A comparative study between diode and thyristor based AC to DC converters for aluminium smelting process

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***Abstract*—Aluminum smelting is one of the most energy consuming industrial processes involving AC-DC conversion using high-power rectifiers. An overview is provided of the most effective power-system configurations employed in this industry. The most reliable and stable rectifier-transformer solutions and their impact on the AC side of the power network are described. Diode- and thyristor-based rectifiers, or AC-DC power converter systems, are compared. Models of the configurations of systems used in the Dubai Aluminium Company smelter power plant are simulated and measured.**

***Index Terms:* smelter rectiformer, high-current diode rectifier, high-current thyristor rectifier, smelter power-plant power quality, rectifier line-current harmonics and THD, saturable reactors or transductor current control, aluminium smelter potline.**

I. INTRODUCTION

The design and operation of high-power rectifiers for aluminium smelting plants presents considerable challenges, with a need for careful harmonic emission and voltage stability control measures on the AC side of the network, and a requirement on the DC side for very precise current control in very low impedance. To be able to supply and regulate very high DC current, a number of naturally commutating high-current diode- and thyristor-rectifier systems are used. These are well known for their nonlinear loading characteristics which draw highly distorted line-currents rich in odd harmonics. Without preventative measures, this would have an unacceptable impact on the quality of voltage waveform at the point of connection to the AC network, and reduce utilisation of power system components up-stream of the rectifiers. On the output DC side, the methods used for precisely controlling the very high rectifier output current have to be extremely precise and repeatable so as not to have a damaging effect on the quality of process stability, reliability and availability.

This paper will focus on studying the effects presented on the AC side of the network associated with two configurations:

1. diode based AC/DC convertor models where on load tap changers (OLTC) and saturable reactors are used for DC output current regulation and control;
2. thyristor based AC/DC convertor models where a firing angle control is used to regulate the DC output current.

Diodes are principally used in the main aluminium smelter Potline rectifiers while thyristor rectifiers are used in booster rectifiers [1]. These rectifier choices are widely adopted in the majority of aluminium smelters across the globe with minor exceptions due to certain unique conditions. For comparison of rectifier system performance, this paper will utilize rectifier and smelting process statistics, measurements and data taken from the Dubai Aluminium Corporation (DUBAL) network configuration *. DUBAL is the industrial pride of Dubai and one of the key industrial flagships in the United Arab Emirates. It owns and operates one of the world's largest aluminium smelters with a production capacity of around 1.1 million tons per annum. The smelter has its own dedicated power station with a capacity exceeding 2400MW (at 30°C) [2]. The company production is obtained from six major Potlines and three booster Potlines.

Regulating rectifier-transformer combinations which are applied to primary aluminum production smelters are known as *rectiformers*. Out of the 44 rectiformers deployed in DUBAL, 7 are based on thyristors and those are implemented to serve the PL5 Eagle potline. The other 37 units are all based on diode configuration and are mainly utilized to serve the main Potlines. The simulations and measurement data were modeled and collected by comparing Potline 21 rectifiers as an example of diode based converters and Potline 5 Eagle booster rectifiers as an example of thyristor based converters.

* The data and statistics utilized in the paper are obtained with the kind permission of Dubai Aluminium who are sponsoring this work.

II. Diode vs. Thyristor Based Power Converters

Practical AC-DC converter circuits were developed during the 1930s using mercury arc rectifiers which dominated high-power industrial applications. Until the mid-fifties they were used with magnetic-amplifier transductors to provide output voltage or current regulation. The invention of the thyristor in the late fifties, and the rapid increase in current and voltage handling capability in the sixties, produced a revolution in industrial power electronics, and more robust solid-state power electronics devices and systems could be reliably employed in high-power machine and power control applications [3]. Diodes and thyristors remain the most reliable and robust power semiconductor devices; the only devices that may be directly protected against over-current with a fast fuse link.

