PLYMOUTH TUBE CO
USA

HARMONIC STUDY

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1. GENERAL

1.1 Purpose of this Study

The purpose of this study is to check the harmonic distortion at the Point of Common Coupling in compliance with IEEE 519 guidelines, to check voltage and current imbalance, voltage fluctuations and flicker, as well as main transformer capacity for connecting additional loads. This study is based on site measurements from April 16, 2007 10:58 to April 23, 2007 10:58 (at the Main Substation) and April 10, 2007 15:09 to 18:09 (at the Hot Mill, Diescher Mill Roll, Piercer Drive 2 and Induction Heater #1). A system simulation has been performed using ETAP Software Version 5.0.2

The effects of the addition of a 2,000 kVA induction heater and 2,000 kVA Roller Drive in the Hot Mill is also purpose of this study. Increased voltage swing and harmonic impact shall be quantified with the ETAP software.

1.2 Data Available

The following documents were available and used for programming the ETAP simulation model:

Plymouth Tube Co., Nipsco Short Circuit Studies of Plant, Drawing No. CP1030C
Plymouth Tube Co., Winamac 12.47 kV Distribution, Main Single Line, Drawing No. CE3273 Rev.6

1.3 General Assumptions

Following the data specified above and having installed the one line diagram on ETAP, the following assumptions were made:

Utility Impedance: Z1 = 13.756 + J28.146 Ohm @ 69 kV
Z0 = 25.753 + J60.844 Ohm @ 69 kV

Utility Impedance Values (100 MVA base) on ETAP:

Positive Sequence: R = 28.89% X = 59.12%
Isc = 1.272 kA @ 69 kV
Psc = 151.97 MVA @ 69 kV

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1.4 Executive Summary

Harmonic Currents – IEEE519 Compliance

As per Section 3.2 of this report, marginal IEEE compliance was found for measured values. Marginal compliance was confirmed with the ETAP simulations. The high maximum value of third harmonic distortion can be considered an abnormal event, probably due to extreme sporadic current unbalance. From the ETAP model it is not possible to predict the much higher 5th harmonic currents measured, but adding large non-linear loads will most likely not deteriorate this problem, as 5^{th} harmonic current distortion (%) decreases with increasing plant loading.

Voltage Imbalance

As per Section 2.3 of this report, voltage imbalance is in line with IEEE Std. 141-1993 recommendations, well below 2.5%, with the exception of some isolated sporadic peaks probably caused by metering transients or because of extremely sharp drive starting and / or reversing.

Current Imbalance

As per Section 2.3 of this report, current imbalance is also in line with IEEE Std. 141-1993 recommendations, with the exception of some isolated sporadic peaks probably caused by extremely sharp drive starting or reversing.

Voltage Swing (Flicker)

Voltage Swing was found critical and non-acceptable as far as Flicker is concerned. The addition of large drives in the future will furthermore deteriorate voltage swing reaching high intolerable levels, up to 16% as indicated on Section 3.4 of this Report.

Transformer Capacity

Actual loading conditions imply that the main transformer is not critically loaded as far as RMS demand is concerned, but the periodic peak overloading should be checked with the transformer manufacturer. With the addition of future loads the transformer would reach borderline loading, but will still be within reasonable loading limits as indicated on Section 3.4 of this Report.

Possible Solutions

The only problem that really needs to be addressed to allow for the planned load expansion is the flicker. Three possible solutions are:

- Increasing main transformer capacity by adding a transformer or replacing the existing with a larger one.
- Isolating sensitive load on a separate transformer and/or adding mitigating equipment locally where the problems occurs.

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- Addition of a real time filter bank at the Hot Mill fed from a dedicated isolation transformer will provide flicker mitigation and reduction while also correcting power factor and reducing utility charges.

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2. RESULTS

2.1 Harmonic Current Measurements

The following data was captured during measurements performed on April 16, 2007 10:58 to April 23, 2007 10:58 (Main Substation) and on April 10, 2007 15:09 to 18:09 (Hot Mill, Diescher Mill Roll, Piercer Drive 2 and Induction Heater #1). All values listed below listed are average and maximum values measured during the corresponding sampling periods. The Main Substation variables were sampled at a sampling time of 300 seconds. The Hot Mill variables were sampled at a sampling time of 3 seconds, one hundred times faster. This fact introduced some apparent misalignment of measured power, but this is only a metering issue which can be explained by the fact that with increasing sampling frequency average and maximum values get closer. Generally, faster sampling means closer maximum and average values.

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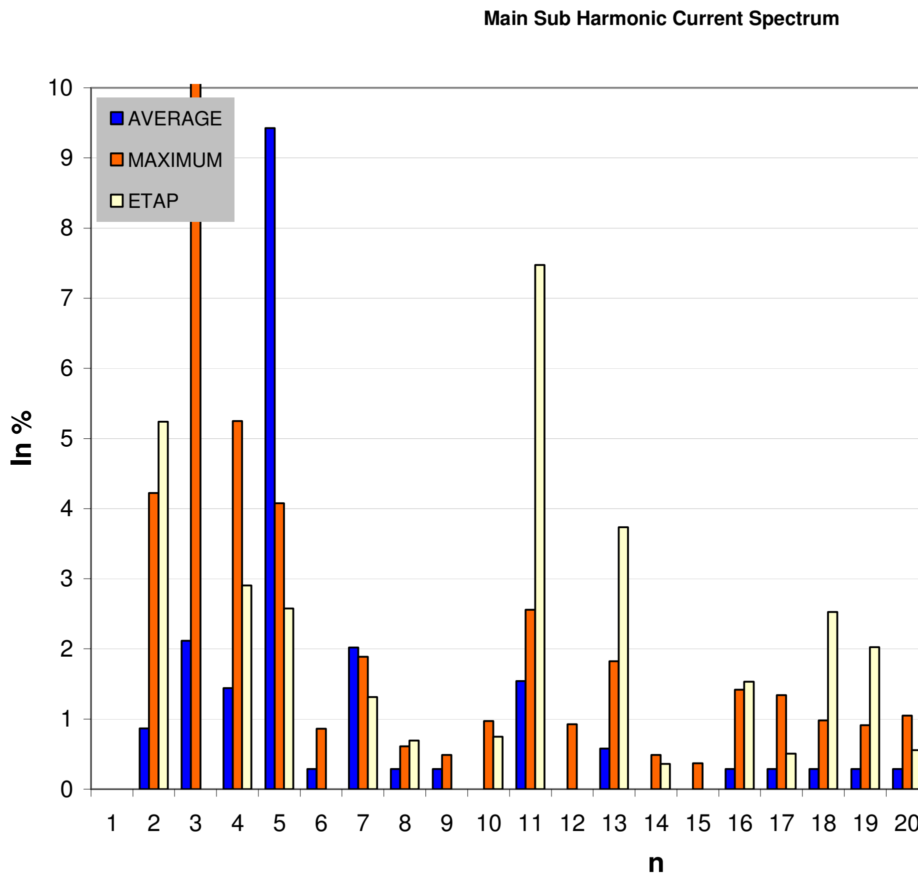
Main Substation Harmonic Currents: April 16, 2007 10:58 to April 23, 2007 10:58



	AVERAGE VALUES	MAXIMUM VALUES
Fund. Amps	107.73	510.58
1	100%	100%
2	0.8652	4.2227
3	2.1144	11.7503
4	1.4425	5.2470
5	9.4247	4.0779
6	0.2887	0.8643
7	2.0190	1.8869
8	0.2887	0.6121
9	0.2887	0.4896
10	0.0000	0.9738
11	1.5395	2.5563
12	0.0000	0.9258
13	0.5774	1.8260
14	0.0000	0.4869
15	0.0000	0.3673
17	0.2887	1.4197
19	0.2887	1.3391
23	0.2887	0.9792
25	0.2887	0.9129
29	0.2887	1.0494
31	0.2887	1.0404
35	0.2887	0.9129
37	0.1928	1.0956
41	0.0000	0.6174
43	0.0000	0.6087
47	0.0000	0.4869
49	0.0000	0.5556

Average and Maximum harmonic percent values in the table are maximum and average harmonic currents referred to the average and maximum fundamental currents of the complete measuring period of April 16, 2007 10:58 to April 23, 2007 10:58. The first column on the table indicates average percent values referred to the fundamental current indicated on the second line.

It is important to note that average values of current and power do not represent well the dynamic loading of the system, as one has to consider the sampling time of 5 minutes taken for the long time reading on the Main Substation. Maximum values can reach several times the average values. The harmonic currents of the larger drives are adding or canceling each other, depending on the drive speeds. Harmonic currents add (or cancel) in multiples (or fractions) of harmonic periods. Harmonic phase angles do play a role in the harmonic spectrum propagation through the system when dealing with multiple drives running asynchronously. As often the case, the lightly loaded conditions will exhibit a larger percent current distortion, that is why the average values for 5th and 7th harmonics are higher then the maximum values as the sampling period included a fair amount of lightly loaded periods.

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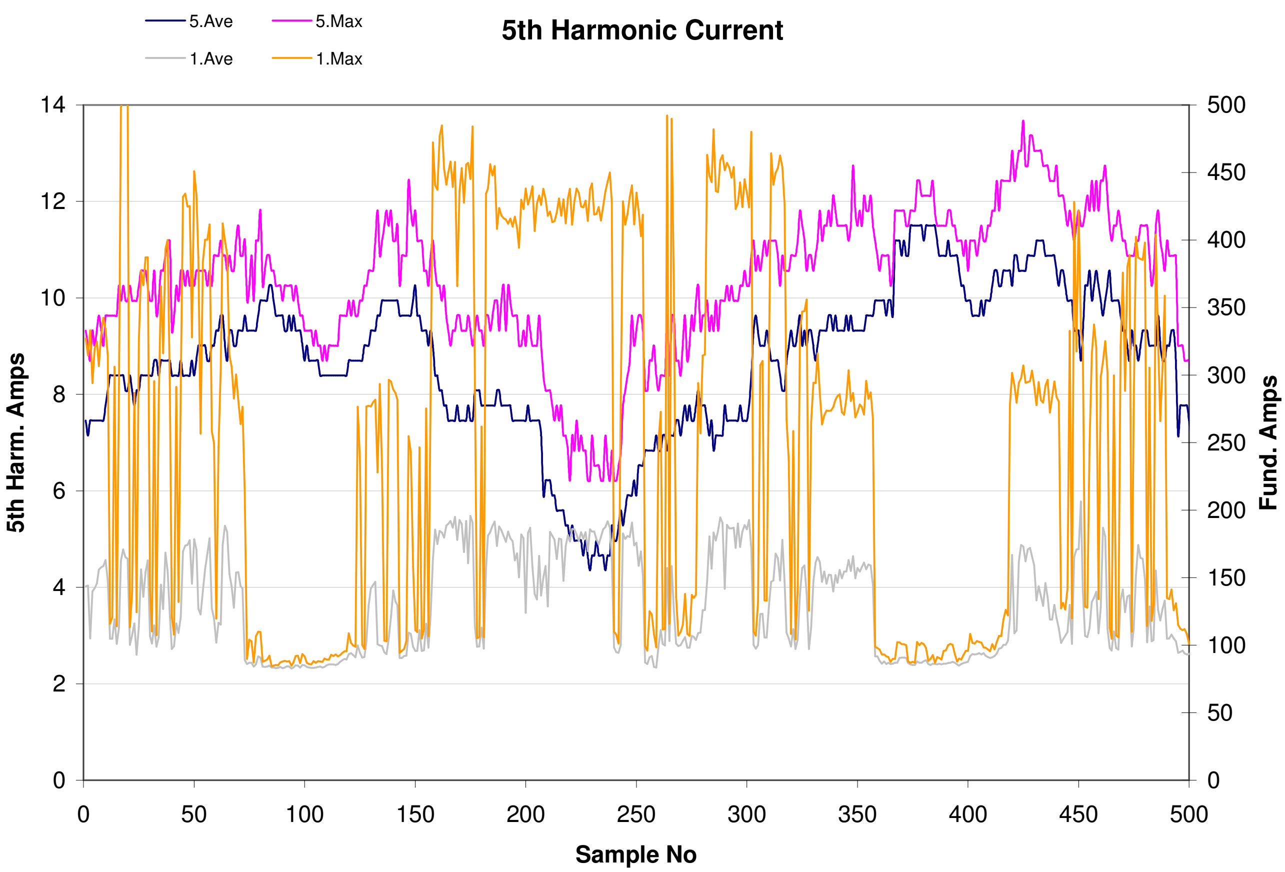
Direct correlation between actual plant load and absolute 5th harmonic current cannot be seen directly if looking at the current values (Amps) from the next chart. Considering that the plant loading is strongly dependent on the Hot Mill loading it would be possible to conclude that the Main Substation 5th harmonic current average and maximum percent values do not reflect proportionally the Hot Mill 5th harmonic current average and maximum percent contribution. Samples 0 to 500 were chosen here as an example but any other sample range shows a similar picture. [Please do refer to Section 3.2 and Section 4.3 for further information regarding this issue]



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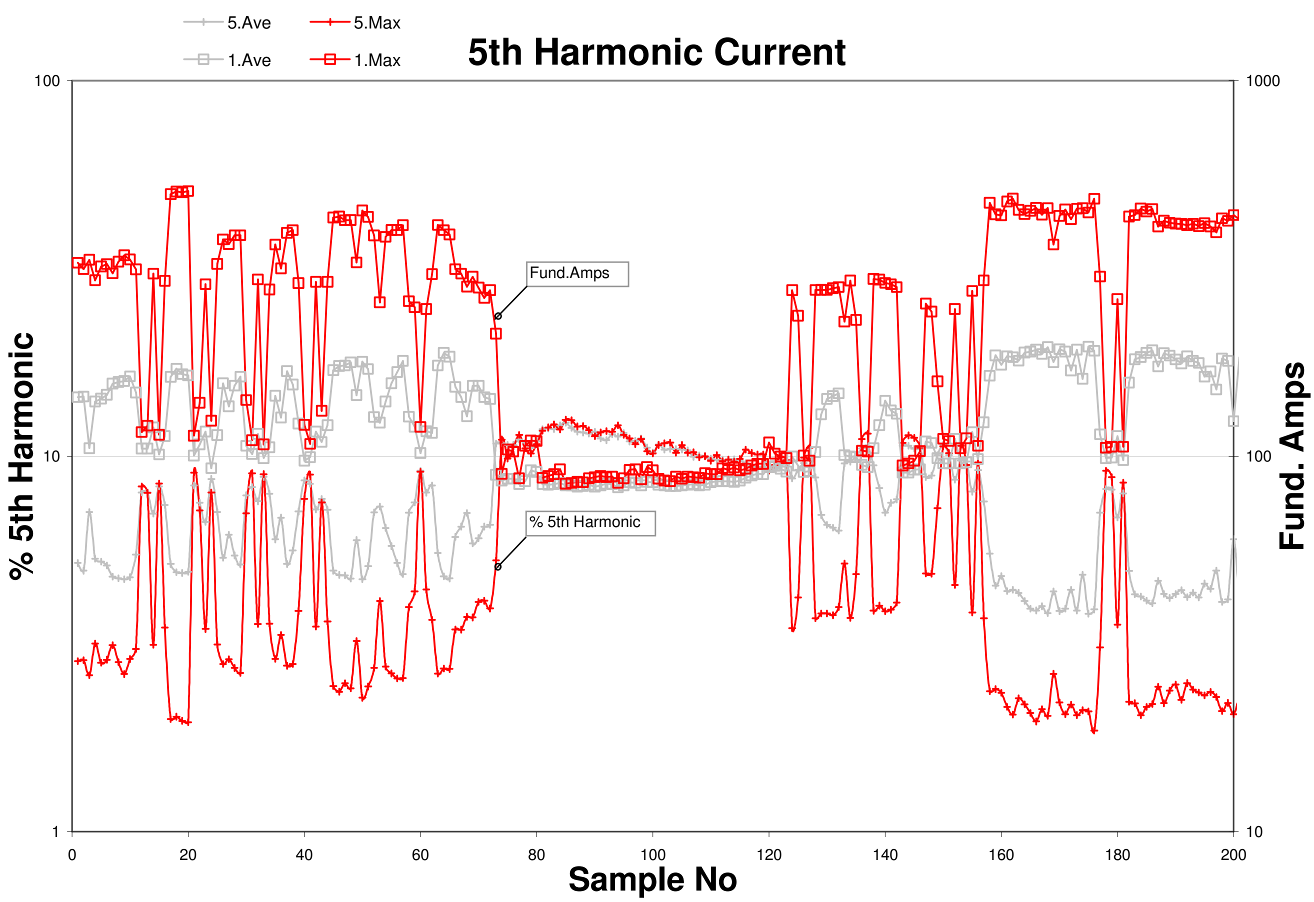
When changing the above representation to 5th harmonic current percent values and main substation current amps and using logarithmic scales (next chart), it becomes apparent that there is canceling action of the Hot Mill 5th harmonic current contribution. The following chart pictures clearly a base 5th harmonic current which is not generated by the large drives. This base 5th harmonic current represents a harmonic noise floor coming from another, most likely external source. The fact that there is at least partial cancellation of this harmonic current hints to a 30 degrees phase shift between the external harmonic source and the internal one from the Hot Mill. This is in line with the main power transformer having DY vector group. The existing filter must be absorbing external 5th harmonic current.



