INVESTIGATION INTO THE HARMONIC BEHAVIOUR OF MULTIPULSE CONVERTER SYSTEMS IN AN ALUMINIUM SMELTER

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Abstract

Modelling of diode rectifier systems in smelters and their impact on HV supply system is made difficult by a number of factors. Such systems contain multipulse configurations and are connected to HV networks of large capacities and their physical extent is difficult to gauge for modelling purposes. In the converter outputs, there are output current regulation techniques that are unique to these systems. Modelling is also made difficult further by the uncertainty of the device and system parameters and the background disturbance levels especially as the pulse number of converters is high. The paper outlines the methodology adopted in an investigation at a smelter, highlighting the approaches taken to overcome some of the difficulties. Results of the simulation work carried out in both time and frequency domain are also summarised.

1 INTRODUCTION

The operation of large Aluminium smelters is very much dependant on AC to DC converters. These are often three-phase diode rectifier systems having multipulse configurations in order to eliminate characteristic low order harmonics. Smelters normally derive their supply from the high voltage grid with their own step-down transformers and phase shifting transformers. Pulse number of these converter systems could be as low as 12 and high as 96 or more. Elimination of characteristic low order harmonics with the use of phase shifting transformers is a cost effective approach instead of using tuned filters at the high voltage level [1]. The output dc current of these converter systems is often regulated using an appropriate means.

Based on the pulse number and the ideal operating conditions the current harmonics can be relatively easily predicted and their impact on the high voltage network and on other system connected components (such as capacitor banks, filters and loads) can be established. However, due to non-ideal conditions such as finite supply system impedance and its unbalance, asymmetry in the system impedances in both the supply network and phase shifting transformers the converter systems produce non-characteristic harmonics [1]. The high voltage system configurations can change from time to time and often requirements to upgrade within a plant place an important emphasis on simulation studies to investigate the impact of such variations. It is possible to check the simulation results with measurements once such operational changes have been carried out.

This paper outlines the layout of the Boyne Smelter in Gladstone and the nearby high voltage network. The objectives of the study are summarised and a description of the methodology adopted and tools used are briefly described. Some of the problems encountered in the study are presented followed by some results and conclusions on the outcome of the study.

2. LAYOUT OF THE HV SUPPLY NETWORK, THE SMELTER AND THE REDUCTION LINES

As shown in Figure 1 the Boyne smelter is supplied by 132kV and 275kV transmission lines (system shown is only a part of the Queensland transmission system). The 275kV/132kV step-down transformers fed by the Wurdong lines are connected to the 132kV bus within the smelter. There are also capacitor banks (with detuning inductors) at Wurdong and Gin Gin.

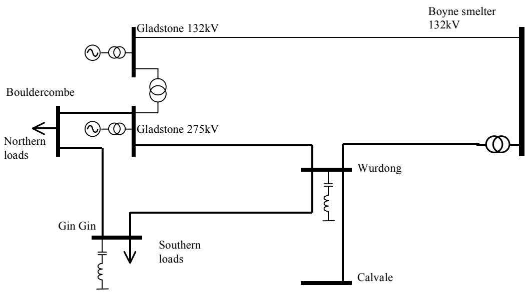

Figure 1 HV network in the vicinity of the smelter

A simplified plant layout of the smelter is shown in Figure 2. There are 3 reduction lines (RL1-RL3) with a total capacity of approximately 780MW. Each reduction line supplies 4 groups of 12-pulse rectifiers. The plant also contain capacitor banks (with detuning inductors) and harmonic filters tuned to 5th, 7th, 11th and 13th harmonics. The other loads primarily consist of induction motors supplied by step-down transformers.