Diodes and thyristors are now routinely employed in arrays of three-phase rectifier bridges in high-voltage or high-current applications, such as HVDC power transmission where they are effectively series connected, and electrolytic processes where they are effectively parallel, connected, to increase the voltage or current handling capability of individual rectifier bridges [4]. Within rectifier bridges, a number of directly series- or parallel-connected diodes and thyristors may also be used to form one higher capacity rectifier element, known as a valve, provided voltage or current sharing snubber circuits are used.

A. Diode Based Rectiformers General Layout(PL21)

Traditionally, in aluminium smelting process applications diode based rectiformer systems comprise five units connected in parallel. For the purpose of this study, Potline 21 rectiformers are used each with a capacity of 50 kA rated current and 1500 V rated voltage. The units AC inputs are phase shifted through transformer phase shifts of -12°, -6°, 0°, +6° & +12°. Each unit is a 12 pulse bridge rectifier, resulting in a total of 60 pulses on the DC bus bar [5]. The single line diagram of the main Potline is shown in Fig.1.

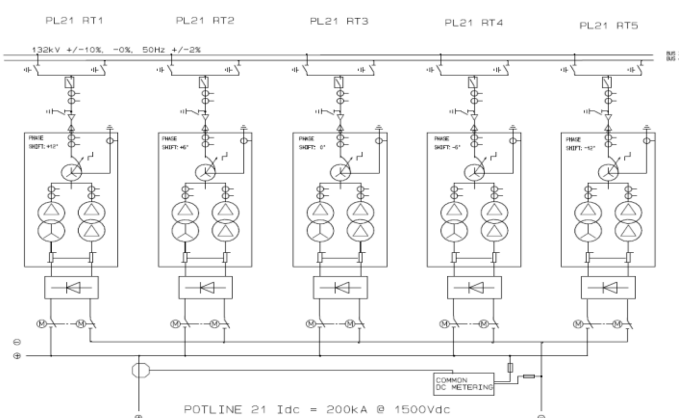

Fig. 1 Single line diagram of diode-based potline. (taken from [4]).

The single Line diagram of each rectiformer is shown in Fig.2. For aluminium smelter Potline, the regulation range is very wide; it varies between 0 V to approximately 1500 VDC depending on the number of pots connected in series within the Potline. At each rectiformer, there are 3 transformers: an auto-regulating unit, in addition to two rectifier transformers arranged in a parallel configuration. A delta primary winding is used, while secondary windings are alternately wound delta and star. This configuration results in an additional 30° phase shift which doubles the number of DC-side pulses to 12. The auto-regulating transformer is equipped with an on-load tap changer (OLTC) for stepping down the voltage and coarse regulation. The single line diagram of the auto-regulating and the rectifier transformers is shown in Fig.2.

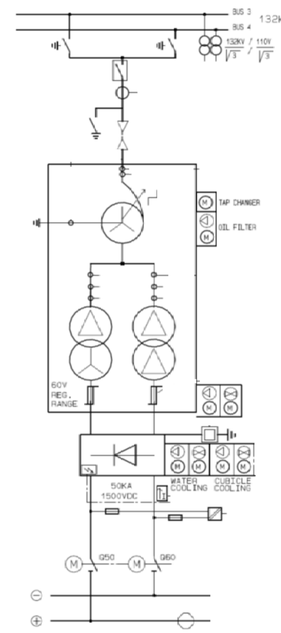

Fig. 2. Single line diagram of diode-based converter (taken from [4]).