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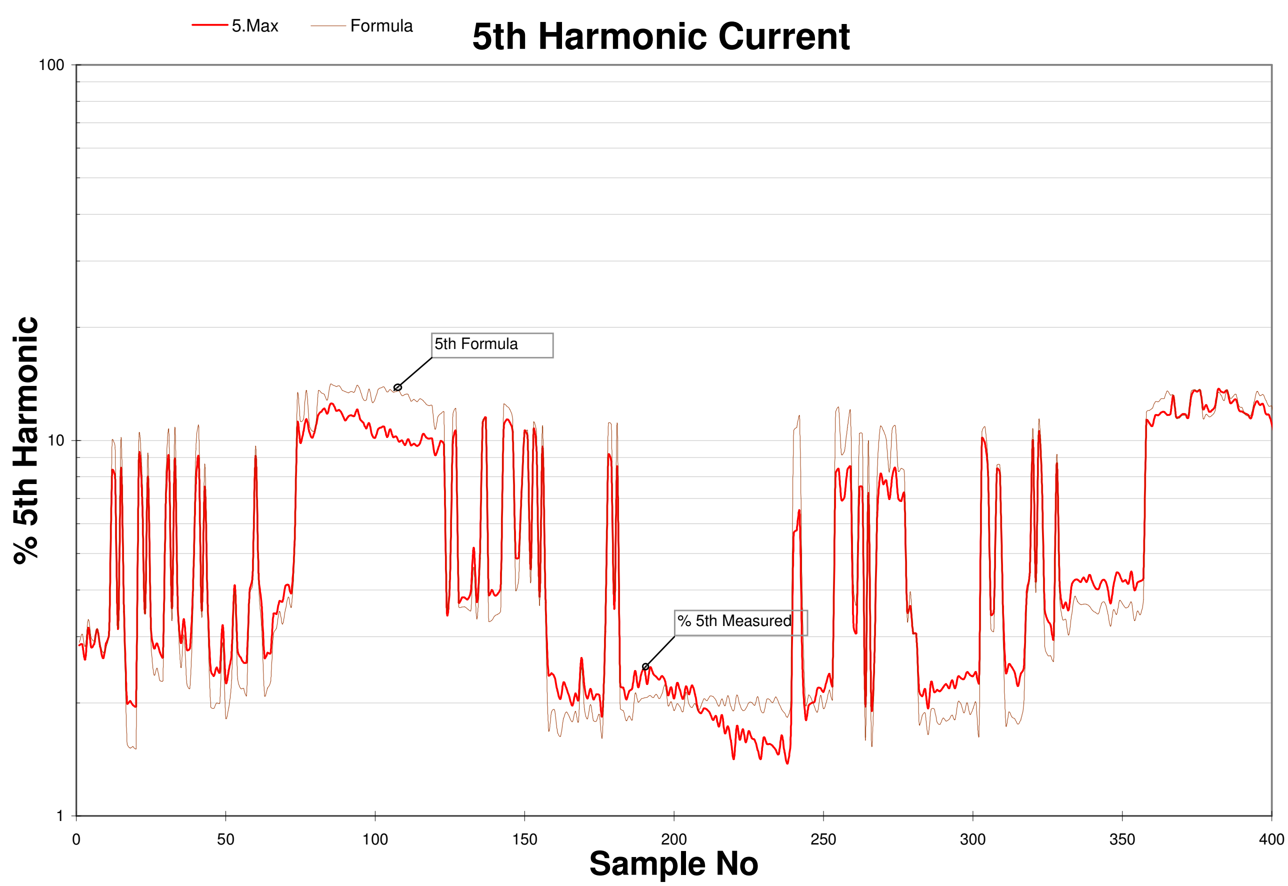
Introducing a simplified equation, it is possible to conclude that the % 5th harmonic current is basically an external 5th harmonic noise floor N (t) divided by the fundamental current I_1(t) times 100 minus the Hot Mill 5th harmonic partial contribution. It is also possible to simplify further N (t) ≈ 12 A as hinted from samples #1400 to #1800, when basically no load current is flowing into the Hot Mill (when the Main Substation fundamental current being approximately 100 A). The non-linear 5th harmonic current from the Hot Mill was set at relatively low constant rate of 1.5%. The herewith calculated values are presented in the following chart, showing good consistency with the measured maximum percent values. This presents reasonable support for the theory that the 5th harmonic current might be coming mainly from an external source, and this one being only partially canceled by the large Hot Mill drive 5th harmonics.

Simplified Equation: $\% \, 5^{th} \approx 100 \times N_5(t) / I_1(t) - 1.5 \times I_{DR} / I_1(t)$

With: $I_{DR} \approx I_1(t) - 100$

And with: N5 (t) ≈ 12 A



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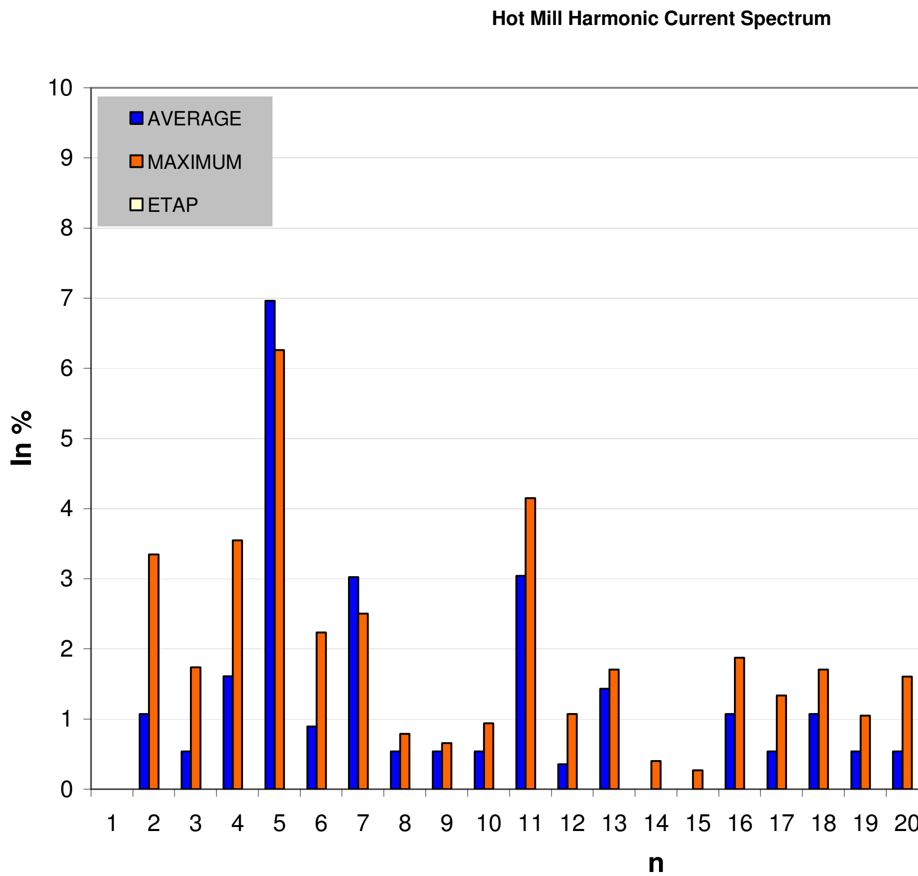
Hot Mill Harmonic Currents April 10, 2007 15:09 to 18:09



	AVERAGE VALUES	MAXIMUM VALUES
Fund. Amps	96.51	394.15
1	100%	100%
2	1.0735	3.3466
3	0.5368	1.7403
4	1.6103	3.5479
5	6.9644	6.2599
6	0.8952	2.2339
7	3.0222	2.5036
8	0.5368	0.7885
9	0.5368	0.6571
10	0.5368	0.9372
11	3.0423	4.1500
12	0.3585	1.0708
13	1.4301	1.7083
14	0.0000	0.4017
15	0.0000	0.2678
17	1.0735	1.8742
19	0.5368	1.3386
23	1.0735	1.7083
25	0.5368	1.0511
29	0.5368	1.6064
31	0.5368	1.3386
35	0.5368	0.6694
37	0.1783	0.7885
41	0.0000	0.8033
43	0.0000	0.7885
47	0.0000	0.6571
49	0.0000	0.9200

The difference between maximum and average values is also apparent here, but to a slightly lesser degree, probably because of the different sampling time, here of only 3 seconds, a hundred times faster than the sampling time chosen for the Main Substation. Average and Maximum harmonic percent values in the table are maximum and average harmonic currents referred to the average and maximum fundamental currents of the complete measuring period of April 10, 2007 15:09 to 18:09

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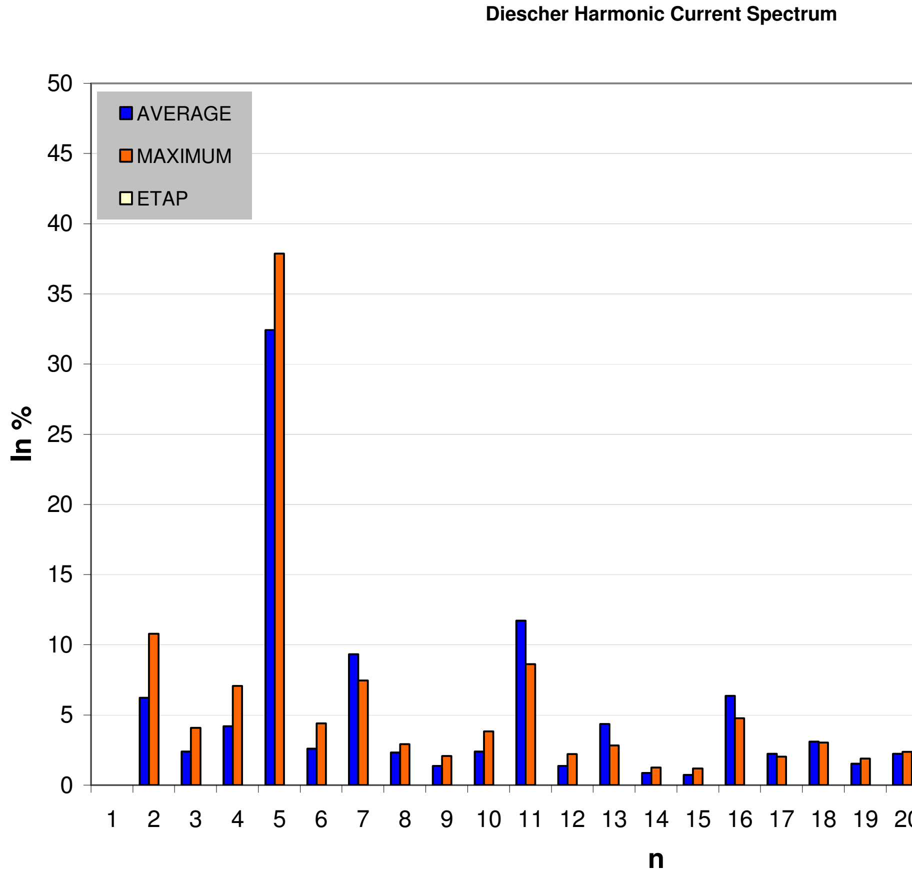
Diescher Mill Roll Harmonic Currents April 10, 2007 15:09 to 18:09



	AVERAGE VALUES	MAXIMUM VALUES
Fund. Amps	298.03	1441.79
1	100%	100%
2	6.2263	10.7914
3	2.3898	4.0862
4	4.2000	7.0593
5	32.4190	37.8698
6	2.6078	4.4006
7	9.3382	7.4587
8	2.3169	2.9227
9	1.3758	2.0683
10	2.3898	3.8219
11	11.7304	8.6331
12	1.3758	2.2212
13	4.3440	2.8327
14	0.8691	1.2573
15	0.7242	1.1786
17	6.3718	4.7598
19	2.2444	2.0234
23	3.1133	3.0372
25	1.5201	1.8885
29	2.2444	2.3572
31	1.1581	1.5738
35	1.7378	1.8133
37	1.2305	1.5288
41	1.4482	1.5412
43	0.7965	1.3489
47	1.0862	1.4959
49	0.7965	1.3920

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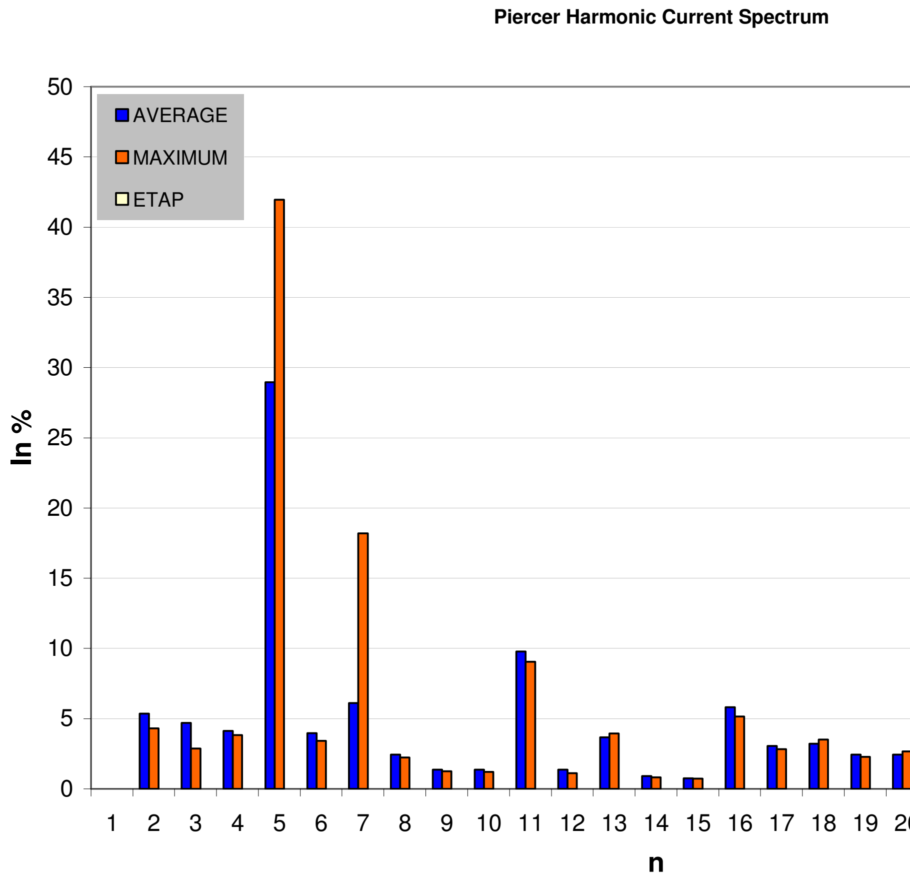
Piercer Drive 2 Harmonic Currents April 10, 2007 15:09 to 18:09



	AVERAGE VALUES	MAXIMUM VALUES
Fund. Amps	141.14	1873.62
1	100%	100%
2	5.3634	4.3193
3	4.7044	2.8785
4	4.1353	3.8355
5	28.9623	41.9579
6	3.9733	3.4115
7	6.1123	18.2022
8	2.4446	2.2468
9	1.3782	1.2440
10	1.3782	1.2094
11	9.7842	9.0618
12	1.3782	1.1057
13	3.6754	3.9405
14	0.9190	0.8174
15	0.7571	0.7259
17	5.8109	5.1528
19	3.0543	2.8344
23	3.2162	3.5181
25	2.4446	2.2806
29	2.4446	2.6652
31	1.6761	1.9011
35	2.1355	2.2033
37	1.9736	1.6592
41	1.8381	1.8834
43	1.3782	1.5555
47	1.6761	1.6347
49	1.3782	1.4518

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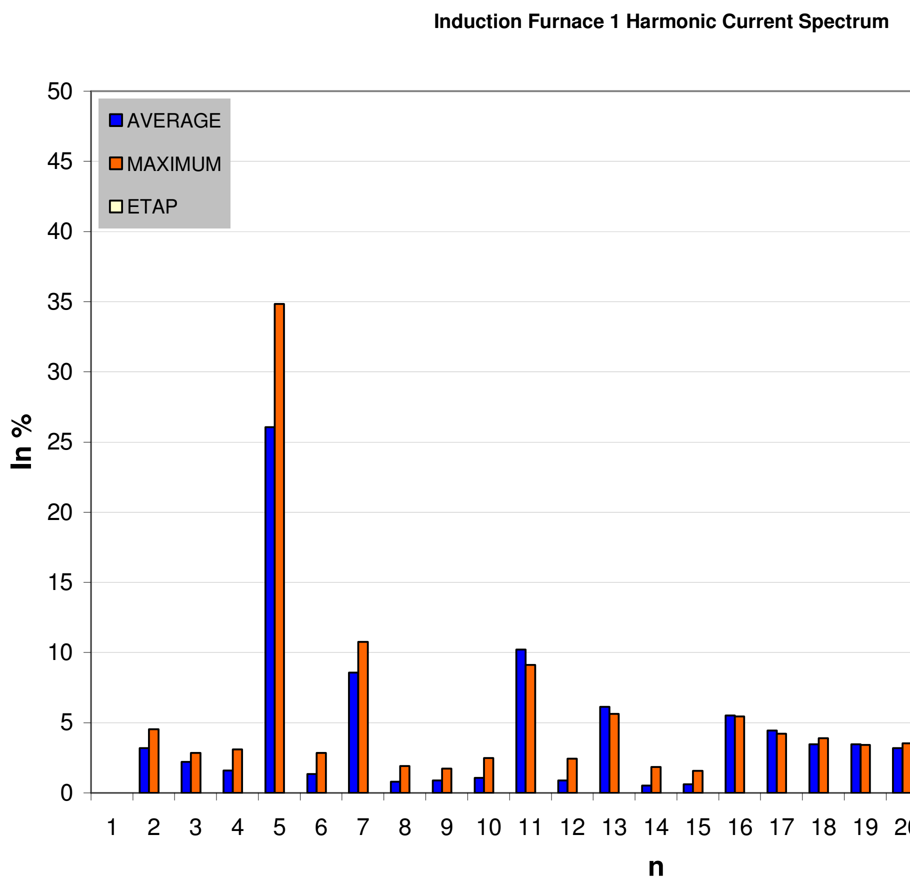
Induction Heater #1 Harmonic Currents April 10, 2007 15:09 to 18:09



	AVERAGE VALUES	MAXIMUM VALUES
Fund. Amps	242.78	1072.77
1	100%	100%
2	3.2002	4.5262
3	2.2218	2.8501
4	1.5999	3.0979
5	26.0710	34.8440
6	1.3334	2.8365
7	8.5679	10.7558
8	0.7999	1.9207
9	0.8899	1.7349
10	1.0669	2.4784
11	10.2224	9.1187
12	0.8884	2.4480
13	6.1339	5.6303
14	0.5334	1.8587
15	0.6232	1.5691
17	5.5105	5.4468
19	4.4452	4.2228
23	3.4667	3.9033
25	3.4667	3.4077
29	3.2002	3.5316
31	2.9337	3.8020
35	1.8668	2.7261
37	1.8668	2.5403
41	1.5999	2.2933
43	1.5115	2.5951
47	1.5101	2.3536
49	1.1552	2.6554

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2.2 Site Measurements: Power Flow

Main Substation Power Flow

The following chart presents active, reactive and apparent power values measured during the period from April 16, 2007 10:58 to April 23, 2007 10:58 at a sampling period of 300 seconds. The power factor values (gray curve) are referred to the right vertical axis and expressed in %. Power values (KVA, etc.) do relate to the left vertical axis. Note the reactive power curve is well centered with respect to 0 already, which indicates that the 3 x 800 kVAR (7620 V) filter was on.