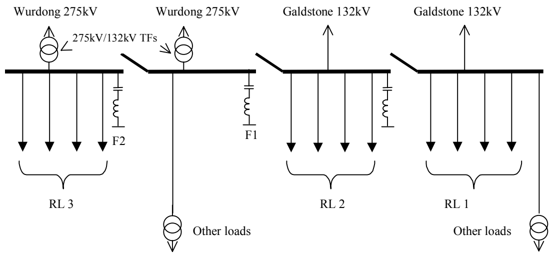

Figure 2 Layout of the smelter

Each rectiformer unit consists of a step-down transformer and two phase shifting zig-zag transformers as shown in Figure 3. Each zig-zag transformer supplies a 6-pulse rectifier and the output terminals of the two rectifiers are connected to the dc bus to form a 12-pulse system via saturable current regulation devices. The phase shifting in the zig-zag transformers in the different reduction lines are such that when paralleled on the dc bus the required 48-pulse or 96-pulse operation is established.

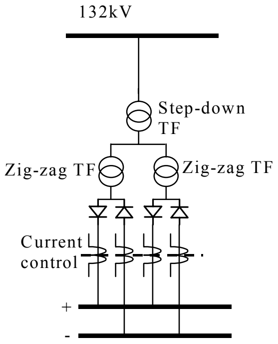

Figure 3 Layout of a 12-pulse rectiformer

3. OBJECTIVES OF THE HARMONIC STUDY

There were several objectives of the study. Time domain and frequency domain simulation studies were to be carried out to examine the impact of the smelter on the capacitor banks, filter banks and other connected equipment. There were also some measurement results that were available giving the current spectra of the reduction lines which were to be used in the study. A sensitivity study was also to be carried out to examine the effect of some variations in the operating conditions.

4. METHODOLOGY OF THE STUDY AND THE PROBLEMS ENCOUNTERED

The project was to be a first stage and was not to involve a complete time domain analysis of the system due to time and cost limitations. Further, it is often difficult to have confidence in the results obtained from such a study unless the results from a more simplified study or extensive measurements are available for comparison. Also, if a simplified study gives the expected results with acceptable accuracy then the effort and the costs incurred on a major time domain study would have been avoided.

One of the major problems with a complete frequency domain study is the establishment of the frequency spectra of the injected currents by the reduction lines. Such spectra would enable the determination of the impact on the HV network as well as capacitor banks, harmonic filter systems and other connected equipment. Although some frequency spectra of reduction line currents were available through previous measurements the HV network operating conditions under which these were measured did not coincide with what had to be investigated.

In 6-pulse operation of a rectifier it is possible to account analytically for the overlap angle and its effect on current harmonics. However, when several converter inputs are paralleled on the AC side (132kV bus) the commutation within one converter can interact with other converters and thus the prediction of the current harmonics can become too difficult. In this situation only a time domain simulation seems to be the option available.

For the reasons given above, a hybrid approach involving both time and frequency domain analysis was adopted. In this approach, the frequency spectra of current established for various operating configurations (of reduction lines and the HV network) using time domain simulations are to be used in frequency domain to examine the impact on HV network, the capacitor banks and the filter capacitors. In the time domain analysis of the reduction lines it was assumed that the filter capacitors and other loads connected to the network have a second order effect on the current spectra. Hence the HV network was simplified to a Thevenin's voltage source and impedance. The effect of other loads are to be taken into account in the frequency domain analysis.

For time domain analysis the tool that was available was PSCAD®/EMTDC™ [2] which is widely used in the power system industry. The frequency domain analysis was carried out using MATLAB® and these results were to be checked partially against the results from a spreadsheet program previously developed.

PSCAD®/EMTDC™ allows representation of diode rectifiers systems and transformers. However, there is no readily useable model for the saturable reactors that are connected at the output of the rectiformers as shown in Figure 3. As the current regulator operates as a switch delaying the turn on of the diodes, the rectifiers can be represented by an SCR converter with an equivalent firing angle based on the voltage variations specified.