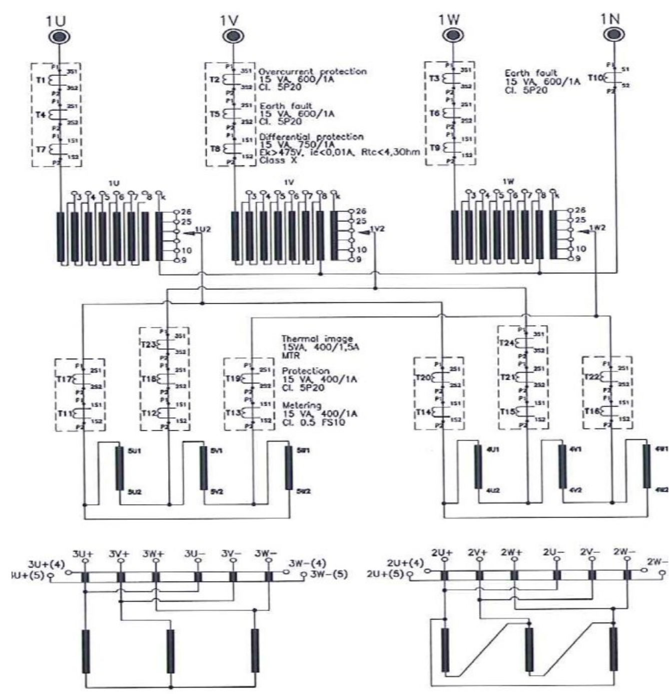

Fig. 3. Single line diagram of rectiformer (taken from [4]).

The fine tuning of rectifier output current is achieved using saturable reactors, i.e. transductors, which employ a control current in bias coils to effectively control the point of onset of transductor saturation within the AC-side phase-voltage pulses ahead of the diode bridge. The resulting period of phase-voltage blocking is used to control the rectifier current. The control range of rectifier output voltage is usually between 60-80 VDC. The circuit diagrams of saturable reactors deployed in Potline21 rectiformer systems is shown in Fig.4.

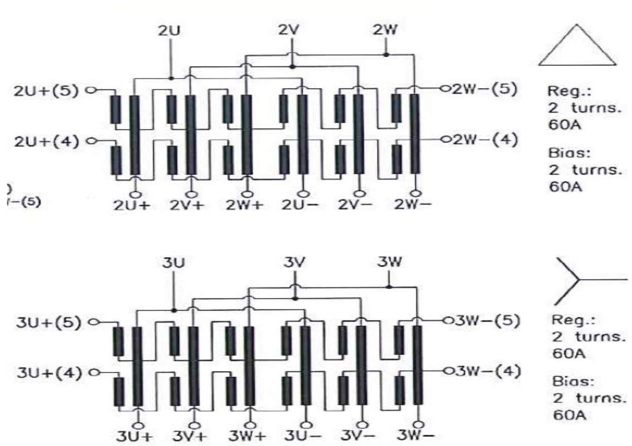

Fig. 4. Saturable reactor configuration(taken from [4]).

The transductor bias current flows in the opposite direction to the main current, presenting a cancelling flux to that produced by the main current flow. This effect allows the output current to be regulated as illustrated below.

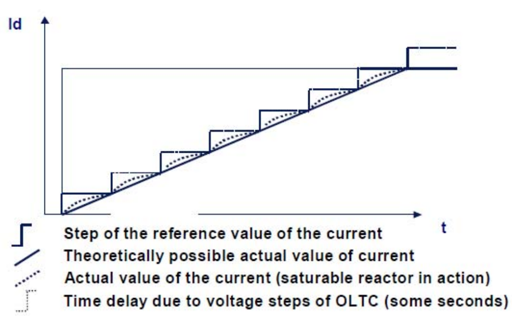

Fig. 5. Current control of diode rectifier (taken from [1]).

B. Thyristor Based Rectiformers General layout(Eagle)

Usually, a thyristor-based rectifier comprises a smaller number of units in parallel than the diode-based configuration. However, in this case study, Potline 5 Eagle comprises 7 rectifier units: five of them with an individual rated capacity of 30 kA and 60 V , while the other two are each of a rated capacity 40 kA and 60 V. The unit AC inputs are phase shifted apart by using different transformer configuration to give phase shift values of 0°, 0°, 0°, +30°, +30°, -15° and +15° respectively from unit 1 to 7 [6]. Each individual rectifier constitutes a 6-pulse bridge rectifier; hence the six different phase options produce a total of 24 pulses on the DC bus bar.

The single line diagram of the main Potline is given in Fig.6.