Furthermore, all curves (with exception of the red KVA Max curve) are 1-sample average values. Peak (maximum) KVA values surpass considerably the main transformer KVA rating, causing considerable periodic voltage drop and thus voltage flicker. Adding future non-linear loads will severely affect further this negative aspect. Maximum KVA values were calculated from the harmonic data set of fundamental current. They can be calculated from maximum phase currents as well, the difference between both calculation methods being very low. KVA average values are copied from the measured KVA set and represented in blue. It is better to compare the KVA Max values of the Main Substation with the Hot Mill KVA average values as the last ones do derive from a much faster sampling. To note that the last ones are average power values, but referred to a sampling period of only 3 seconds or a 100 times shorter: average values do get closer to maximum values when shortening sampling time. Considering only the Main Substation KVA, KW, KVAR and PF Average Values can lead to a false perception of the real dynamical loading of the plant. Real PF dips are thus proportionally much lower than the average values indicated in the gray curves on the following charts. It was though not possible to calculate minimum PF values from the maximum phase current data (or from the fundamental currents from the harmonic data set) because maximum reactive power values are not available.

A second chart presents a partial period of time for showing better time domain resolution. The partial period taken here covers the range between samples #100 and #200 for a partial period 5 minutes long.

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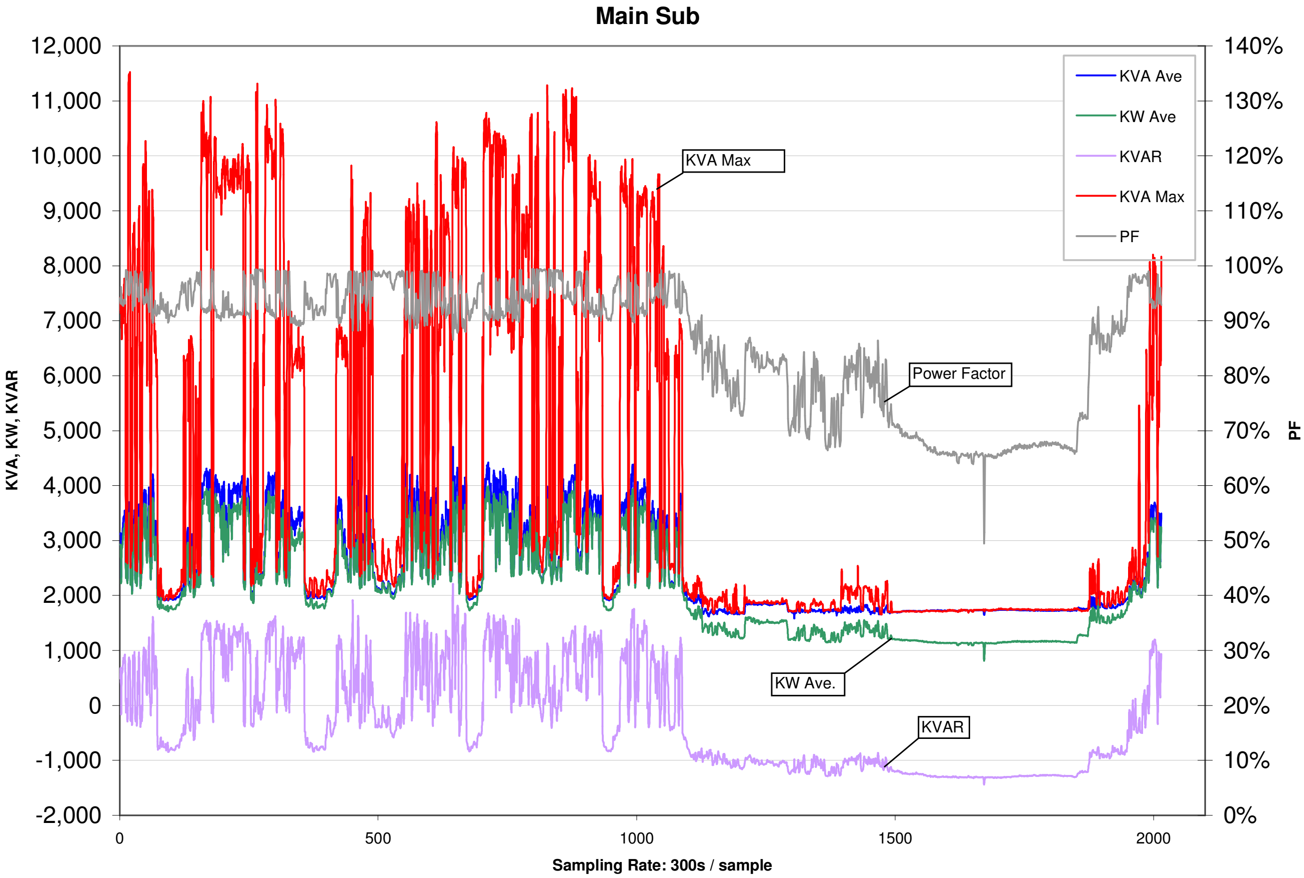
Entire Period



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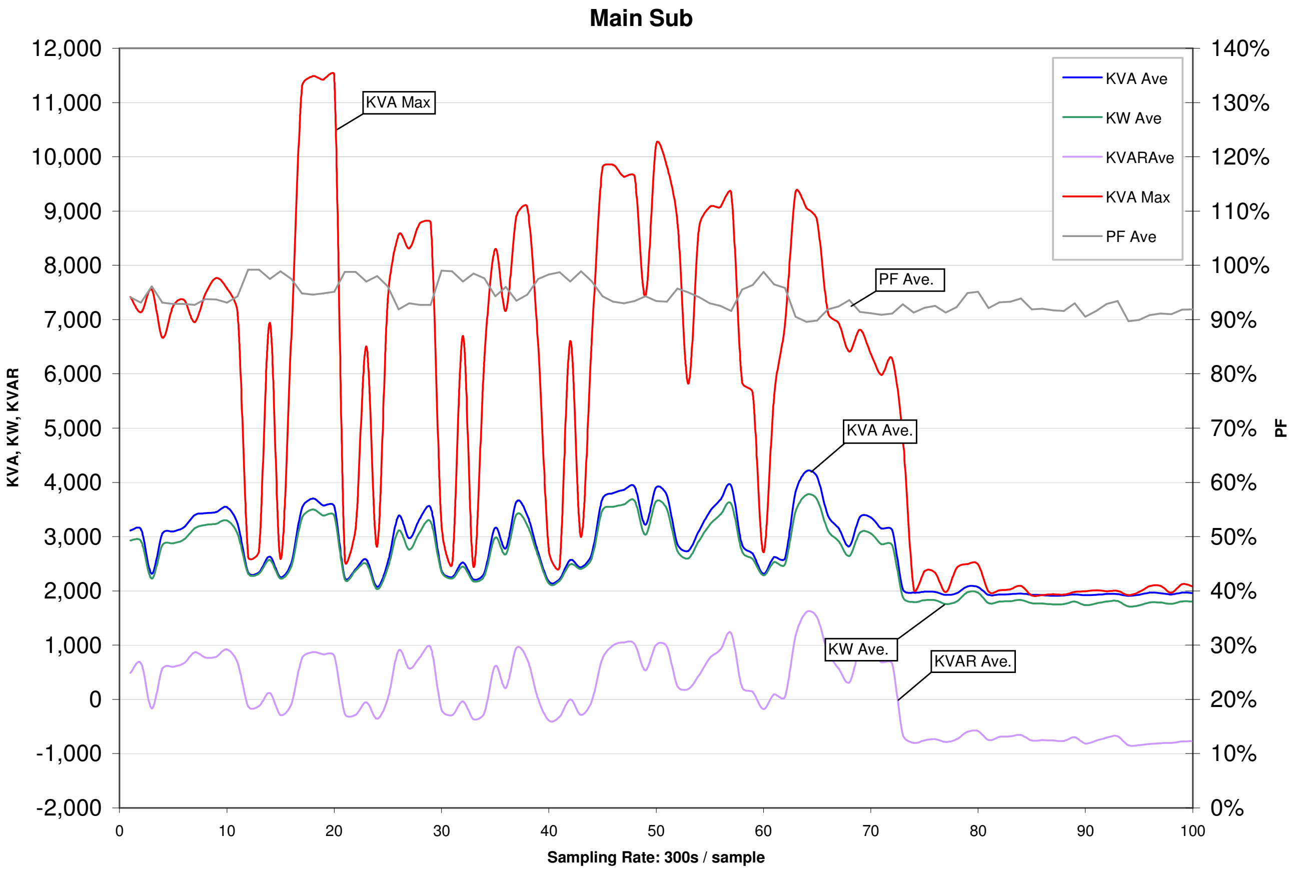
Partial Period



Comment

Heavy loading of the main transformer occur within periods of about 5 hours (samples #15 to #75). The maximum KVA values do correspond though to a 300 s sampling time: one should refer to the Hot Mill set of data for better analysis. As far as voltage swing is concerned, this chart is quite revealing though, showing clearly the wide dynamic load variation. Average KVA values are still within the range of 2 to 4 MVA, but referring to the Hot Mill power chart we can estimate the Main Substation cyclic power levels adding a flat base load of 1 MVA for all other loads but the Hot Mill load:

Cyclic Level 1:	3.5 MVA (30 s / minute)
Cyclic Level 2:	6 MVA (24 s / minute)
Average Peak:	7 to 8 MVA (6 s / minute)
Maximum Repetitive Peak:	9 to 10 MVA
Non Repetitive Peaks:	up to 11.5 MVA
Cyclic Average:	4.5 MVA
Base Load:	2 MVA

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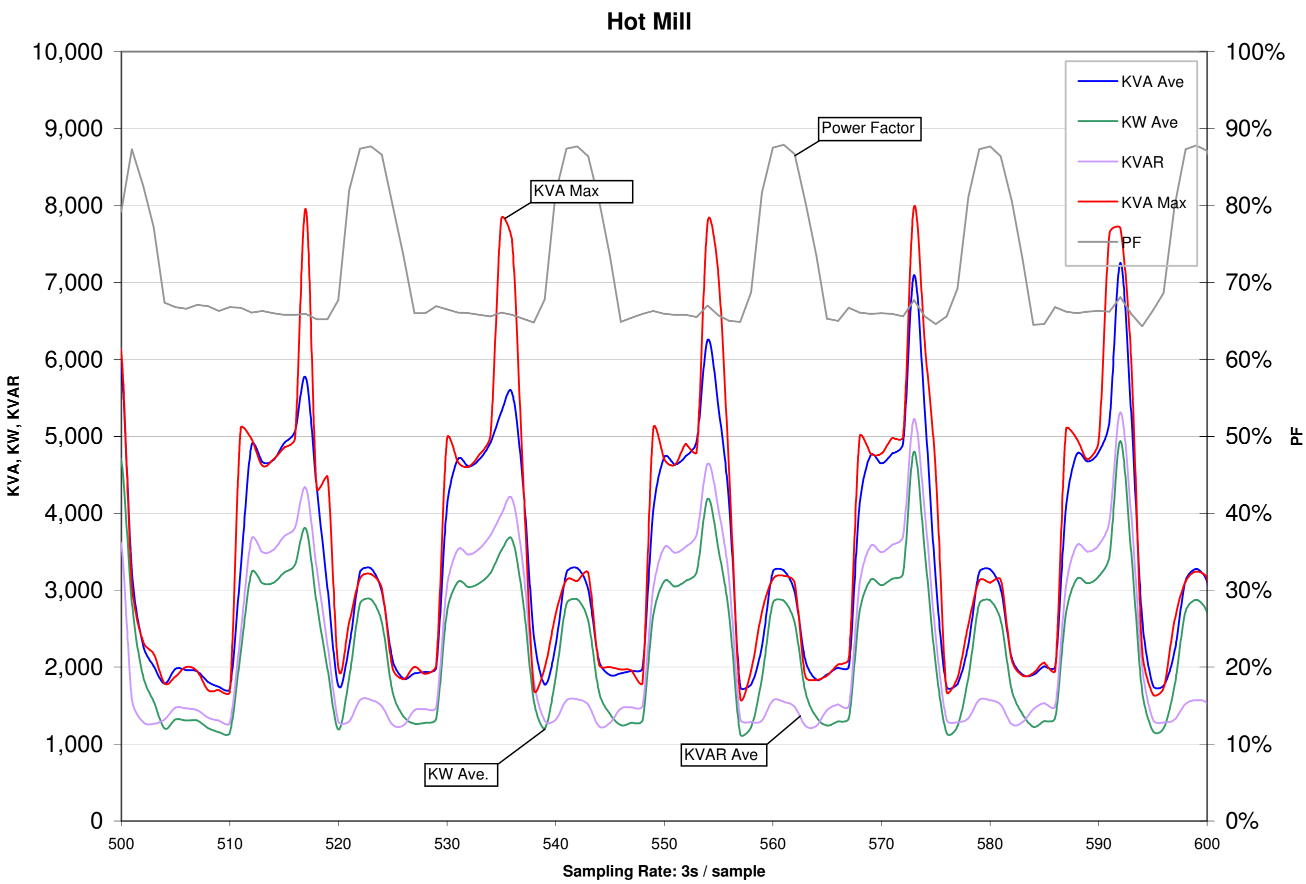
Hot Mill Power Flow

Similarly as for the Main Substation, but for the time period from April 10, 2007 15:09 to 18:09, the following chart shows the power demand for the Hot Mill for a partial period between samples #500 and #600 (5 minutes long). From the chart below it is apparent that the power demand behaves periodically at about 20 samples (60 s) per period. Based on average readings (blue curve), the following power levels can be identified:

Cyclic Level 1:	2.5 MVA (30 s / minute)
Cyclic Level 2:	5 MVA (24 s / minute)
Average Peak:	6 to 7 MVA (6 s / minute, blue curve)
Maximum Repetitive Peak:	8 to 9 MVA (red curve)
Cyclic Average:	3.5 MVA
Base Load:	1 MVA

Partial Period



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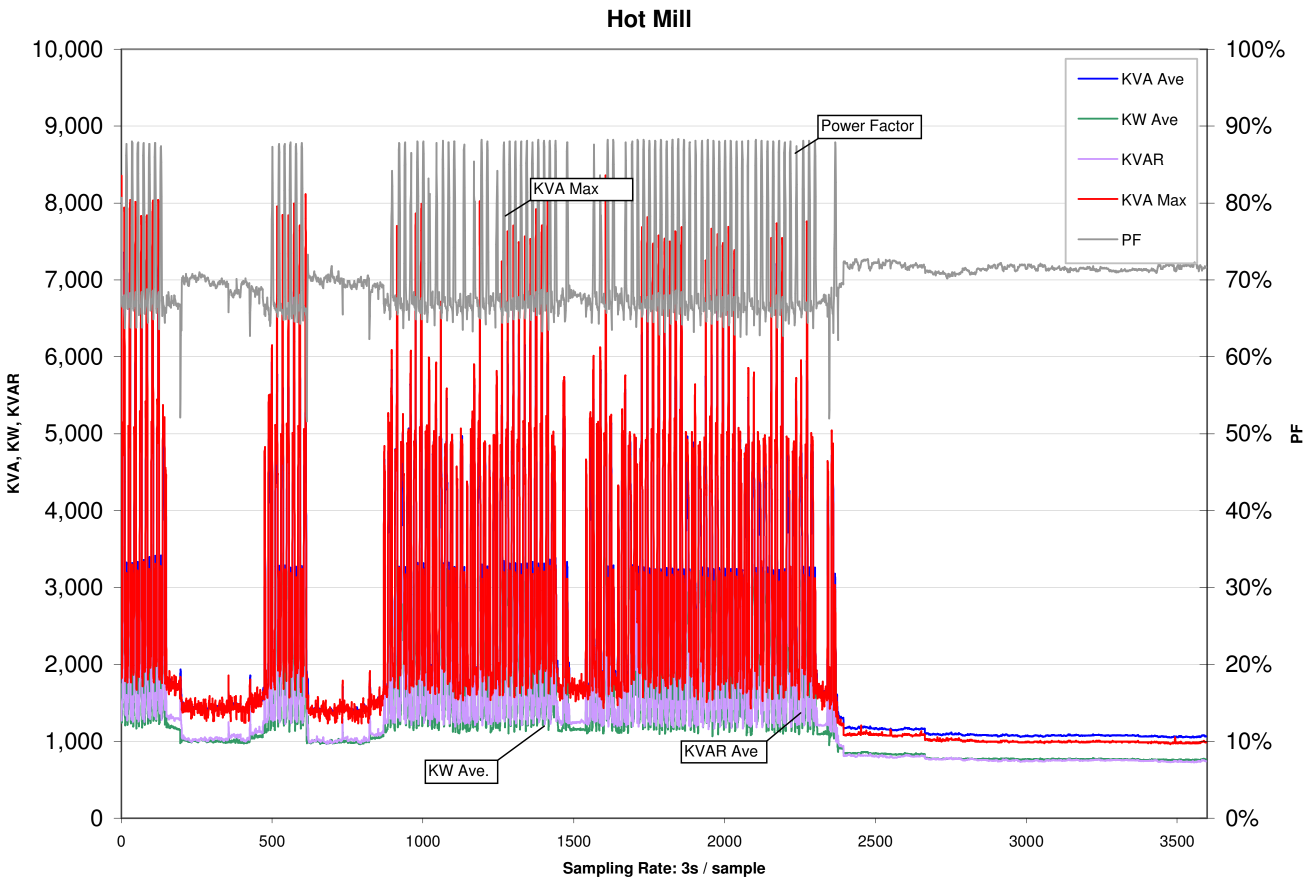
Complete Period