The 1:1 zig-zag transformers of the rectiformer units were modelled by interconnecting the three winding single-phase transformer units available in PSCAD®/EMTDC™. The number of turns of the three windings of a zig-zag transformer configuration giving the required phase shift can be established using the set of equations:

$$\begin{aligned} n_1 &= 1 \\ n_2 &= \frac{2}{\sqrt{3}}\sin(60-\theta) \qquad (1) \\ n_3 &= \frac{2}{\sqrt{3}}\sin\theta \end{aligned}$$

where n_1, n_2, n_3 are the pu voltages of the primary, secondary and the tertiary phase windings of a transformer unit and θ is the required phase shift between the primary and the total (interconnected) secondary. As input parameters in the setting up of the zig-zag transformers in PSCAD®/EMTDC™ it is required to specify the pu leakage reactances x_{12}, x_{13} and x_{23} where the subscripts 1, 2 and 3 represent the primary, secondary and the tertiary windings. The effective leakage reactance x_T (pu) of a zig-zag transformer can be expressed as [3]:

$$\begin{aligned} x_T &= \frac{2}{\sqrt{3}}\left[x_{12}\sin(60-\theta)\cos\theta + x_{13}\cos(60-\theta)\sin\theta\right] \\ &- x_{23}\frac{2}{3}\sin(60-\theta)\sin\theta \qquad (2) \end{aligned}$$

However, the distribution of the leakage reactances between the three different windings is not known in many practical situations unless design details are known. For the smelter zig-zag transformers only the total reactance x_T was known. For the special case when $x_{12} = x_{13} = x_T$ and $x_{23} = 0$ the effective reactance given by equation (2) simplifies to x_T for any phase shift θ. Therefore, the setting up of the transformer parameters within PSCAD®/EMTDC™ became simpler.

In PSCAD®/EMTDC™ for modelling the combination of a diode rectifier system and its saturable reactor the standard SCR converter (HVDC valve group model) with firing angle control using a phase locked oscillator (PLO) was used. In the study, the commutation bus for the synchronisation of the firing pulses for the SCR converters was selected to be the zig-zag transformer primary voltages. The above model also enables the monitoring of the actual firing angle (including the extinction angle) as a simulation proceeds, therefore any instabilities in the firing angle can be detected. The model also allows phase locked loop oscillator gains to be modified.

In simulating the dc side load of the SCR converter multipulse operation problems were encountered. The SCR firing angle was set to a selected value for all converters and simulation proceeded quite well when each converter had a separate isolated load. However, when all outputs of the converters were paralleled to form a single load (as in practice) the firing angle became oscillatory. Although attempts were made to adjust the PLO gains satisfactory results were not obtained. The problem may be attributed to the high frequency circulating current between the different converters. It was hence decided that the simulations be carried out using individual SCR converters having representative loads.

PSCAD®/EMTDC™ also comes with an FFT block which is able to give the harmonic components up to the 31st order as a simulation proceeds. As the software allows exporting of the time domain data to other platforms MATLAB® was also used to obtain the frequency spectra especially when higher order harmonics greater than 31st were of interest. In the present study harmonics up to 49th were of concern. As the smelter operation involved 12-pulse, 48-pulse and 96-pulse operation of converters a wide range of characteristic harmonics are to be expected (as low as 11th). More importantly, the low order non-characteristic harmonics that would be caused by unbalance in the supply and asymmetries in the transformers and lines are important in the present study.

The time domain studies were also extended to carry out some sensitivity investigations. These included the operation of the SCR converters (in the simulation) at 0° and subject to small variations around the operating firing angle that was mentioned before. The asymmetry in the equivalent system impedance, and its unbalance (both magnitude and phase), sensitivity of the converters to external (background) harmonic voltages (5th in particular) were also examined in order to obtain a representative current spectra.

The frequency domain models of the HV network including Gladstone power station, filter capacitors and loads were established for frequency response study. As the highest frequency of interest was 49th harmonic both short line (lumped parameter) and long line (distributed parameter) models were developed for the HV network where considerable lengths of lines involved. Once the various nodes of the network are identified the node voltages and node injected currents can be related by the complex matrix equation

$$[\mathbf{I_h}]=[\mathbf{Y_h}][\mathbf{V_h}] \qquad (3)$$

for a harmonic order h where $[\mathbf{Y_h}]$ is the complex bus admittance matrix at harmonic order h. Any background harmonic voltage that can be assumed at a remote bus also can be incorporated if its phase angles is known. The injected currents in the use of the frequency response study were based on both the time domain simulations and the experimental results that were provided. Once the harmonic voltages are established the harmonic line currents can be easily worked out. In the MATLAB® program automatic checks have been included to flag any exceedances in the harmonic line currents, filter inductor currents and voltage limits.

