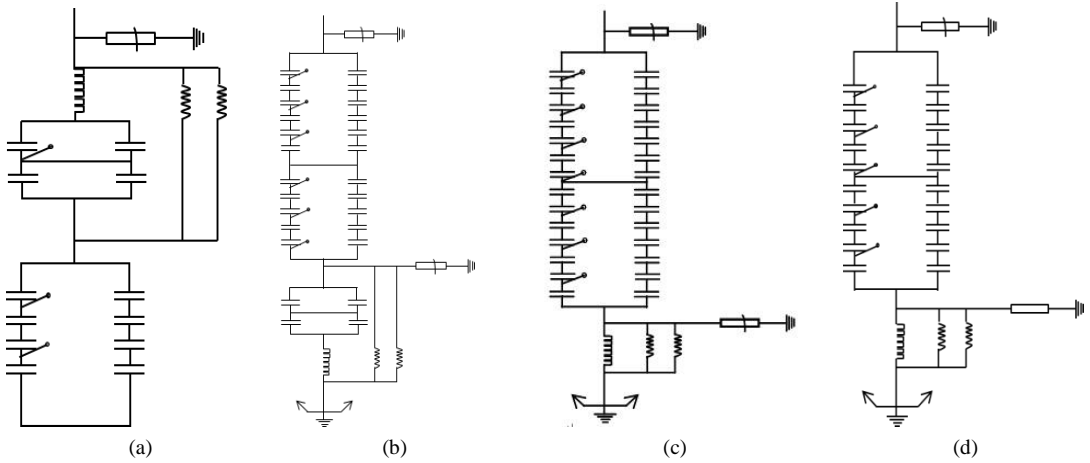


Fig. 7. Scheme of filters: (a) 3rd order tuned C-type, (b) 5th order tuned C-type, (c) 11th order tuned high pass, and (d) 13th order tuned high pass

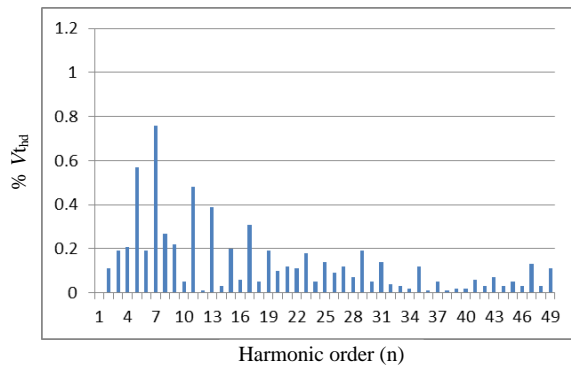


Fig. 8. Estimated results (V_{thd}) in the network considering mitigation recommendations (harmonic filters)

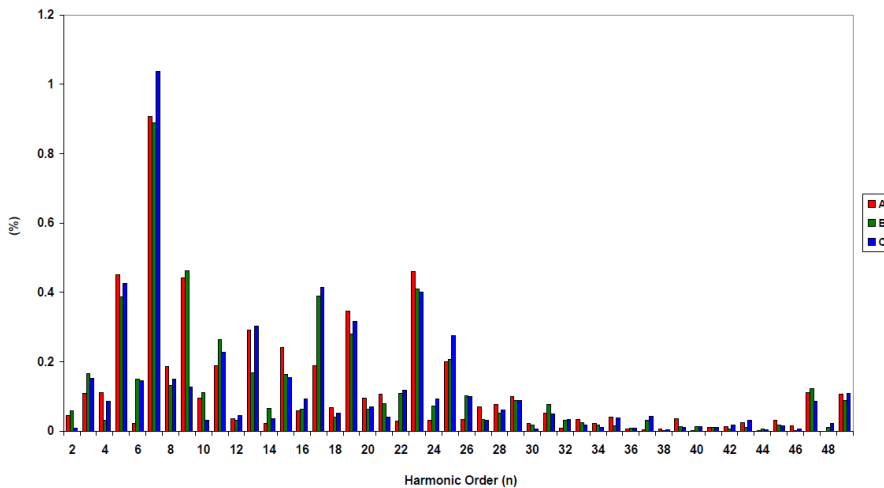


Fig. 9. Total voltage harmonics – actual measurements after filter installations

5. Actual Harmonic Measurements after Installation of Filters

Actual measurements are performed at all the important nodes of the network to compare the study results with the software estimations. The results of individual voltage harmonics are presented in Fig. 9

[7]. The voltage waveform is presented in Fig. 10. Total voltage harmonics at different nodes of the plant are presented in Table 3.

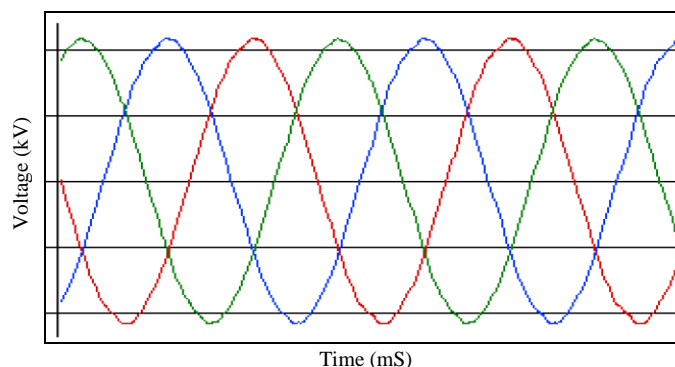


Fig. 10. Voltage waveform post harmonic filter installations

Table 3 Total voltage harmonic distortions after installations of harmonic filters

Node / Substation*	Voltage level	V_{thd}
420A	132kV	2%
4200	132kV	1.7%
4321	132kV	1.3%
4200	33kV	1.2%

* Nodes are as per network sketch presented in Fig. 2.

6. Observations

For the case study under considerations, following observations are noted:

- Actual harmonic measurements at specific nodes of the network are compared with the simulation results and found to be realistically matching.
- The simulation results through software analysis provide good estimation of the actual performance of the harmonic filters and network as a whole.
- The total voltage harmonics as well as all the individual harmonics are observed to be well within the limits defined in international standards.
- All the probable resonance peaks at possible individual harmonics order are smoothed and / or shifted to non-critical orders of harmonics.
- Additional reactive power generated from filters (shunt capacitors) helped improve power factors and increase system voltages throughout the network.

7. Conclusions

Power quality issues in terms of harmonics are a major problem in Aluminium smelters. Merely design of RT phase shifting is not sufficient to reduce the harmonics and ensure an unpolluted supply due to several practical problems mentioned in this paper and as may be applicable to many Aluminium smelters in operations. The mitigation measure by means of system wide passive harmonic filters would be a good practice which not only provide cost effective harmonic mitigation measures but also generate free reactive power much needed for large Aluminium smelters.

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