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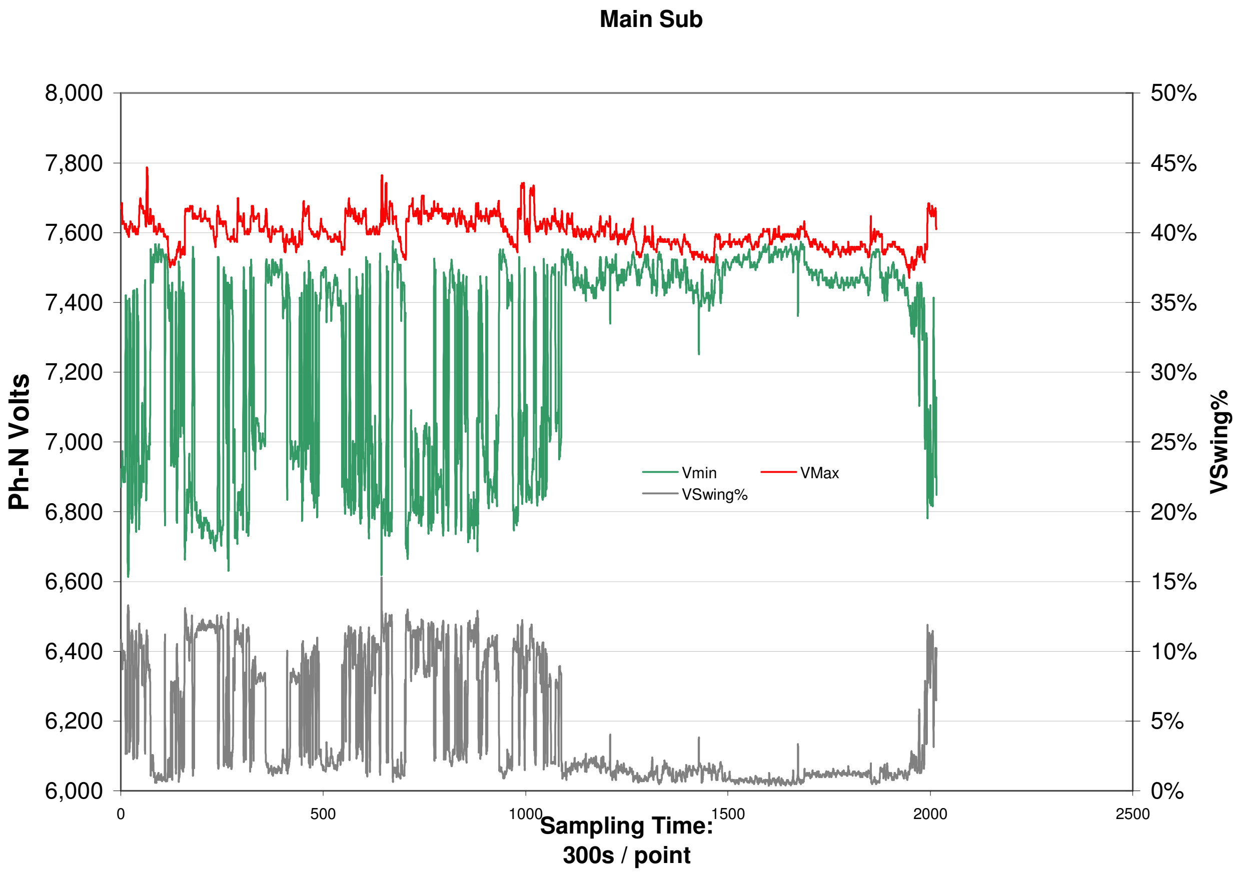
2.3 Site Measurements: Voltage Swing and Voltage Imbalance

Main Substation Voltage Swing

The voltage swing curves were calculated as the absolute maximum and minimum values for all maximum and minimum phase voltage values of each sample for the complete period of time from April 16, 2007 10:58 to April 23, 2007 10:58 at a sampling rate of 1 sample every 300 seconds. The voltage swing in % was calculated basically (*) dividing the spread (maximum minus minimum) by a nominal voltage of 7,450 V. The spread is to be seen as the difference between the red and green curves shown in the graph below. Note the voltage swing reaches up to approximately 12.5%.



* **NOTE:** the exact formula would be Swing% = 100 * maximum of (Max-Min, Nominal-Min, Max-Nominal) / Nominal

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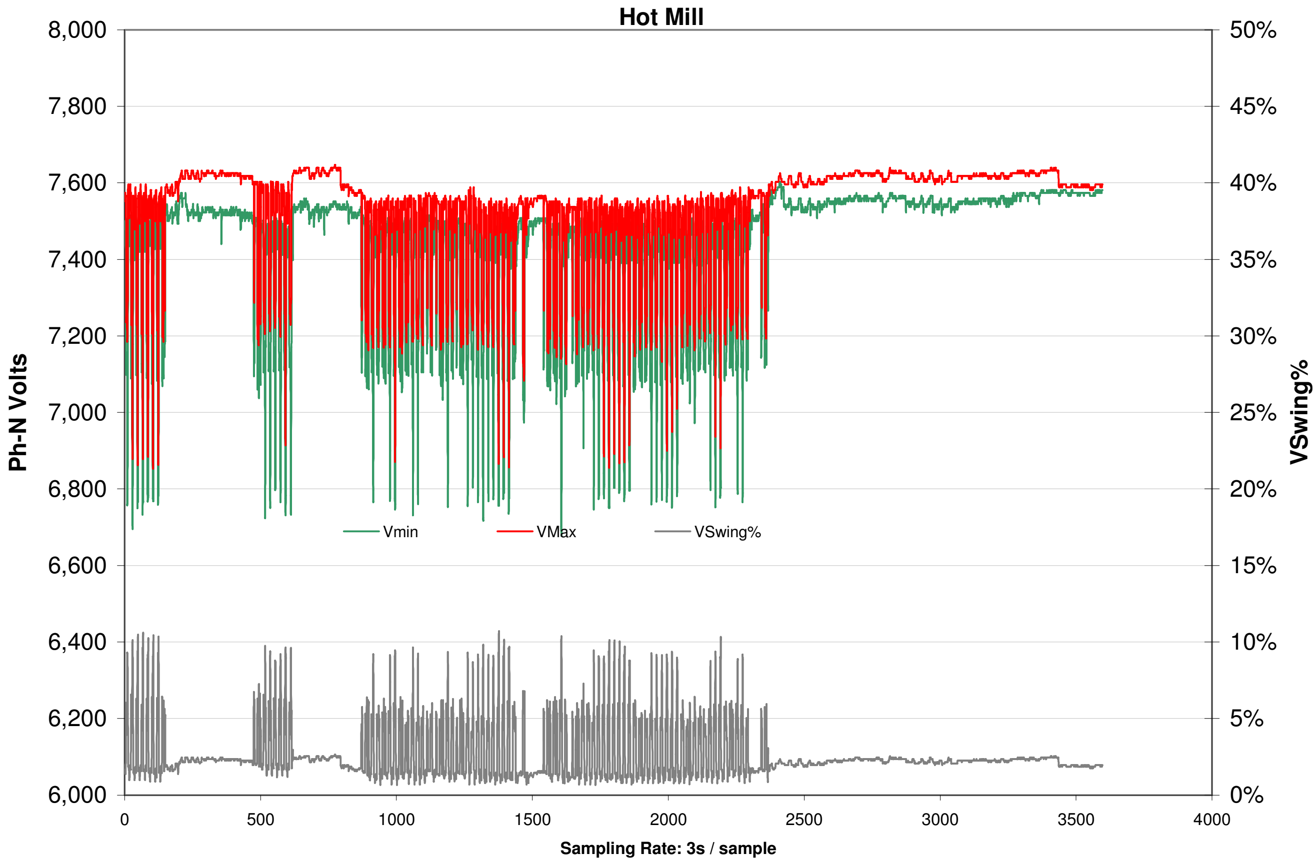
Hot Mill Voltage Swing

The voltage swing for the Hot Mill is shown in similar way as before but for the time period from April 10, 2007 15:09 to 18:09. Note the voltage swing reaches up to approximately 12% compared with up, to 12.5 % at the Main Substation, but it has to be considered that measurements were taken on different occasions and at different sampling rates.



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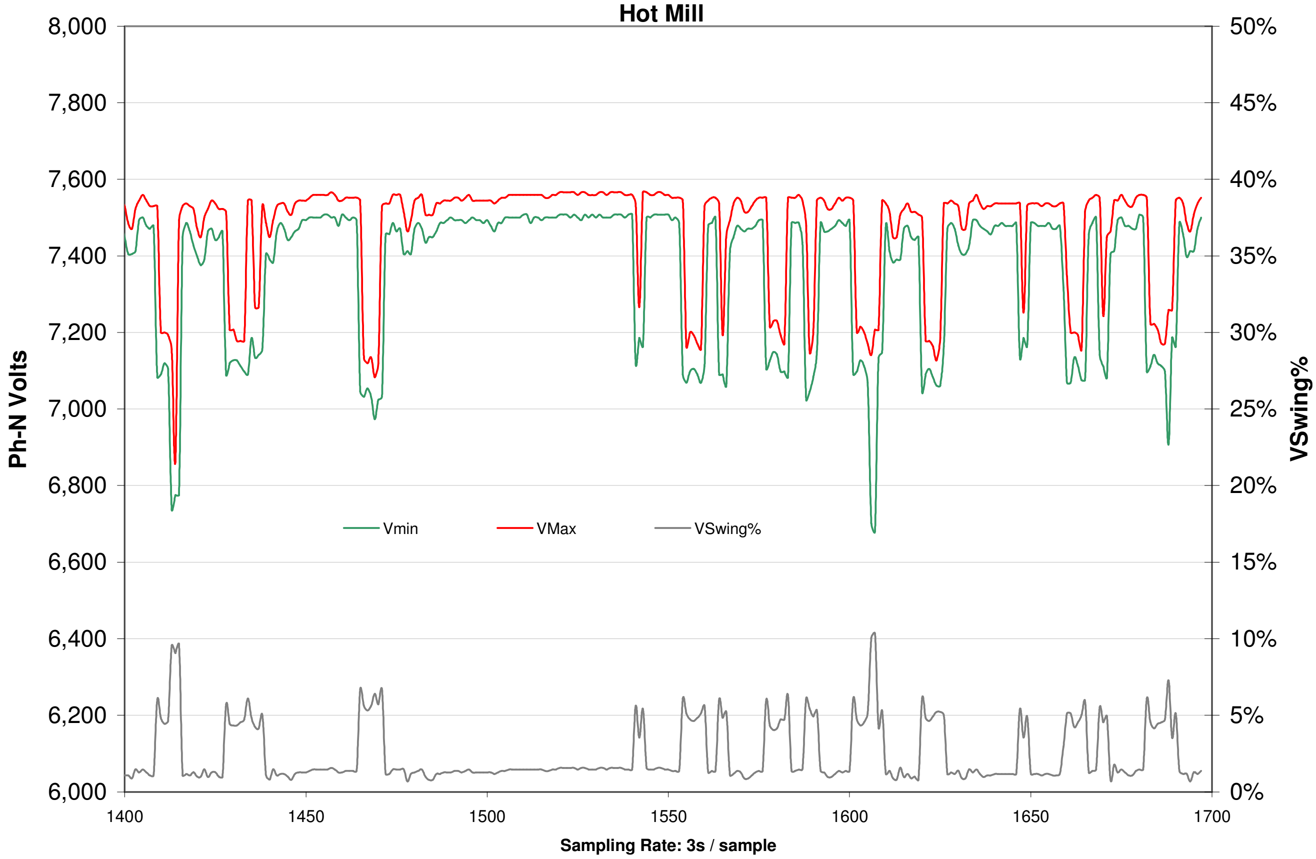
The chart above can be zoomed for a partial period between samples 1400 and 1700:



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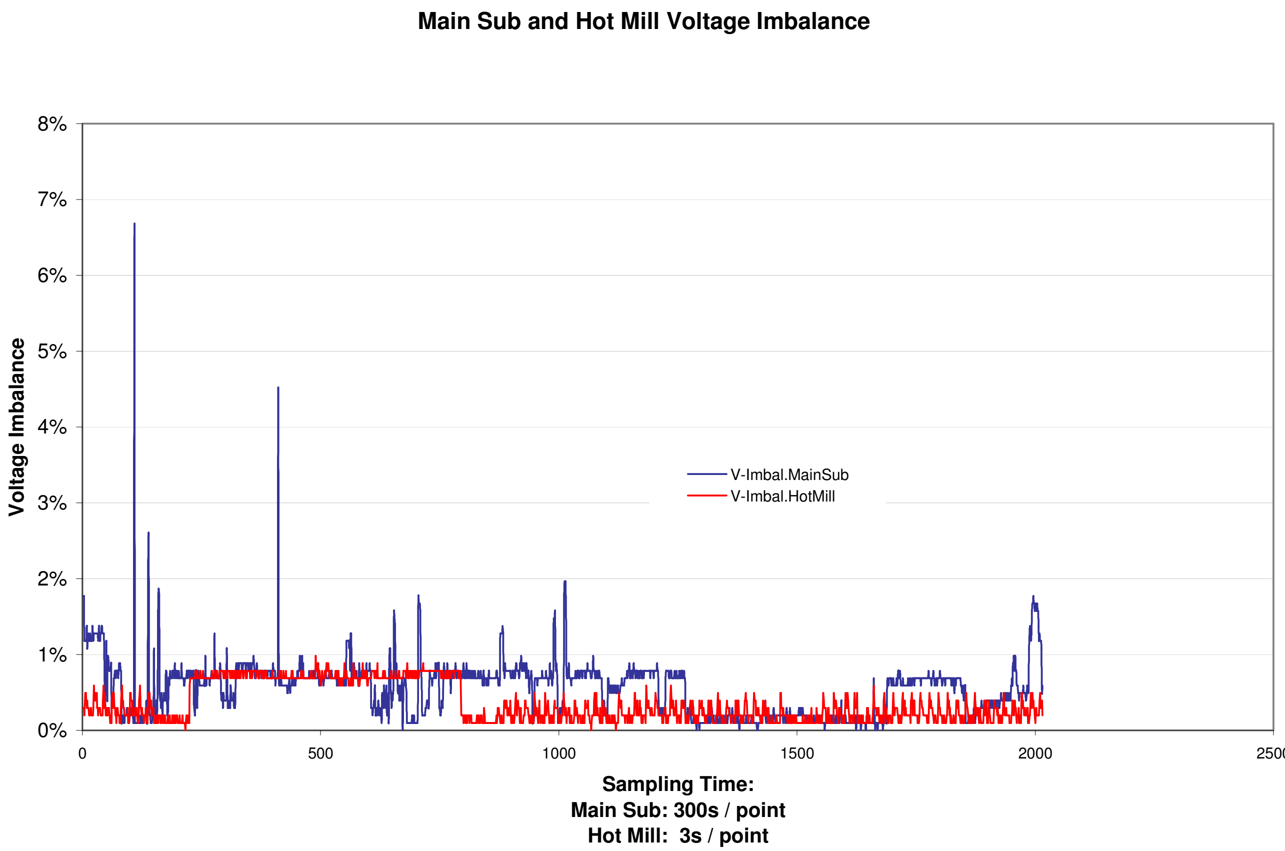
Main Substation and Hot Mill Voltage Imbalance

The voltage imbalance is presented for the Main Substation and Hot Mill in a single chart to show that the imbalance magnitude at both locations derive very likely from the large Hot Mill drives (identical values, not synchronized though because of the different timing. The voltage imbalance values are in line with IEEE Std. 141-1993 recommendations being well below 2.5% with only some isolated sporadic larger peaks which could have been caused by metering errors, metering noise or because of sharp drive starting (or reversing) within 1/6 of a cycle, which sometimes do occur in applications when current controllers need to be well optimized and therefore set very fast and close to stability limits, which is typically the case of rolling mill drives.