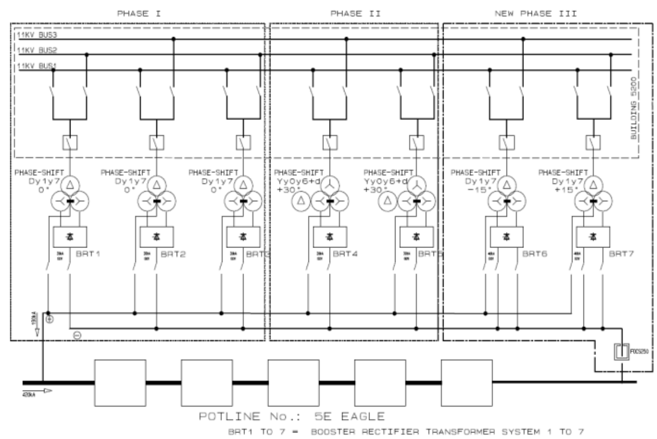

Fig. 6. Single line diagram of thyristor-based potline (taken from [5]).

The single-line diagram of each rectifier unit is given in Fig.7

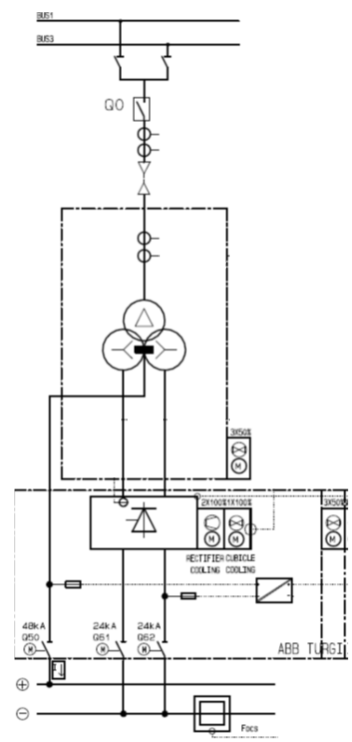

Fig. 7. Single line diagram of thyristor-based converter (taken from [5]).

The transformer deployed in the thyristor-based rectiformer is usually a delta-star-star, DSS, transformer with an interphase transformer, IPT, where:

1. two 180°-shifted secondary star windings eliminate the DC component of the flux in the secondary side;
2. the two rectifier outputs are paralleled via an IPT, hence the DC current is doubled and the DC voltage is halved, which suits the application of a booster high-power rectifier.

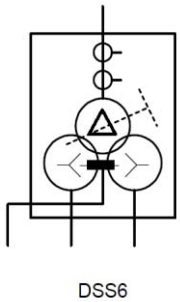

Fig. 7. Single line diagram of thyristor-based converter transformer layout.

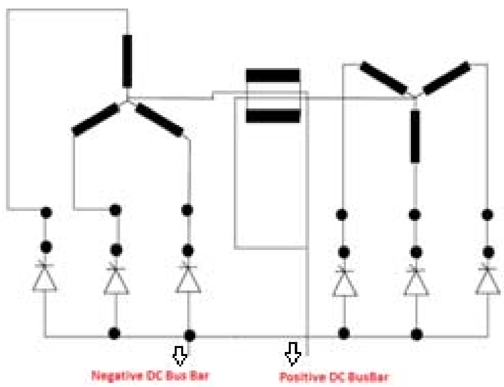

Fig. 8. Thyristor-based rectiformer secondary side and rectifier.

The current regulation of the thyristor-based rectiformers is performed through firing angle control of the thyristor gates. There are two ways to trigger thyristors to conduct; either via the application of a relatively low-level current signal to the gate or by the application of a voltage greater than the break-over voltage across the thyristor. The thyristor gate signal is a small pulsed-current signal that triggers a thyristor from forward blocking mode into forwarding conducting mode.

