TCPL - Siemens

CAPACITOR BANK STUDY

(Revision 3)

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12 November, 2008

1. Power Factor Calculation

Based on customer data for the 4,000 HP and 5,000 HP pump motors, the following tables illustrate the calculated Final PF values when using 450 KVAR and 525 KVAR capacitor banks for each motor.

4000 HP Motors

Load Factor	0.25	0.50	0.75	1.00	1.15
HP x Load Factor	1,000.00	2,000.00	3,000.00	4,000.00	4,600.00
Initial PF (Inductive)	0.819	0.906	0.920	0.916	0.909
Efficiency (Eff)	0.942	0.963	0.966	0.965	0.963
Calculated Amps	131.42	237.60	350.98	470.01	544.67
Real Amps = Calc Amps / Eff	139.51	246.73	363.33	487.06	565.60
Initial KVAR (Inductive)	277.34	206.57	217.70	325.97	445.37
Required Cap. KVAR for PF = 1.00	554.61	723.54	986.54	1,353.75	1,633.26
Final PF with 450 KVAR Capacitors	0.991382	0.984757	0.974196	0.959815	0.949009

5000 HP Motors

Load Factor	0.25	0.50	0.75	1.00	1.15
HP x Load Factor	1,250.00	2,500.00	3,750.00	5,000.00	5,750.00
Initial PF (Inductive)	0.815	0.906	0.920	0.917	0.911
Efficiency (Eff)	0.947	0.966	0.968	0.966	0.964
Calculated Amps	165.08	297.00	438.72	586.87	679.35
Real Amps = Calc Amps / Eff	174.32	307.45	453.22	607.53	704.72
Initial KVAR (Inductive)	356.36	258.22	272.13	396.37	531.74
Required Cap. KVAR for PF = 1.00	699.83	901.62	1,230.63	1,678.95	2,013.55
Final PF with 525 KVAR Capacitors	0.984590	0.981485	0.971440	0.958097	0.948304

Conclusion

Adding 450 KVAR capacitors on the 4,000 HP motor, the resulting PF is better than 0.949 Inductive at variable load factor from 0.25 to 1.15
Adding 525 KVAR capacitors on the 5,000 HP motor, the resulting PF is better than 0.948 Inductive at variable load factor from 0.25 to 1.15

Note 1: these calculations show the PF improvements due to the installation of capacitors. The total number of motors should not affect these results as each motor would have its own associated capacitor bank.

Note 2: auxiliary loads have been neglected.

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PF Calculations - Formulas

Initial PF = KW / Initial KVA and Initial Phi = ArcCos (KW / Initial KVA) (1)
KW mech. = 0.74569987 * HP (2)
KW electric = KW = KW mech. / Eff (3)

Replacing 1 and 2 in 3:
KW = 0.74569987 * HP / Eff (4)
Initial KVAR = KW * Tan (Initial Phi) = KW * Tan (ArcCos (PF Pump)) (5)
Final KVAR = Initial KVAR – Capacitor KVAR (6)
Final Phi = ArcTan (Final KVAR / KW) (7)
Final PF = Cos (Final Phi) (8)

Replacing 6 and 7 in 8:
Final PF = Cos (ArcTan ([Initial KVAR - Capacitor KVAR]/KW)) (9)

Replacing 5 in 9:
Final PF = Cos {ArcTan([KW*Tan(ArcCos(KW/Initial KVA)) - CapacitorKVAR]/KW)}

Re-arranging:
Final PF = Cos {ArcTan([Tan(ArcCos(KW/Initial KVA)) - CapacitorKVAR/KW])} (10)

Finally, replacing 1 and 3 in 10:
Final PF = Cos {ArcTan([Tan(ArcCos(InitialPF)) - (EffxCapacitorKVAR)/(0.7457*HP)])} (11)

Adding Auxiliary Loads:

Final PF with Caps = Total KW / Total KVA
Total KW = KW Pump + KW Aux
= (0.74569987 * HP / Eff) + (KVA Aux * PF Aux)
Total KVAR = KVAR Pumps + KVAR Aux
= KW Pump * Tan (ArcCos (PF Pump)) + KVAR Aux
= KW Pump * Tan (ArcCos (PF Pump)) + KVA Aux * Sin(ArcCos(PF Aux))
And
Total KVA $= \sqrt{\text{Total KW}^2 + \text{Total KVAR}^2}$

Finally:
$\text{Final PF}_{w/Caps} = [0.74569987 \cdot \text{HP/Eff} + \text{KVA Aux} \cdot \text{PF Aux}] / [\sqrt{\text{Total KW}^2 + \text{Total KVAR}^2}]$ (12)

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Auxiliary Loads

The effect of auxiliary loads on the final Power Factor calculation for the 4,000 HP Pump Stations is shown in following table:

VOLTS	4,000.00	V			
MOTOR HP	4,000.00	HP			
FINAL PF (TARGET)	0.95				
AUXILIARY LOAD / PUMP	250.00	KVA			
AUXILIARY LOAD PF	0.84				
CAP KVAR / PUMP	450.00	KVAR			
PUMP LOAD FACTOR	0.250	0.500	0.750	1.000	1.150
PUMP POWER FACTOR	0.819	0.906	0.920	0.916	0.909
PUMP EFFICIENCY	0.942	0.963	0.966	0.965	0.963
PUMP HP (MECHANIC)	1,000.00	2,000.00	3,000.00	4,000.00	4,600.00
PUMP KW (ELECTRIC)	791.61	1,548.70	2,315.84	3,090.98	3,562.01
PUMP KVA	966.56	1,709.38	2,517.22	3,374.44	3,918.61
PUMP KVAR	554.61	723.54	986.54	1,353.75	1,633.26
CAP KVAR (PF = FINAL PF)	277.34	206.57	217.70	325.97	445.37
CAP KVAR (PF = FINAL PF and PUMP Efficiency)	294.42	214.51	225.36	337.79	462.48
CAP KVAR (PF = 1 and PUMP Efficiency)	554.61	723.54	986.54	1,353.75	1,633.26
AUXILIARY LOADS KVA	62.50	125.00	187.50	250.00	287.50
AUXILIARY LOADS KW	52.50	105.00	157.50	210.00	241.50
AUXILIARY LOADS KVAR	33.91	67.82	101.73	135.65	155.99
TOTAL KW	844.11	1,653.70	2,473.34	3,300.98	3,803.51
TOTAL KVAR	138.52	341.37	638.28	1,039.40	1,339.25
TOTAL KVA	855.40	1,688.57	2,554.37	3,460.76	4,032.41
FINAL PF with CAPS, with AUX LOADS	0.986802	0.979352	0.968278	0.953833	0.943236
FINAL PF with CAPS, without AUX LOADS	0.991382	0.984757	0.974196	0.959815	0.949009

The results show little impact on the Total Power Factor when adding auxiliary loads (compare last two lines on the table above). It should be noted, we have taken 250 KVA / Pump as a reasonable value for this load because the maximum estimated auxiliary load of 500 KVA should be referred to the total number of connected pumps and associated capacitors.

The table above has been generated from an Excel spreadsheet. Formulas used for this calculation are shown on Page 3.

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The effect of auxiliary loads on the final Power Factor calculation for the 5,000 HP Pump Stations is shown in following table:

VOLTS	4,000.00	V			
MOTOR HP	5,000.00	HP			
FINAL PF (TARGET)	0.95				
AUXILIARY LOAD / PUMP	250.00	KVA			
AUXILIARY LOAD PF	0.84				
CAP KVAR / PUMP	525.00	KVAR			
PUMP LOAD FACTOR	0.250	0.500	0.750	1.000	1.150
PUMP POWER FACTOR	0.815	0.906	0.920	0.917	0.911
PUMP EFFICIENCY	0.947	0.966	0.968	0.966	0.964
PUMP HP (MECHANIC)	1,250.00	2,500.00	3,750.00	5,000.00	5,750.00
PUMP KW (ELECTRIC)	984.29	1,929.87	2,888.82	3,859.73	4,447.90
PUMP KVA	1,207.72	2,130.09	3,140.02	4,209.08	4,882.44
PUMP KVAR	699.83	901.62	1,230.63	1,678.95	2,013.55
CAP KVAR (PF = FINAL PF)	356.36	258.22	272.13	396.37	531.74
CAP KVAR (PF = FINAL PF and PUMP Efficiency)	376.31	267.31	281.12	410.32	551.59
CAP KVAR (PF = 1 and PUMP Efficiency)	699.83	901.62	1,230.63	1,678.95	2,013.55
AUXILIARY LOADS KVA	62.50	125.00	187.50	250.00	287.50
AUXILIARY LOADS KW	52.50	105.00	157.50	210.00	241.50
AUXILIARY LOADS KVAR	33.91	67.82	101.73	135.65	155.99
TOTAL KW	1,036.79	2,034.87	3,046.32	4,069.73	4,689.40
TOTAL KVAR	208.74	444.44	807.37	1,289.60	1,644.54
TOTAL KVA	1,057.60	2,082.84	3,151.49	4,269.16	4,969.40
FINAL PF with CAPS, with AUX LOADS	0.980329	0.976968	0.966628	0.953285	0.943654
FINAL PF with CAPS, without AUX LOADS	0.984590	0.981485	0.971440	0.958097	0.948304

The results show little impact on the Total Power Factor when adding auxiliary loads (compare last two lines on the table above).

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2. Transient Simulation

Following data was considered for simulating capacitor switching using ATP software:

5 x 5000 HP AC MOTORS & 5 x 525 KVAR CAPACITORS

UTILITY		
100 MVA BASE XR	0.138270	Ohms
100 MVA BASE XL	0.328100	Ohms
XR	26.32	Ohms
XL	62.45	Ohms
XL/XR	2.372900	
Isc	1.175600	A
TRANSFORMER		
PRIMARY VOLTAGE	138	kV
SECONDARY VOLTAGE	4.16	kV
MVA	15	MVA
Z	8.5	%
MOTORS		
RATED POWER	5000	HP
RATED POWER	3728.5	KW
POWER FACTOR	0.9	PF
KVA	4150	KVA
AMPS RMS	608	A
MOTOR MODEL		
XR	12.51	Ohms
XL	1.2	Ohms
CAP BANKS		
KVAR at 4.16 KV	525	KVAR
C(Y) uF / Ph	80.47	uF
CAP BANK FUND. PHASE CURRENT	72.2	A
INRUSH REACTORS	0.00	uH
CABLES 325 MCM / PH	35	m
XR	0.0615	Ohms/1000ft
XL	0.0375	Ohms/1000ft