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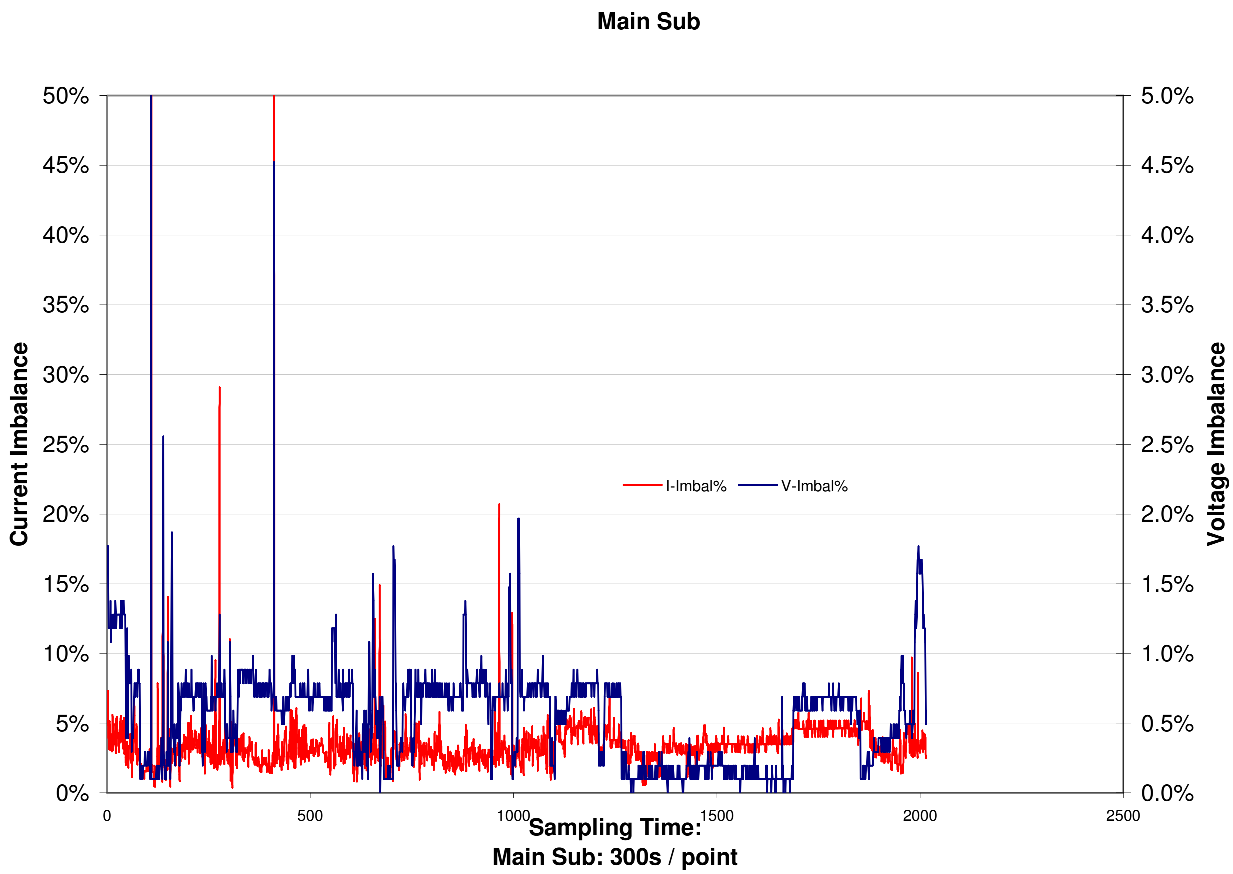
Main Substation Current and Voltage Imbalance

The current and voltage imbalance is presented for the Main Substation in a single chart to show that some limited correlation exists for the very large imbalance spikes. These spikes could be related to very large load jerks produced at the mill drives or else, caused by digital delay (jitter) when polling data from the input buffer into the meter's memory during one scan exactly when current is rising too sharply. A further investigation of the real origin of these spikes would require using a fast recording oscilloscope. Otherwise, current imbalance stays normally below 5% and voltage imbalance below 1%.



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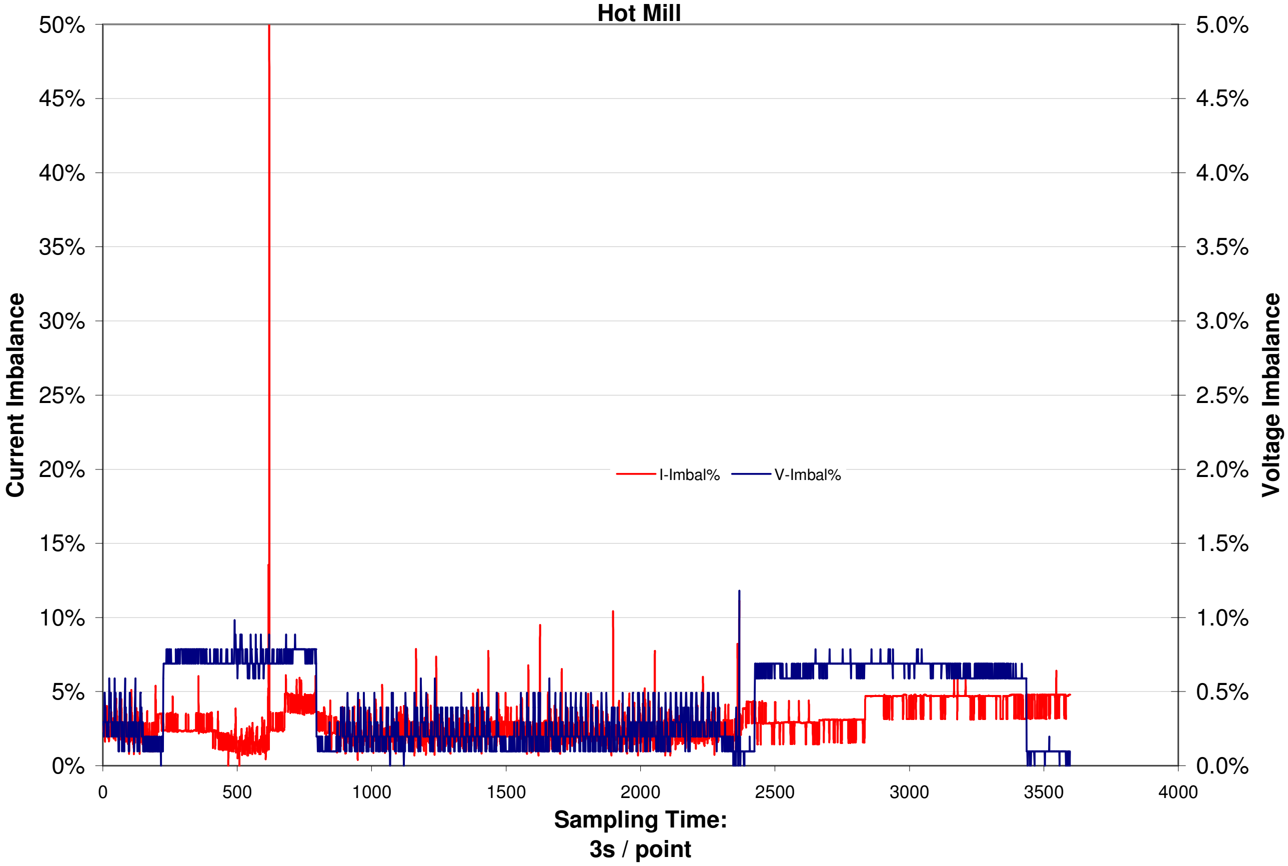
Hot Mill Current and Voltage Imbalance

The current and voltage imbalance is presented for the Hot Mill in a single chart as well. There is no evidence of any correlation between current and voltage imbalance here. Current imbalance stays normally below 5% and voltage imbalance below 1%.



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2.4 ETAP Simulation

A first simulation run - Base Configuration - was performed using following main load settings:

	KVA	AC Volts	%EFF	%PF	%LOAD	HARM.
Bench1	259	220	92	95	20	6p-VFD
Bench2	445	600	92	95	20	6p-VFD
Bench3	173	480	92	95	20	6p-VFD
Bench4	337	192	92	95	20	6p-VFD
Bench5	437	480	92	95	20	6p-VFD
CSM	402	762	92	65	35	DD
Diescher Mill Roll	1950	800	92	65	35	DD
Diescher Disk	908	610	92	65	35	DD
Piercer1	1220	525	92	65	25	PD
Piercer2	1220	525	92	65	25	PD
Heater1	3545	720	92	65	35	HTR
Heater2.1	1772	386	92	65	35	HTR
Heater2.2	1772	386	92	65	35	HTR

Note: DD means Diescher Drive, PD means Piercer Drive and HTR means heater.

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The harmonic current injection of the non-linear loads programmed in the simulation was the following:

	Diescher Mill Roll (Ave.)		Piercer Drive (Average)		Induction Furnace (Ave.)	
n	%Amplitude	Phase Angle	%Amplitude	Phase Angle	%Amplitude	Phase Angle
2	6.23	209.48	5.36	209.48	3.20	209.48
3	2.39	355.17	4.70	355.17	2.22	355.17
4	4.20	26.19	4.14	26.19	1.60	26.19
5	37.87	88.81	41.96	88.81	34.84	88.81
6	2.61	354.52	3.97	354.52	1.33	354.52
7	7.46	347.85	18.20	347.85	10.76	347.85
8	2.32	261.50	2.44	261.50	0.80	261.50
9	1.38	44.19	1.38	44.19	0.89	44.19
10	2.39	39.29	1.38	39.29	1.07	39.29
11	11.73	121.87	9.78	121.87	10.22	121.87
12	1.38	26.19	1.38	26.19	0.89	26.19
13	4.34	135.89	3.68	135.89	6.13	135.89
14	0.87	295.56	0.92	295.56	0.53	295.56
15	0.72	69.15	0.76	69.15	0.62	69.15
17	6.37	143.97	5.81	143.97	5.51	143.97
19	2.24	211.33	3.05	211.33	4.45	211.33
23	3.11	173.91	3.22	173.91	3.47	173.91
25	1.52	228.77	2.44	228.77	3.47	228.77
29	2.24	193.56	2.44	193.56	3.20	193.56
31	1.16	267.44	1.68	267.44	2.93	267.44
35	1.74	221.29	2.14	221.29	1.87	221.29
37	1.23	302.01	1.97	302.01	1.87	302.01
41	1.45	246.23	1.84	246.23	1.60	246.23
43	0.80	328.57	1.38	328.57	1.51	328.57
47	1.09	277.67	1.68	277.67	1.51	277.67
49	0.80	20.56	1.38	20.56	1.16	20.56

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3. CONCLUSIONS

3.1 Comparing Actual and Simulated Results

Comparing real harmonic currents with simulated results from the ETAP model at the PCC point, some deviations are found. These deviations could not be fully compensated with setting adjustments (harmonic current injection, load variations or drive speed adjustments).

The complexity of several large drives operating simultaneously and not at the same speed (or firing angle), is very difficult to reproduce in any simulation. This problematic limitation is originated by partial cancellation or amplification of harmonic currents, depending on relative phase angles. A comprehensive simulation would require changing not only load values (KVA) but also drive speeds (firing angles) at the same time. To complicate even more the mathematical approach, only harmonic currents amplitudes are normally measured, seldom their phase angles. ETAP includes relative phase shift angles, which must be limited between -180 and +180 degrees for every harmonic, but meters do normally measure phase angles referred to fundamental frequency. The measured angles have to be corrected for each harmonic number and limited to a permissive range of -180 to +180 degrees. Taking phase angles equal zero for all the harmonic current injections produces non-realistic results when having multiple drives operating at different speeds and / or fed from different drive transformers of different vector groups.

Furthermore, if average values are taken as reference, these never occur exactly at the same time for all harmonic currents. The same happens for maximum values.

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Base Configuration: RUN1 @ 2218 KVA and RUN2 @ 3710 KVA

The simulation results for the actual configuration of the system, without future loads, for harmonic currents at the Hot Mill and Main Substation are listed below:

HOT MILL					MAIN SUB				
						MEASURED		ETAP	
	MEASURED		ETAP		MAIN XFMR	AVERAGE VALUES	MAXIMUM VALUES	RUN1 2218KVA	RUN2 3710KVA
	AVERAGE VALUES	MAXIMUM VALUES	RUN1	RUN2	Primary Amps	20.437	96.862	18.6	31.04
Fund. Amps	96.51	394.15	127.52	199.35	Secondary Amps	107.73	510.58	98.04	163.62
n	%	%	%	%	n	%	%	%	%
2	1.0735	3.3466	3.4693	4.5816	2	0.8652	4.2227	5.2398	4.7908
3	0.5368	1.7403	0.0000	0.0000	3	2.1144	11.7503	0.0000	0.0000
4	1.6103	3.5479	2.1624	2.8686	4	1.4425	5.2470	2.9045	2.6591
5	6.2599	6.9644	10.8280	10.5389	5	9.4247	4.0779	2.5777	2.3553
6	0.8952	2.2339	0.0000	0.0000	6	0.2887	0.8643	0.0000	0.0000
7	2.5036	3.0222	2.1328	2.0756	7	2.0190	1.8869	1.3120	1.1985
8	0.5368	0.7885	1.1722	1.3041	8	0.2887	0.6121	0.6930	0.6347
9	0.5368	0.6571	0.0000	0.0000	9	0.2887	0.4896	0.0000	0.0000
10	0.5368	0.9372	1.1990	1.5461	10	0.0000	0.9738	0.7489	0.6833
11	3.0423	4.1500	11.1686	10.0421	11	1.5395	2.5563	7.4734	6.8259
12	0.3585	1.0708	0.0000	0.0000	12	0.0000	0.9258	0.0000	0.0000
13	1.4301	1.7083	5.6092	5.0514	13	0.5774	1.8260	3.7335	3.4071
14	0.0000	0.4017	0.5363	0.6238	14	0.0000	0.4869	0.3618	0.3307
15	0.0000	0.2678	0.0000	0.0000	15	0.0000	0.3673	0.0000	0.0000
17	1.0735	1.8742	1.8220	1.3235	17	0.2887	1.4197	1.5326	1.3949
19	0.5368	1.3386	0.6405	0.5613	19	0.2887	1.3391	0.5067	0.4628
23	1.0735	1.7083	3.5288	3.4213	23	0.2887	0.9792	2.5268	2.3017
25	0.5368	1.0511	2.9584	2.9863	25	0.2887	0.9129	2.0248	1.8439
29	0.5368	1.6064	0.6411	0.6551	29	0.2887	1.0494	0.5553	0.5044
31	0.5368	1.3386	0.3319	0.4354	31	0.2887	1.0404	0.2568	0.2348
35	0.5368	0.6694	1.9811	1.9467	35	0.2887	0.9129	1.4379	1.3068
37	0.1783	0.7885	1.8099	1.8432	37	0.1928	1.0956	1.2488	1.1354
41	0.0000	0.8033	0.4154	0.4263	41	0.0000	0.6174	0.3607	0.3274
43	0.0000	0.7885	0.2291	0.3731	43	0.0000	0.6087	0.1696	0.1553
47	0.0000	0.6571	1.5035	1.5705	47	0.0000	0.4869	1.0842	0.9825
49	0.0000	0.9200	1.1511	1.2774	49	0.0000	0.5556	0.7910	0.7170
					THD	10.187	15.104	11.588	10.581

Comment

The simulation results for the Hot Mill are relatively close to the measured values with the exception of some higher harmonics such as 11th, which is about three times higher in the simulation. The 5th harmonic currents at the Hot Mill simulation are about 25% higher than the measured values but reflecting totally opposite at the Main Substation. The results for the Main Substation are generally not well in line with the measured values, specifically

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considering the much lower predicted 5th harmonic current. Please do refer to Section 2.1 for explaining this deviation. ETAP does not simulate third and its multiple harmonics, therefore all of these harmonics are zero in the simulation columns. Considering the complexity of this system as far as multiple non-linear loads is concerned and the fact that harmonic currents are interacting, partially doubling or canceling in dependence of phase angle (drive speeds and transformer vector groups) the results are not too far away from reality. ETAP does not predict any strong variation of harmonic distortion percent values when changing non-linear load KVA ratings alone, quite differently when changing SCR firing angle.

Simulated Power Demand

The Base Configuration RUN2 shows a total power demand of 3,710 KVA with 91.9% PF at the PCC. The resulting harmonic currents at the PCC are listed on Sections 2.1 and 3.2.