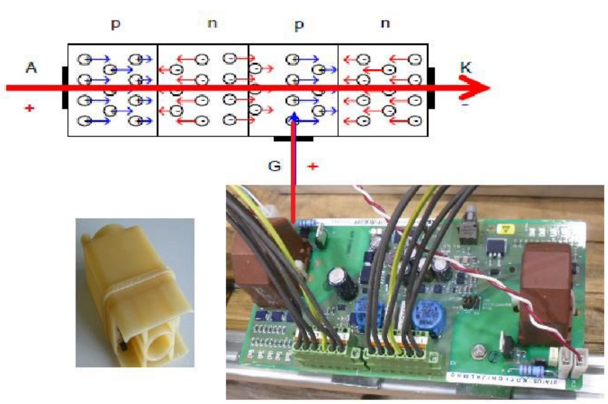

Fig. 9. Thyristor firing angle control illustration and module.

The firing pulses generated from the thyristor control system are electrically isolated from the rectifier by the use of pulse transformers. The pulse transformers are mounted on an insulating board on the direct current busbar.

III. Implications on AC Network

The effect of having a switching device on any AC network can be seen through the huge ramifications it leaves on the power quality of that system. This is evaluated through the total harmonic distortion (THD) imposed on the system and the voltage stability of the network. Harmonics can be defined as undesirable sinusoidal components of periodic waves having frequencies which are integral multiples of the fundamental frequency.

Rectifiers are non-linear circuit elements that generate harmonic currents. The non-sinusoidal harmonic currents drawn by the rectifiers are injected into the AC power lines/transformers /source causing a number of problems for the power distribution network and for other electrical systems in the vicinity of the rectifier deteriorating the power quality at the point of common coupling.

The harmonic generated on the AC network is tightly related to the number of the pulses generated by each switching device as shown by (1) [7].

$$h = k \pm 1 \quad \text{where } k = 1, 2, 3\ldots \qquad (1)$$

Where h is the most significant harmonic order distortion and k is the number of pulses generated by the switching device. The generated harmonics will affect the power quality of the AC network leading to several problems to all power system components and potentially destroying some devices in severe cases [6].

This study compared the thyristor vs diode based convertors from a system and application prospective. The implications of using diodes or thyristors based AC to DC convertors on the AC power network has been investigated in terms of:

a. generated harmonics,
b. voltage stability.

The above parameters have been studied using the power network simulator International Power System Analyser IPSA 2.3.1 and the results are compared with the actual measurements collected from the site.

A. PL21 Simulations and Measurements

As stated above, PL21 has 5 units of 12 pulse rectifier where each unit is 84.1 MVA power rated. The transformer voltage ratio is 132kV/1.227/1.239kV and the transformers are phase shifted as described earlier. All 5 units are connected in parallel to enable units to draw currents in a Phase-staggered manner, resulting in the cancellation of certain harmonics.
The configuration of PL21 rectiformers has been simulated on IPSA2.3.1 within DUBAL power network as shown in Fig.10

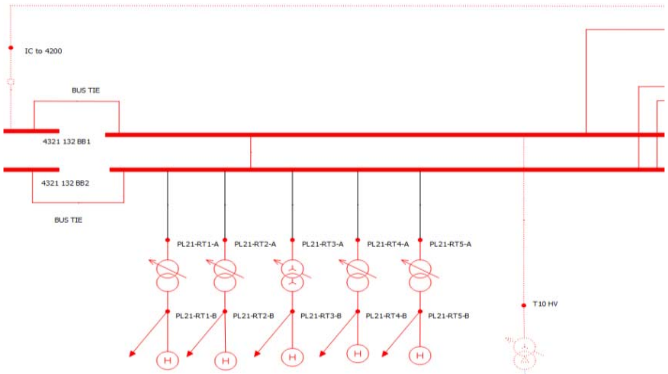

Fig. 10. PL21 Rectiformers simulated on Dubal power network

The study was done to examine the harmonics generated and the results are shown in Fig. 11.