5 SUMMARY OF RESULTS

As a first step, AC HV side current harmonics due to 12-pulse operation had to be established. There were no experimental results available to compare the simulation results with and an experimental spectrum had to be inferred using measurement results available for 48-pulse and 36-pulse operation where both characteristic and non-characteristic low order harmonics (3rd, 5th, 7th etc) have been recorded. It was assumed that the fundamental current due to 12-pulse operation is the difference between 48-pulse and 36-pulse operation (measured while one 12-pulse converter was out of operation). Where the percentage harmonic currents between 48-pulse and 36-pulse operation were the same it was assumed that the same percentage applies to 12-pulse operation as well. Where the percentages were different it was assumed that those harmonics arose due asymmetry of operation caused by the removal of the 12-pulse unit and are equal to the scaled down absolute values for the 36-pulse operation.

A representative current spectrum for 12-pulse operation cannot be easily established using a single time domain simulation as many factors have to be considered which represent the actual operation. As stated earlier the operation of a diode rectifier with saturable reactors were represented by an SCR converter with an appropriate firing angle. The SCR converter outputs when paralleled did not give rise to stable operation when a finite firing angle was used. However, stable operation was obtained for a finite firing angle when individual loads were connected to the 2 converters. Hence the current spectrum for a finite firing angle in the case of single dc load had to be inferred by scaling the results obtained for the operation of the converters having separate dc loads with a finite firing angle. In the individual simulations several tests were carried out where the waveforms and frequency spectra were examined for different firing angles (Figures 4 (a)-(c)). For zero firing angle (although not representative) the higher order current harmonics decrease (due to larger overlap angle) in magnitude indicating that it gives optimistic results compared to operation with a representative firing angle.

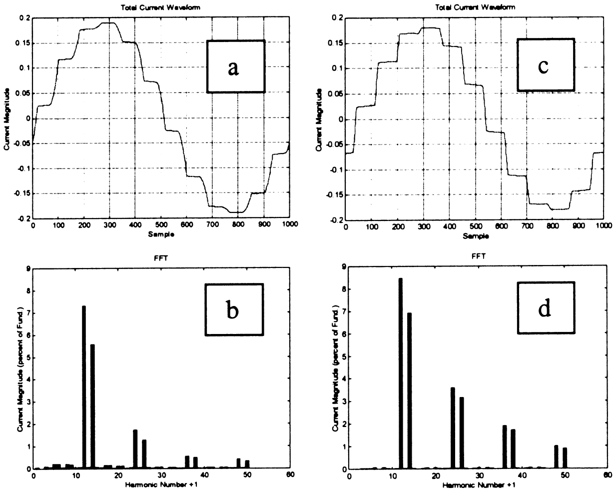

Figure 4 Current waveforms and spectra for 12-pulse operation, (a-b: for α=0°), (c-d: for α=18°)

A supply voltage magnitude (V_s) unbalance of 1% was found to introduce a significant 3rd harmonic. The effect of the presence of 5th harmonic background voltage with assumed phase angles was also examined. From the many simulations carried out it was found that the firing angle had to be known within a few degrees to reach a specified accuracy. The sensitivity to variations in the supply system impedance ($R_s + jX_s$) and its unbalance was also examined in addition to variations in the dc load (R_{dc}). As expected non characteristic harmonics were revealed in these sensitivity studies. To clarify that these harmonics are not due to problems in relation time step selected in the various simulations, shorter time steps were also attempted but there were no changes to the results.

Table 1 summarises required accuracy of major parameters used in the time domain simulations to reach a specified accuracy (18%) of a harmonic magnitude.

Based on the above discussion on simulation results and the experimental (inferred) results harmonic spectrum of the HV side current can be summarised as in Table 2.

From Table 2 it is seen that there are significant differences between the experimental and measurement results. The major differences are primarily in the non-characteristic harmonics (5th, 7th) and there are less differences in the characteristic harmonics. The gross assumptions used to establish both the experimental and theoretical spectra of the 12-pulse operation cannot be easily justified based on the above observations.