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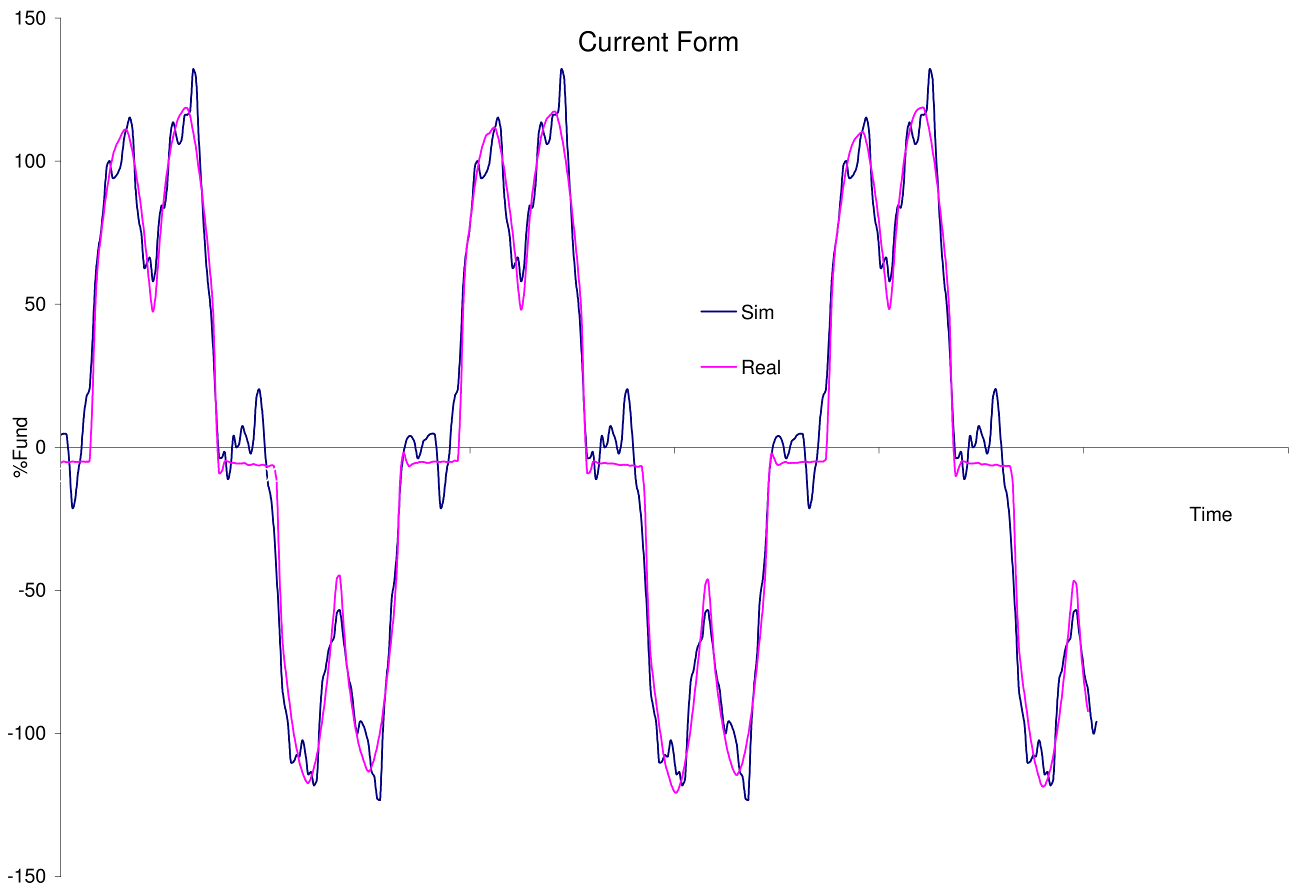
Current Wave Forms

The harmonic currents injected from the drives result in following current wave form in the time domain, shown together with a measured snapshot for the phase B current taken for the Diescher Mill Roll:



Comment

The difference between the measured curve and the model is mainly caused by the extreme sensitivity of the resulting waveform depending on measured harmonic amplitudes and phase angles. The precision of the measured phase angles is critical and represents a major metering issue, specifically for the mid-range harmonics (5th, 7th, 11^{th}, 13th), which are large in amplitude and the impact of phase angle measuring errors are more influent in the resulting curve form. This deviation is not only of cosmetic nature, it also affects the resulting harmonic current spectrum at any other point in the model.

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3.2 IEEE Compliance

The following table shows the compliance with IEEE maximum limits for Isc/In <50:

	MAXIMUM VALUES	ETAP MODEL	IEEE Limit	MAXIMUM COMPLIANCE	ETAP COMPLIANCE
Sec. Amps	510.58	98.04			
1	0.00	0.00			
2	4.2227	5.2398	7.0	YES	YES
3	11.7503	0.0000	7.0	ABNORMAL	YES
4	5.2470	2.9045	7.0	YES	YES
5	4.0779	2.5777	7.0	YES	YES
6	0.8643	0.0000	7.0	YES	YES
7	1.8869	1.3120	7.0	YES	YES
8	0.6121	0.6930	7.0	YES	YES
9	0.4896	0.0000	7.0	YES	YES
10	0.9738	0.7489	7.0	YES	YES
11	2.5563	7.4734	7.0	YES	MARGINAL
12	0.9258	0.0000	3.5	YES	YES
13	1.8260	3.7335	3.5	YES	MARGINAL
14	0.4869	0.3618	3.5	YES	YES
15	0.3673	0.0000	3.5	YES	YES
17	1.4197	1.5326	3.5	YES	YES
19	1.3391	0.5067	2.5	YES	YES
23	0.9792	2.5268	2.5	YES	MARGINAL
25	0.9129	2.0248	1.0	YES	NO
29	1.0494	0.5553	1.0	MARGINAL	YES
31	1.0404	0.2568	1.0	MARGINAL	YES
35	0.9129	1.4379	0.5	NO	NO
37	1.0956	1.2488	0.5	NO	NO
41	0.6174	0.3607	0.5	MARGINAL	YES
43	0.6087	0.1696	0.5	MARGINAL	YES
47	0.4869	1.0842	0.5	YES	NO
49	0.5556	0.7910	0.5	MARGINAL	NO
THD	15.10	11.59	5.0	NO	NO

Comments

The above table shows in general there is marginal IEEE compliance for measured and simulated values. The third harmonic distortion can be considered an abnormal event due to sporadic current unbalance. From the ETAP model it is not possible to predict the higher 5th harmonic currents, even changing all drive transformer vector groups to D / Y configuration, assuming a very high (70%) 5th harmonic injection in the Cold Mill drives and simulating an extreme case with the Hot Mill completely switched off having only the Cold Mill drives running at 100% rated load.

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Only when simulating a very small 5th harmonic voltage distortion of 0.01% at the PCC, a considerable increase of 5th harmonic current at the Main Transformer by additional 5% is obtained. This can be explained from the fact that the Main 69KV Bus presents a low impedance to the utility at n = 4 to 5 because of the existing filter bank tuned at n = 4.73. The relatively high 5^{th} harmonic current at the Main Substation could be originated by very small voltage distortion at the PCC, though there is no direct measured evidence of such external perturbation happening.

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3.3 Main Transformer Power Considerations

Actual loading conditions imply that the main transformer is not critically loaded as far as RMS demand is concerned, but the periodic peak overloading should anyhow be checked with the transformer manufacturer. Taking the power demand data (curve) for the Hot Mill and adding an estimated 2 MVA base load it is possible to mimic the cyclic loading of the main transformer as follows:

Cyclic Level 1:	3.5 MVA (30 s / minute)
Cyclic Level 2:	6 MVA (24 s / minute)
Average (Repetitive) Peak:	7 to 8 MVA (6 s / minute)
Maximum (Repetitive) Peak:	9 to 10 MVA (short unknown duration)
Non-Repetitive Peaks:	up to 11.5 MVA
Base Load:	2 MVA
TOTAL RMS / cycle:	5.20 MVA approximated calculation
TOTAL RMS / cycle:	5.63 MVA calculated over a 60 s cycle

The periodic peak loading of the transformer takes about 3 seconds rising at about 9.5 MVA (7.5 MVA at the Hot Mill plus about 2 MVA from the Cold Mill and others) every minute. The cyclic period of one minute covers peak and valley loads during 1 minute. The valley demand is at about 3.5 MVA (Level 1) during 30 s and the mid-platform at 6 MVA (Level 2) during 24 s. The average peak ceiling is at 7 to 8 MVA during 6 s. The Total RMS apparent power for one 60 s cycle is 5.2 MVA (approximated calculation) or 5.63 MVA (Excel calculation), which still shows sufficient headroom. Increasing the average peak power to 11 MVA for 6 s / minute does show a power increase of 0.5 MVA only, due to the short peak duration.

A comprehensive Excel spreadsheet was created importing data from the measurements taken during April 16, 2007 10:58 to April 23, 2007 10:58 (Main Substation) and on April 10, 2007 15:09 to 18:09 (Hot Mill). The complete Excel spreadsheet is available on CD.

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3.4 Adding New Loads and Recommendations

An ETAP simulation including two additional 2 MVA non-linear loads running at 50% and 100% capacity connected from the Hot Mill 12 kV bus through one 4 MVA transformer was run and showed following results:

Future Load	0%	50%	100%
Total KVA	3710	5697	8012
Prim. Amp	31.00	47.65	67.01
Sec. Amp	163.41	251.17	353.22
n	%	%	%
2	4.7908	5.5498	5.6959
3	0.0000	0.0000	0.0000
4	2.6591	3.1365	3.2337
5	2.3553	3.2180	3.4920
6	0.0000	0.0000	0.0000
7	1.1985	1.8131	2.0135
8	0.6347	0.7622	0.8008
9	0.0000	0.0000	0.0000
10	0.6833	0.8436	0.8915
11	6.8259	6.4789	6.0038
12	0.0000	0.0000	0.0000
13	3.4071	2.9914	2.6379
14	0.3307	0.3604	0.3489
15	0.0000	0.0000	0.0000
17	1.3949	2.0783	2.2734
19	0.4628	0.7074	0.7679
23	2.3017	2.0777	1.8166
25	1.8439	1.4834	1.2018
29	0.5044	0.7475	0.7859
31	0.2348	0.3634	0.3784
35	1.3068	1.1757	0.9692
37	1.1354	0.9672	0.7616
41	0.3274	0.4832	0.4779
43	0.1553	0.2446	0.2408
47	0.9825	0.8418	0.6240
49	0.7170	0.6136	0.4429
THD	10.58	11.06	10.83
PF	91.90	82.20	74.90
13.09 KV Bus, %	96.00	94.39	92.47

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Main Substation Duty Cycle Estimate

It is possible to estimate a probable power cycle with the future loads based on the simulated ETAP results above and taking the measured power cycle presented on Section 2.2 as base:

Cyclic Level 1:	4.5 MVA (30 s / minute)
Cyclic Level 2:	8 MVA (24 s / minute)
Average (Repetitive) Peak:	9 to 10 MVA (6 s / minute)
Maximum (Repetitive) Peak:	11.5 to 12 MVA (short unknown duration)
Non-Repetitive Peak:	up to 16 MVA
Base Load:	3 MVA
TOTAL RMS / cycle:	6.76 MVA (approximated calculation)

The Total RMS / cycle is still within the transformer rating, but the problem might be related to the Cyclic Level 2 (24 s / minute), Average Repetitive Peak (6 s / minute) and Maximum Repetitive Peak.

Voltage Swing Projection

Considering the measured voltage swing of up to 12.5 % with the actual loading cycle and the results from the ETAP simulation for maximum future load variation from 0 to 100%:
Future Load Voltage Variation = up to 3.53% (96.00% - 92.47%)
Actual Voltage Swing = up to 12.5%
Projected Voltage Swing = up to 16%
The projected voltage swing is not acceptable.

Recommendations

From the estimated duty cycle presented above it is very likely that the main transformer will be loaded close to its limit. Repetitive (cyclic) power peaks are a valid concern and should be checked with the transformer manufacturer. The main problem of voltage swing (flicker) will be aggravated to an un-tolerable level. It is therefore recommended to practically double its power rating (perhaps adding a second identical transformer). An additional solution could be to separate completely the power supply for the offices and voltage sensitive equipment (automation, etc.) from an independent 96 / 13 kV power transformer. The addition of a SCR-controlled detuned filter bank fed from a 12 / 0.48 kV dedicated transformer at the Hot Mill bus was simulated as well, showing the following main results:

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	MEASURED		ETAP MODEL			
	AVERAGE VALUES	MAXIMUM VALUES	RUN 1	RUN 2	RUN 3	RUN 4
Actual Loads, %	Variable	Variable	23	35	35	35
Future Loads, %	0	0	0	0	0	50
Prim. Amps	20.44	96.86	18.60	31.04	28.55	39.39
Sec. Amps	107.73	510.58	98.04	163.62	150.49	207.63
MAIN KVA	2,443	11,576	2,218	3,710	3,412	4,708
MAIN PF %	93.00	93.00	99.90	91.90	99.80	99.10
13KV BUS VOLTS %			97.41	96.06	97.20	96.76
Filter Bank KVAR	2,328	2,328	2,328	2,328	2,328	2,328
Detuned Filter Bank KVAR	0	0	0	0	1,200	2,400
n						
2	0.8652	4.2227	5.2398	4.7908	5.7287	8.3785
3	2.1144	11.7503	0.0000	0.0000	0.0000	0.0000
4	1.4425	5.2470	2.9045	2.6591	2.1143	1.4802
5	9.4247	4.0779	2.5777	2.3553	2.9970	1.9095
6	0.2887	0.8643	0.0000	0.0000	0.0000	0.0000
7	2.0190	1.8869	1.3120	1.1985	0.4197	1.3029
8	0.2887	0.6121	0.6930	0.6347	0.3083	0.5690
9	0.2887	0.4896	0.0000	0.0000	0.0000	0.0000
10	0.0000	0.9738	0.7489	0.6833	0.4196	0.6545
11	1.5395	2.5563	7.4734	6.8259	4.4234	5.1071
12	0.0000	0.9258	0.0000	0.0000	0.0000	0.0000
13	0.5774	1.8260	3.7335	3.4071	2.3164	2.3878
14	0.0000	0.4869	0.3618	0.3307	0.2293	0.2904
15	0.0000	0.3673	0.0000	0.0000	0.0000	0.0000
17	0.2887	1.4197	1.5326	1.3949	1.0088	1.7017
19	0.2887	1.3391	0.5067	0.4628	0.3354	0.5786
23	0.2887	0.9792	2.5268	2.3017	1.7030	1.7283
25	0.2887	0.9129	2.0248	1.8439	1.3688	1.2353
29	0.2887	1.0494	0.5553	0.5044	0.3835	0.6320
31	0.2887	1.0404	0.2568	0.2348	0.1766	0.3052
35	0.2887	0.9129	1.4379	1.3068	1.0033	1.0068
37	0.1928	1.0956	1.2488	1.1354	0.8718	0.8279
41	0.0000	0.6174	0.3607	0.3274	0.2556	0.4183
43	0.0000	0.6087	0.1696	0.1553	0.1192	0.2100
47	0.0000	0.4869	1.0842	0.9825	0.7745	0.7388
49	0.0000	0.5556	0.7910	0.7170	0.5649	0.5381
THD	10.19	15.10	11.59	10.58	8.97	11.02

Comments

From the table above it can be affirmed that the introduction of a detuned filter bank up to 2400 KVAR will not amplify negatively the harmonic currents, on the contrary it will be of benefit. Furthermore the PF will be improved from 92 to 99% and flicker should be reduced slightly even with the additional load.

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4. APPENDIX

4.1 Simulation One Line Diagram

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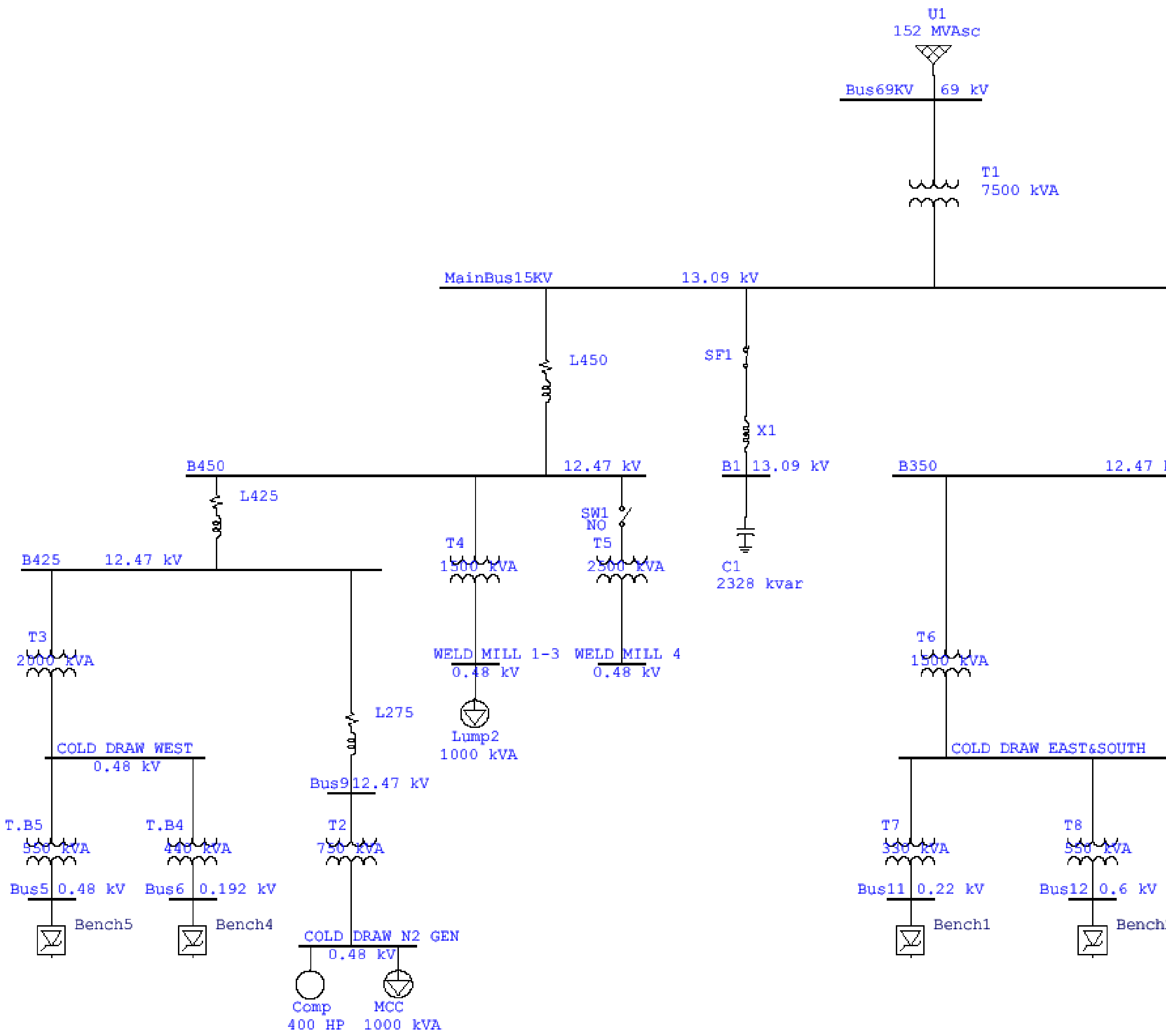