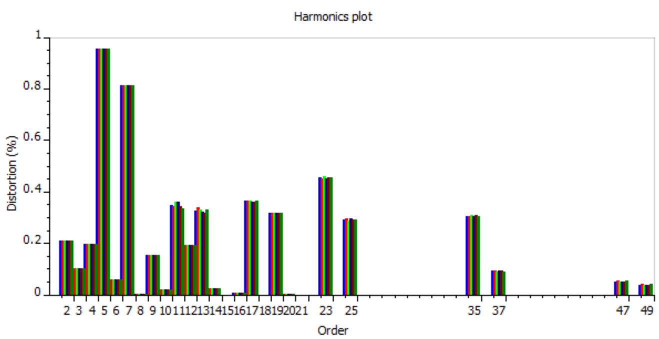

Fig. 11. Harmonics plot for Potline21 132 KV Bus and all RT's

The simulation considered the scenario of all units in service sharing the potline load of 200 kA. The rectiformers were symbolized with harmonic sources and the values of the OEM data sheet harmonics were used. The voltage signal shape of units and feeding bus bars were detected through IPSA as shown in Fig.12.

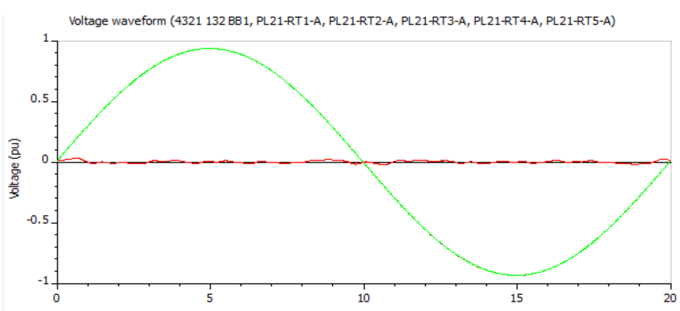

Fig. 12. Voltage waveform for PL21 132 kV bus and the harmonic distortion.

The same scenario parameters were measured at the 132 kV Bus Bar and the results were found as shown attached in appendix A.

B. *Eagle Boosters Simulations and Measurements*

In PL5 Eagle, there are 7 rectiformers connected in parallel with the below details:

1. Booster RT1, 2 & 3 are of 2.396 MVA, 11kV/112.9V/112.9V Dy1y7 + IPT with 0° phase shift.
2. Booster RT4 & 5 are of 2.396 MVA, 11kV/112.9V/112.9V Yy0y6 + d + IPT with 30° phase shift.
3. Booster RT6 & 7 are of 3.743 MVA, 11kV/112.9V/112.9V Dy1y7 + IPT with +15°, -15° phase shift.

The configuration of Eagle rectiformers along with two harmonic filters rated at 8 MVAR has been simulated on IPSA2.3.1 as illustrated in Fig.13.

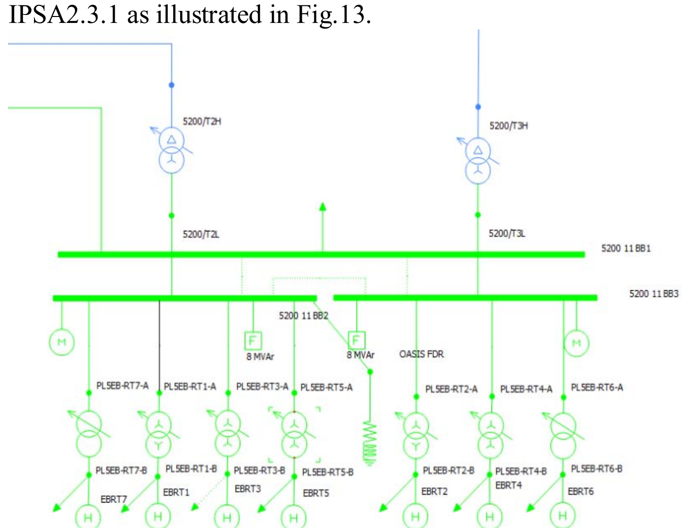

Fig. 13. PL5 Eagle rectiformers simulated on Dubal power network.

The study was done to examine the harmonics generated and the result is shown in Fig.15. The simulation considered the rectiformers as harmonic sources and the OEM data sheet guaranteed values were fed into the simulator. The simulation considered the operation scenario of all units in service sharing the Potline load of 190 kA.