Simulation runs similar to those carried out for the 12-pulse operation were also carried out for 48-pulse converter systems. The various tests indicated that its operation is not as sensitive as the 12-pulse operation and the most sensitive parameter was the firing angle which has to be known within a few degrees. Table 3 compares experimental and theoretical results. As in the case of the 12-pulse operation theoretical spectrum for 48-pulse operation has been established using a number of simulation runs.

It is seen from Table 3 that the characteristic harmonics are close in their magnitudes. The theoretical approach has been unsuccessful in establishing the individual levels of the non-characteristic harmonics levels but the average order of magnitude is in reasonable agreement.

The results for 96-pulse operation are given in Table 4. As seen in 96-pulse operation the simulations have not revealed harmonics in the frequency range of interest

The frequency domain studies show that the long line model gives results which are slightly different to those predicted by the short line models as expected (there is perfect agreement between the two models at low frequencies).

6 SUMMARY AND CONCLUSIONS

A true representation of the reduction lines, converter systems and their current regulators, associated HV transmission systems and other loads within the plant required for a complete harmonic study would mean a great deal of effort and time. In practice, sufficient parameters for a complete study would be difficult to obtain which means satisfactory modelling cannot be easily accomplished. Even if the parameters were available a complete study was beyond the scope of the present study.

In this study a hybrid approach towards theoretical modelling was feasible where both time and frequency domain investigations were carried out using the data available. The results obtained match satisfactorily with some measurement results that were available. Full verification of the simulation results can only be carried out after comprehensive measurement results are

Table 1: Required accuracy in system parameters

Parameter	α	X_s	V_s	V_s unbal - mag	V_s unbal - phase	X_s unbal	V_5	R_s	R_{dc}
Accuracy (%)	2°	9%	-	6%	-	-	18%	-	9%

Table 2: Comparison of 12-pulse rectifier models

h	3	5	7	11	13	23	25	35	37	47	49
I_h(%) expt	0.4	4.31	2.73	9.58	5.75	1.77	1.68	0.10	0.10	0.40	0.40
I_h(%) theory	0.6	0.28	0.16	4.61	4.51	3.94	3.64	0.99	0.89	0.87	0.80

Table 3: Comparison of 48-pulse rectifier models

h	3	5	7	11	13	23	25	35	37	47	49
I_h (%) expt	0.4	0.73	0.47	0.26	0.15	0.1	0.1	0.1	0.1	0.40	0.40
I_h(%) theory	1.16	0.02	0.12	0	0.18	0	0.18	0	0	0.35	0.31

Table 4: Comparison of 96-pulse rectifier models

h	3	5	7	11	13	23	25	35	37	47	49
I_h (%) expt	0.53	0.55	0.31	0.74	0.69	0.35	0.26	0.10	0.10	0.25	0.28
I_h(%) theory	0.01	0.03	0.010	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00

obtained. However, this is usually not possible with a large commercial plant such as the Boyne Smelter because of the cost of setting up and interference with normal production.

The representation of the leakage reactances in zig-zag transformers in the time domain simulation is questionable. However, with the information available the only requirement that could be met was that the total leakage reactance be made equal to the specified value. Obviously, the improper distribution of leakage reactances between the windings in the various zig-zag transformers can give rise to harmonics which are not representative of the true case.

Another major difficulty faced was in the modelling of the diode rectifiers and the associated saturable reactors. For convenience these rectifiers were replaced with SCR converters operating at a specified firing angle. This representation led to a further difficulty with PSCAD®/EMTDC™ (with HVDC valve group model) where a single representative dc load on the multipulse converters did not allow the operation of the converters with a stable firing angle.

Despite the difficulties encountered in the study the results obtained are encouraging considering the relatively simplistic approach taken.

REFERENCES

1. Bathurst, G.N., Smith, B.C, Watson, N.R., and Arillaga, J., ‘Harmonic modelling of high-pulse converters’, IEE Proc.-Electr. Power Appln., Vol. 146, No. 3, May 1999.
2. PSCAD®/EMTDC™ Version 3, Manitoba HVDC Center, Manitoba, Canada.
3. Blume, F., Transformer Engineering: A treatise on the theory, operation and application, John Wiley, 1961.