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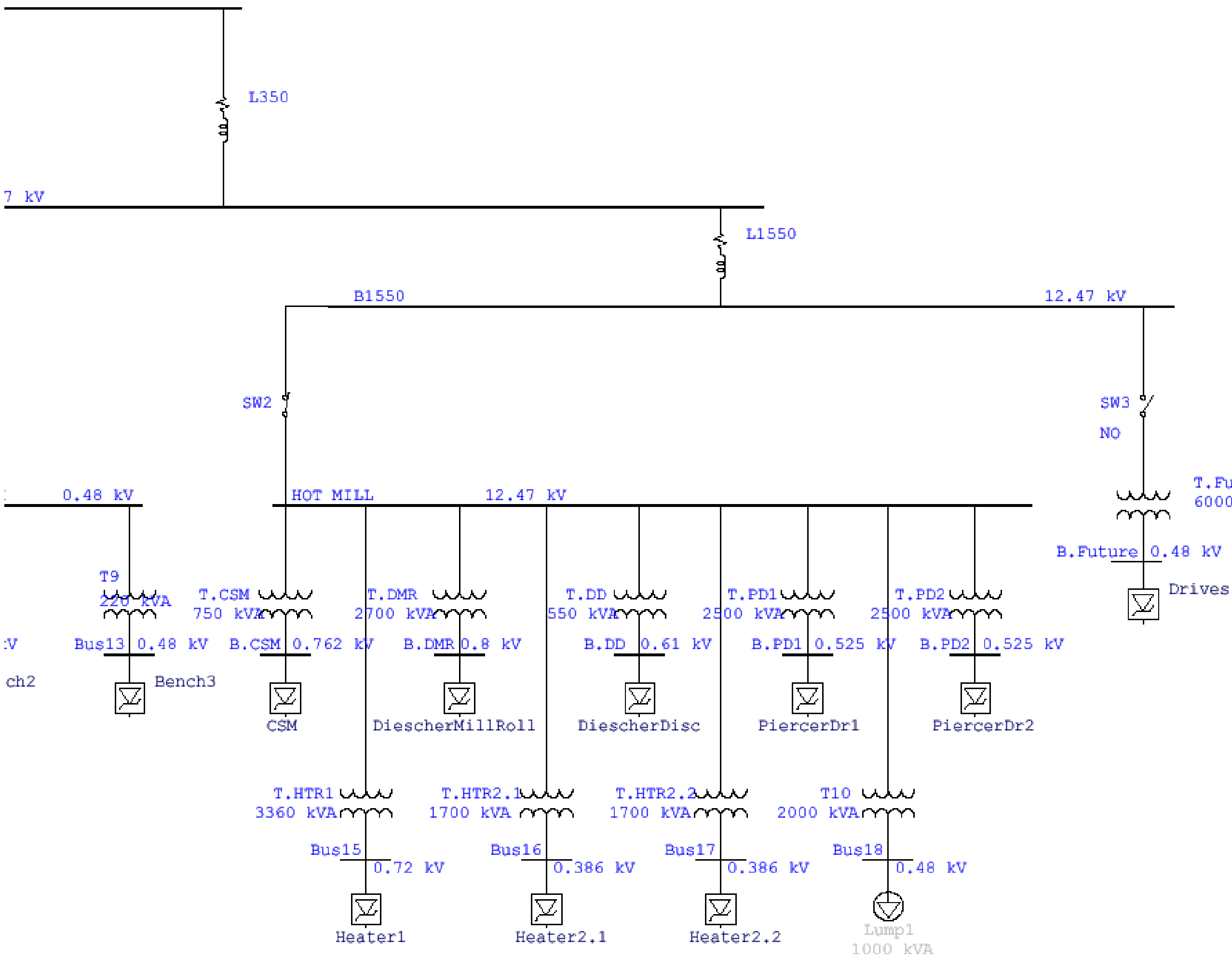

page 2 11:25:40 Jun 08, 2007 Project File: PLYMOUTH_R2

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4.2 Simulation Load Flow

Base Configuration RUN2 no Future Loads: Total Load = 3710 KVA, PF = 91.9%

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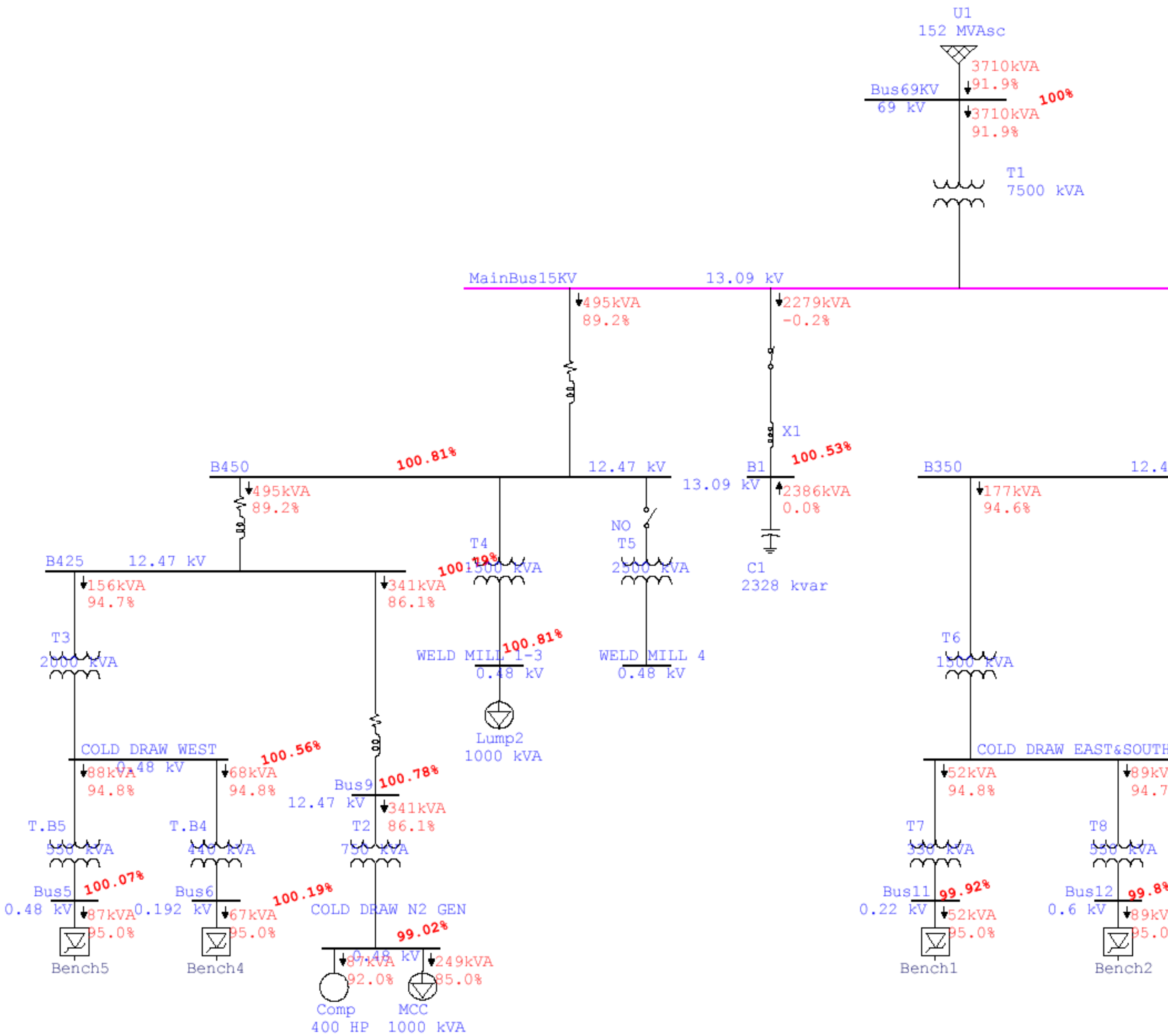

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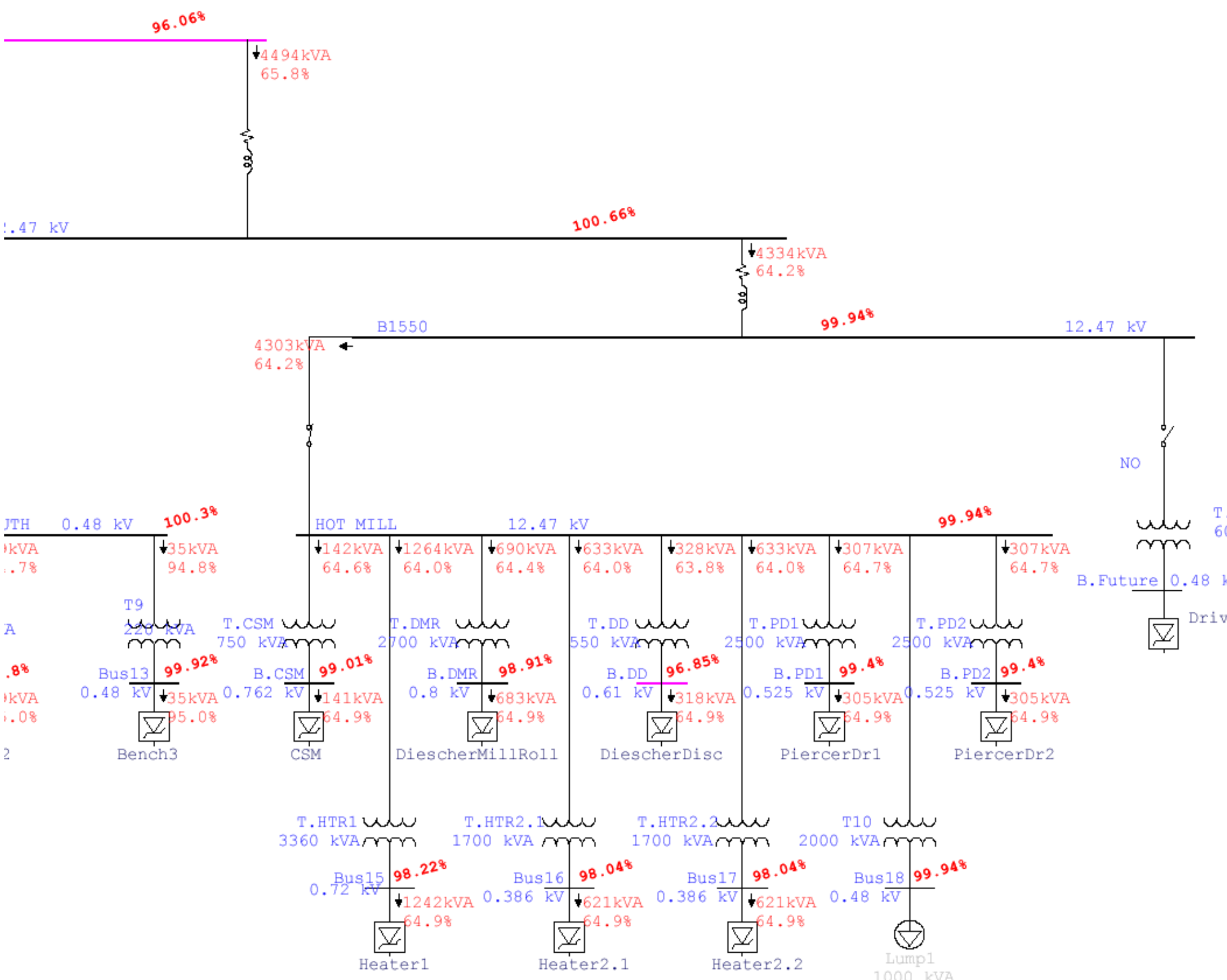

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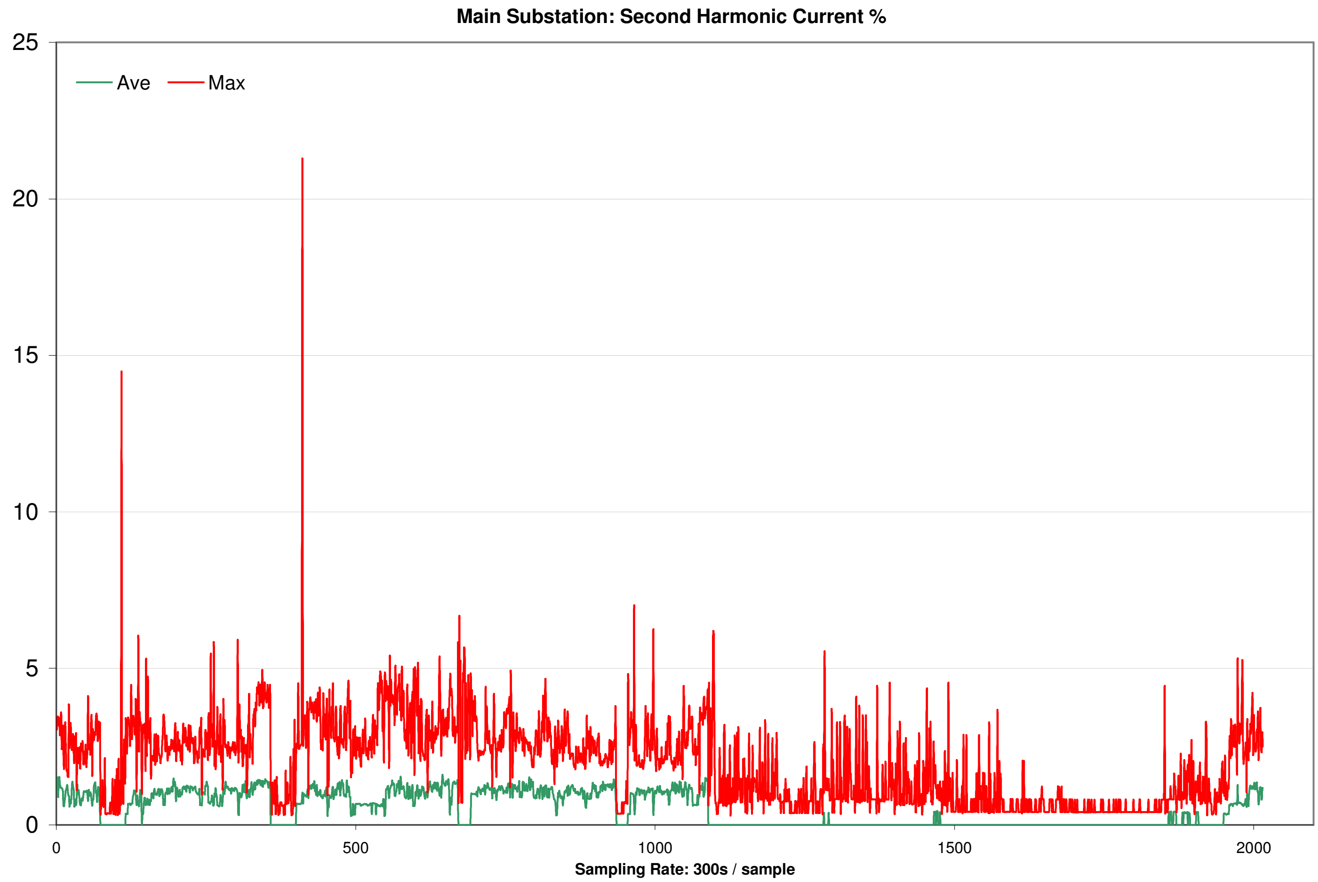
4.3 Harmonic Currents (Time Domain)

2nd Harmonic Current



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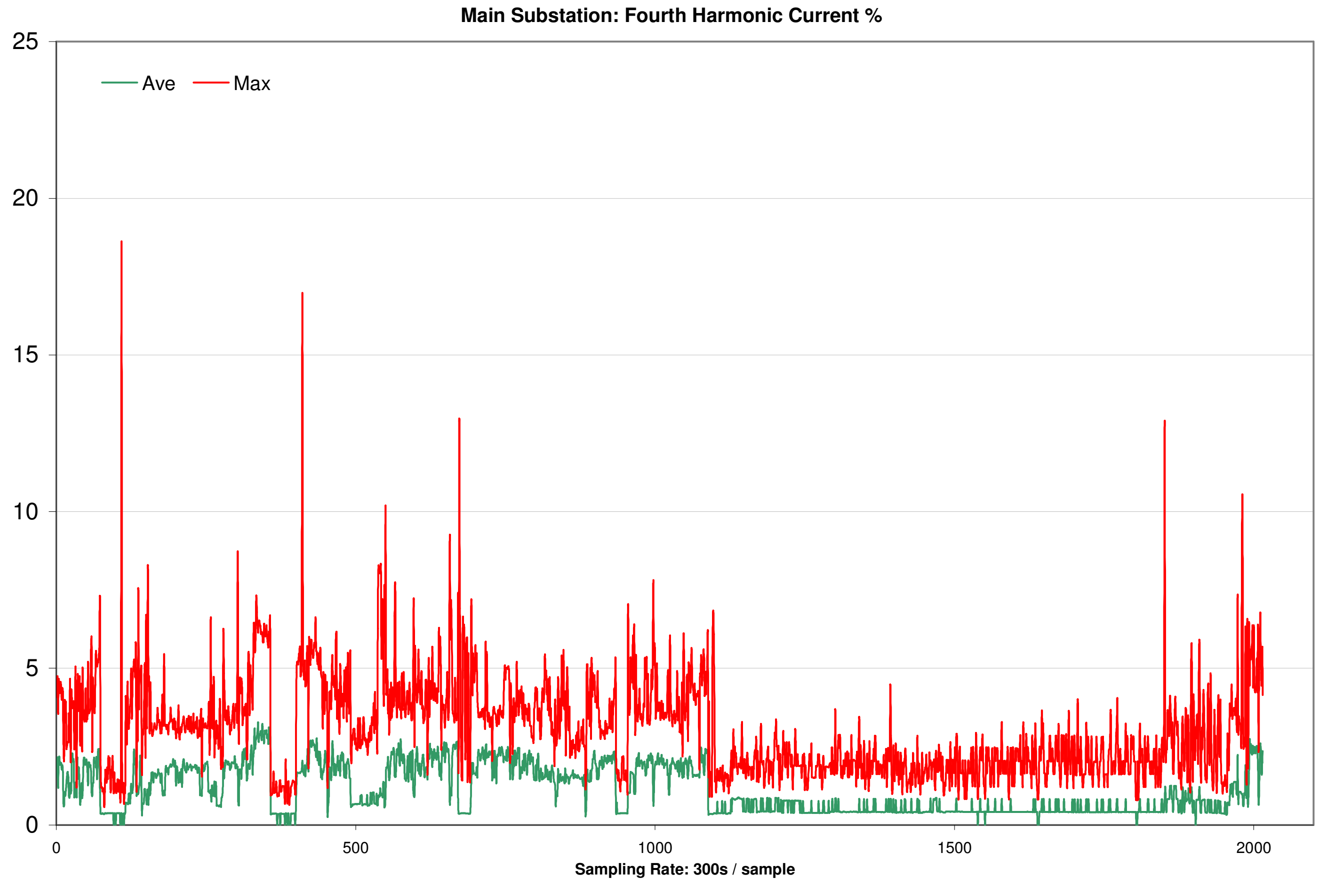
4th Harmonic Current