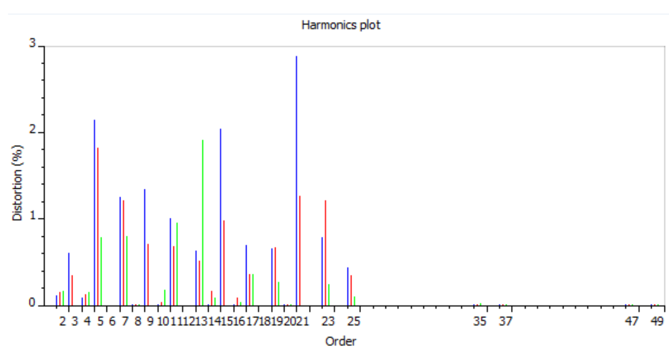

Fig. 14. Harmonics plot for Potline Eagle 11 kV Bus 1, 2 & 3

Sc	PL kA	Unit Status and kA load							Time	
		RT1	RT2	RT3	RT4	RT5	RT6	RT7	Date	Duration
N-0	190	27	27	27	27	27	35	35	19.02.2013	30 mun

The voltage signal shape form was detected through IPSA as shown in Fig.15.

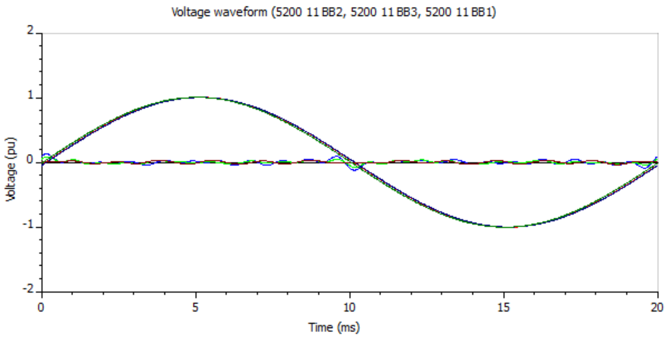

Fig. 15. Voltage waveform for PL Eagle 11 kV Bus and harmonic distortion.

The same operational conditions were fed into the system and the resulting measurements are shown attached in appendix B.

IV. DISCUSSION

From the above simulation results and measurement data, it is clear that the thyristor based rectiformers generate higher THD than the ones generated through the diode based ones. The same is explained due to:

1. The number of pulses used in the thyristor-based rectifier is 6. That will generate higher harmonics on the 5^{th} and the 7^{th} harmonic order which has more serious ramifications on the system.
2. The AC input of the thyristor-based converter is 11kV system. The lower the voltage level, the higher the tendency of harmonics to affect it as the voltage will be less stable when it encounters fast switching.

In PL21, the simulation and the measurement data displays better harmonic levels which do not exceed 1%.The limits are still below the requirements of the THD level stated under IEEE-519-1992 standard [8] of the system voltage THD of 2.5%. In PL 5 Eagle, the simulation and the measurement data displays higher harmonics levels. However, with the existing implemented harmonics filters, the level of existing harmonics do not exceed for any single order 3% THD which is matching with the IEEE-519-1992 standard and the total THD is way below the 5% THD required for 11KV bus bar at <2%.

CONCLUSION

The above study highlighted the main features of the two main technologies used in rectification applications for aluminium smelting process. The study demonstrates better performance of the diode-based AC-DC converter in comparison with their equivalent thyristors-based converters, in terms of their effect on the feeding AC network within the scope of the aforementioned configuration. However, the thyristor rectifier still offers several other advantages. The fast regulation performance is preferred advnatage for certain industrial process plants, better fine tuning on the DC network side, and faster response to Frequency Load Control schemes when connected to grid. These can play a major part in favoring thyristor-based AC-DC converters over diode-based ones in many situations. This study was based on a 6-pulse thyristor rectiformer; hence, the above results would be different in the case of using a 12-pulse thyristor rectifier at the same voltage level.

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