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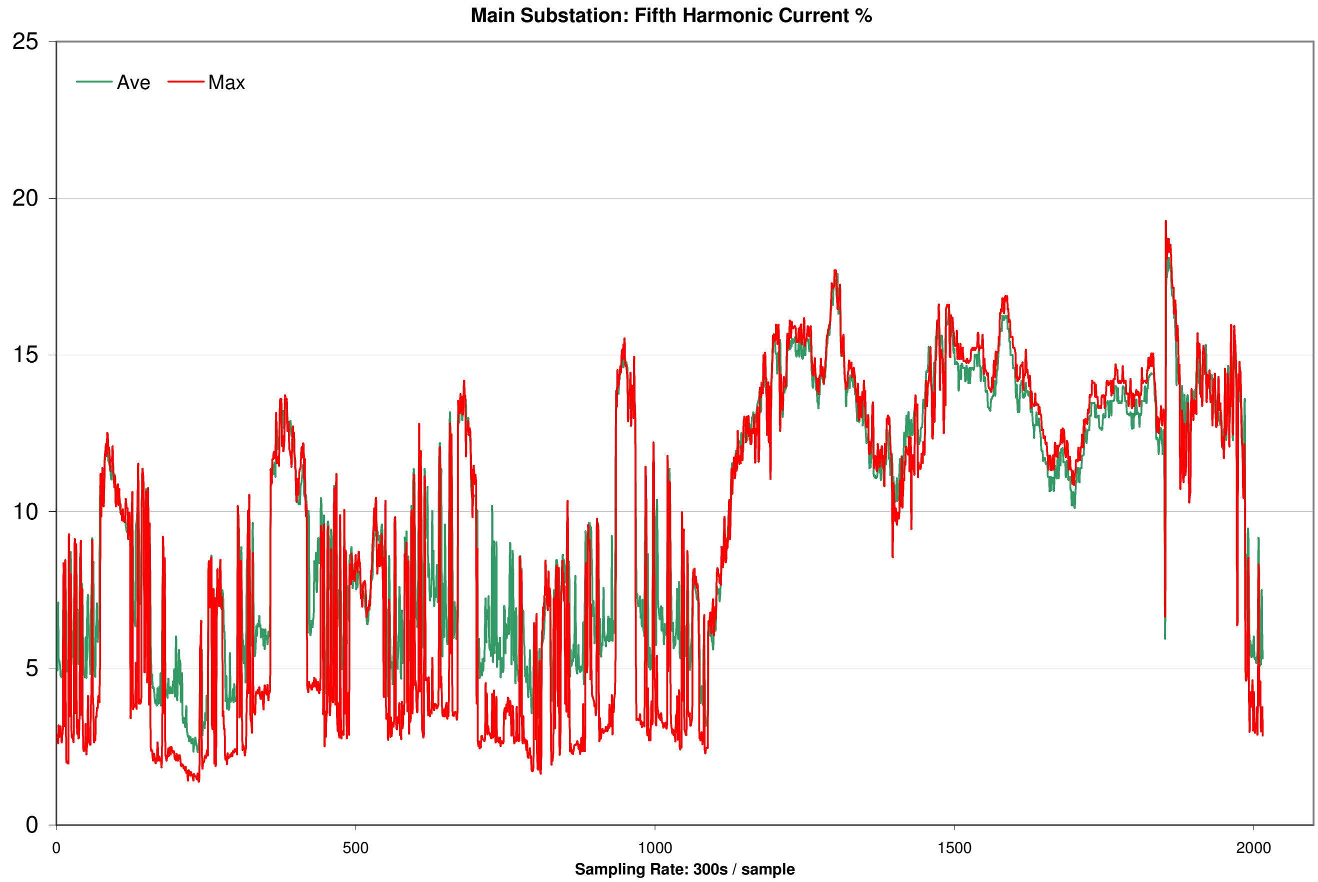
5th Harmonic Current



Comment

For samples 1100 to 2000, when no substantial Hot Mill drives are operational, the 5th harmonic distortion fluctuates between 10 to 15% and more. When the Hot Mill is fully operational (samples 0 to 1100), the 5th harmonic distortion fluctuates between 2.5 and 12.5%.

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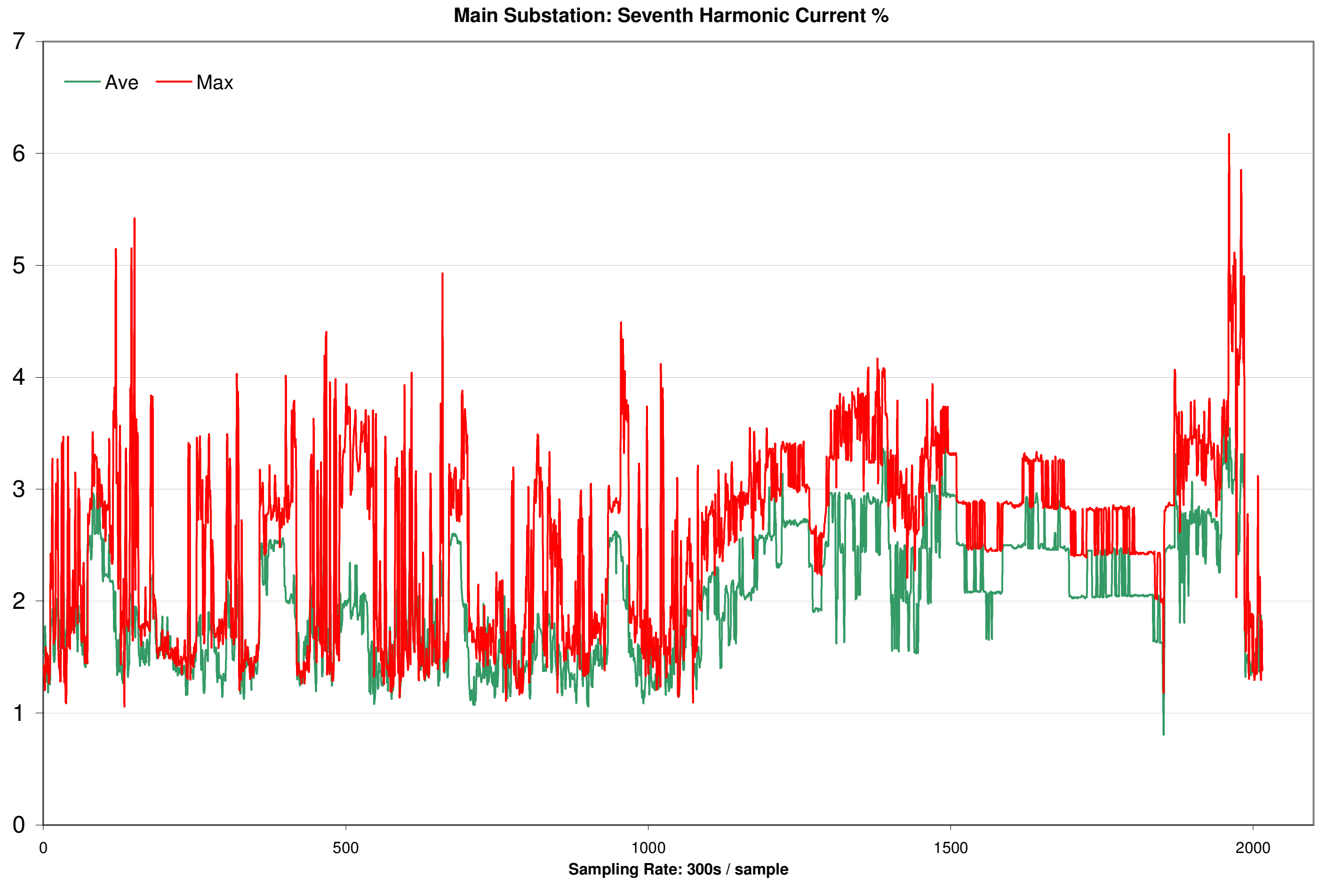
7th Harmonic Current



Comment

For samples 1100 to 2000, when no substantial Hot Mill drives are operational, the 7th harmonic distortion fluctuates between 2.5 to 4.5%. When the Hot Mill is fully operational (samples 0 to 1100), the 7th harmonic distortion fluctuates between 1 and 3.5%.

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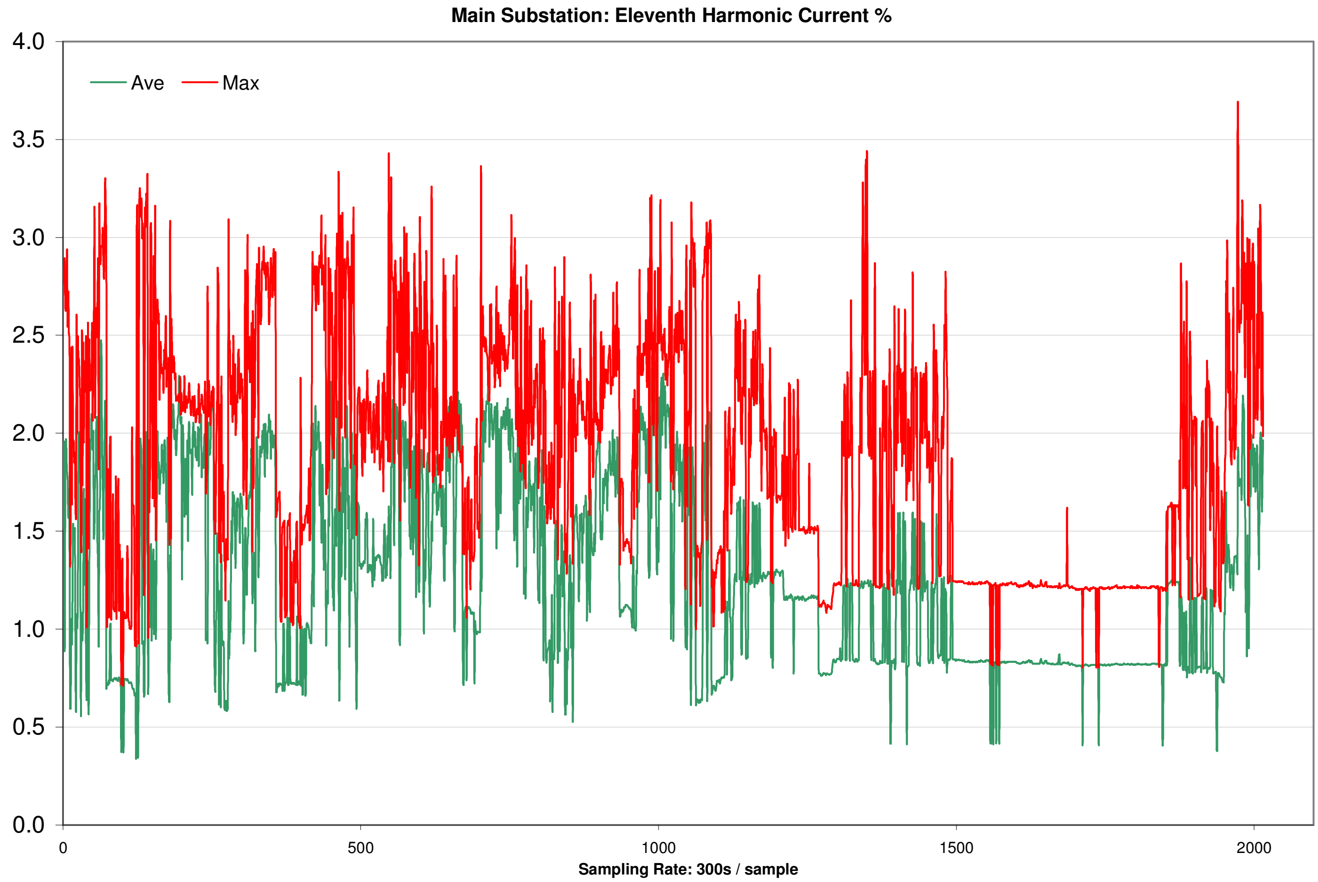
11th Harmonic Current



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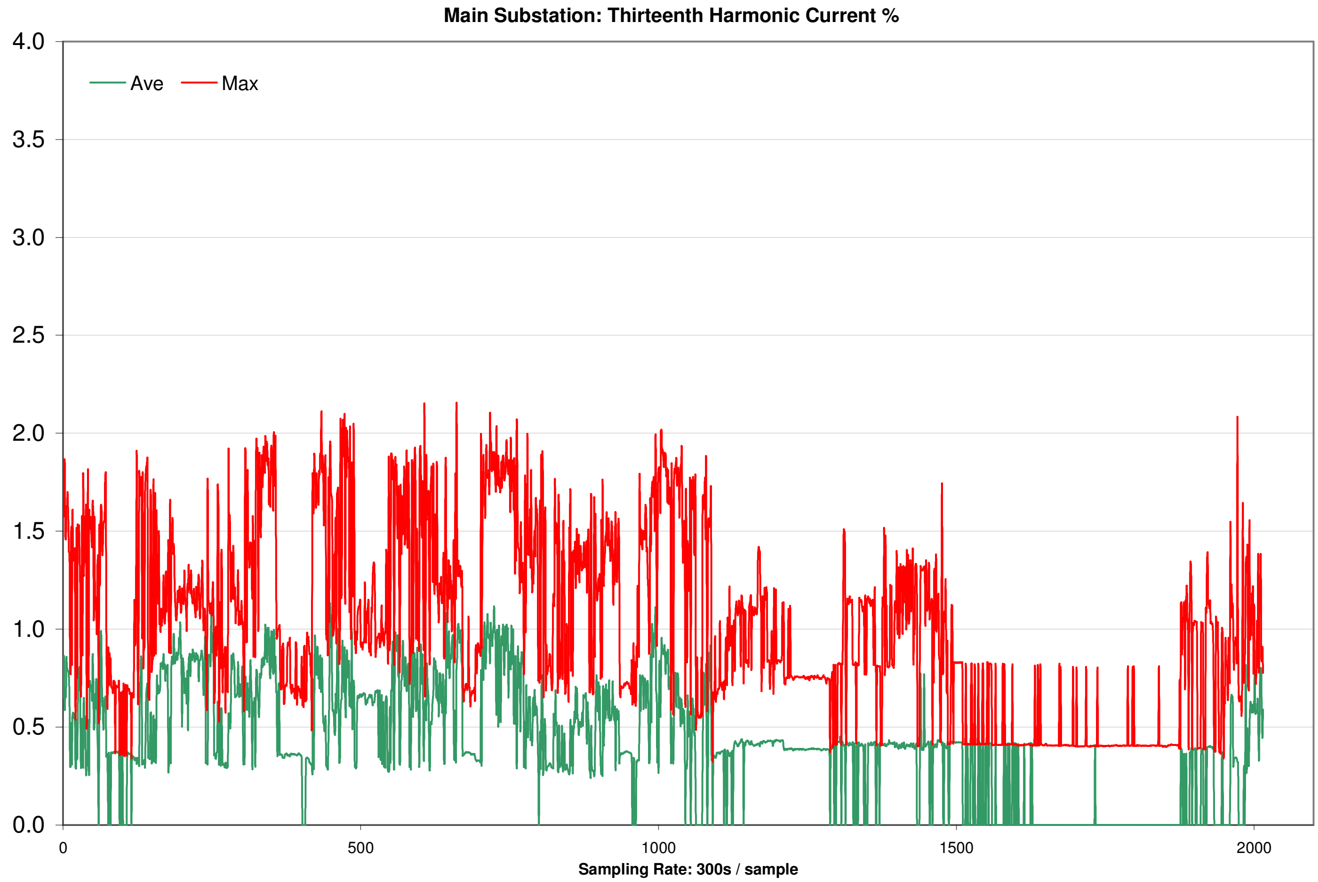
13th Harmonic Current



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4.4 IEEE Guidelines

IEEE 519 Guidelines for Current Distortion

IEEE Std 519-1992 IEEE RECOMMENDED PRACTICES AND REQUIREMENTS

Table 10-3—Current Distortion Limits for General Distribution Systems (120 V Through 69 000 V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

* All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where
I_{sc} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

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IEEE 519 Guidelines for Voltage Distortion

Table 10-2—Low-Voltage System Classification and Distortion Limits

	Special Applications*	General System	Dedicated System†
Notch Depth	10%	20%	50%
THD (Voltage)	3%	5%	10%
Notch Area (A_N)‡	16 400	22 800	36 500

NOTE — The value A_N for other than 480 V systems should be multiplied by V/480

*Special applications include hospitals and airports.
†A dedicated system is exclusively dedicated to the converter load.
‡In volt-microseconds at rated voltage and current.

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