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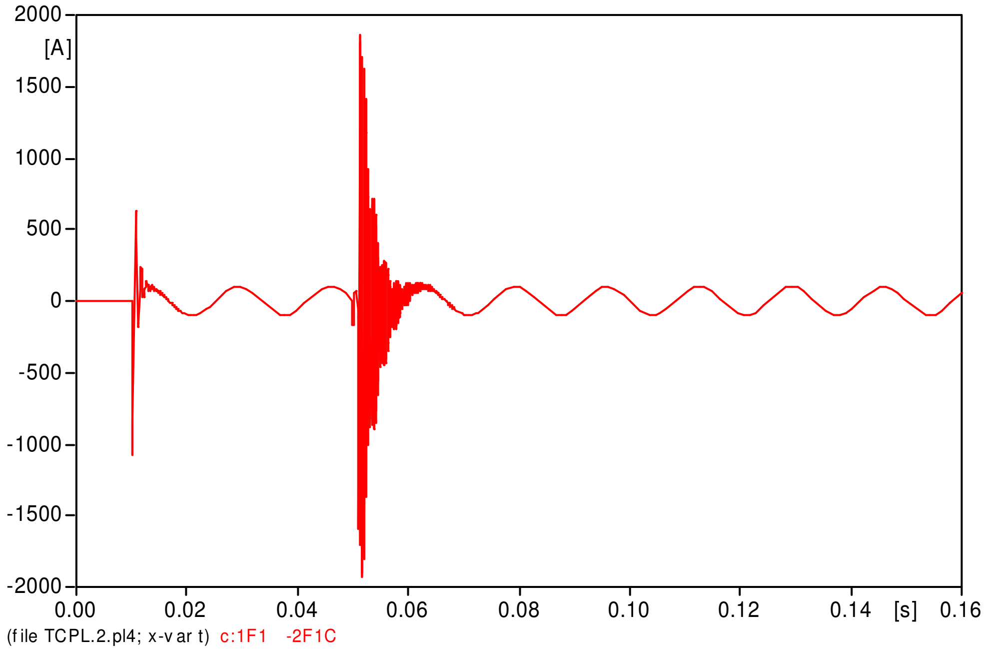
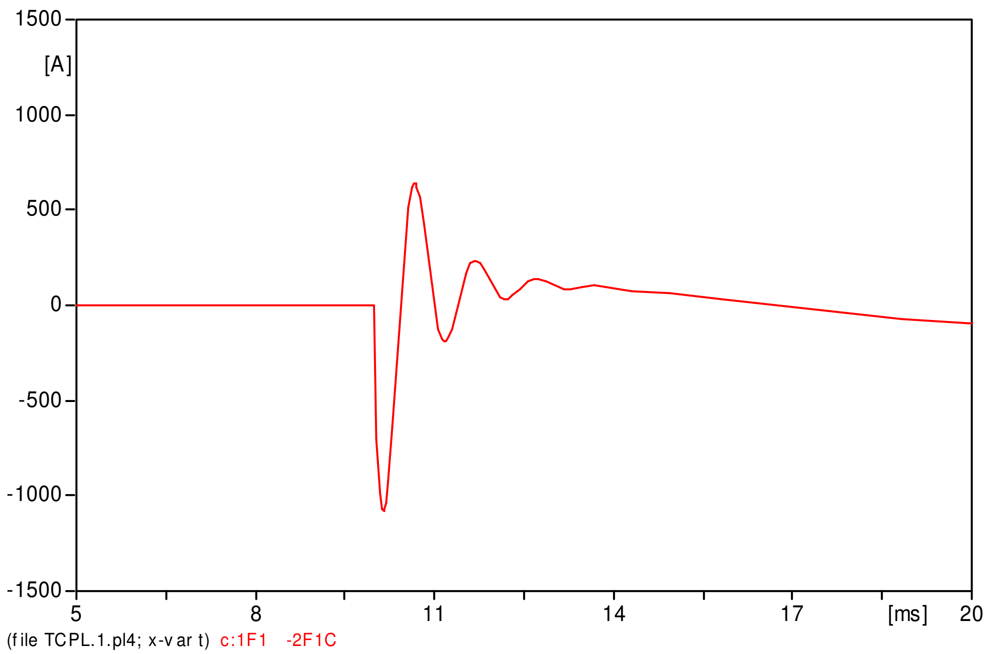
Simulation Results

The first chart below shows the capacitor currents of the first 4 motors and associated capacitors when switching them on at t = 0.01 seconds and then switching on the fifth motor with its associated capacitor at t = 0.051 seconds. Note the timing between switching has been shortened unrealistically as to allow a reasonable amount of calculated points, avoiding thus memory overflow and computing time-out error. There is though no impact on the simulated results for the second step as current transients do settle in less than one cycle.

STEPS 1 TO 4 CAPACITOR CURRENTS:



MAGNIFIED ON TRANSIENT (t = 10 ms):



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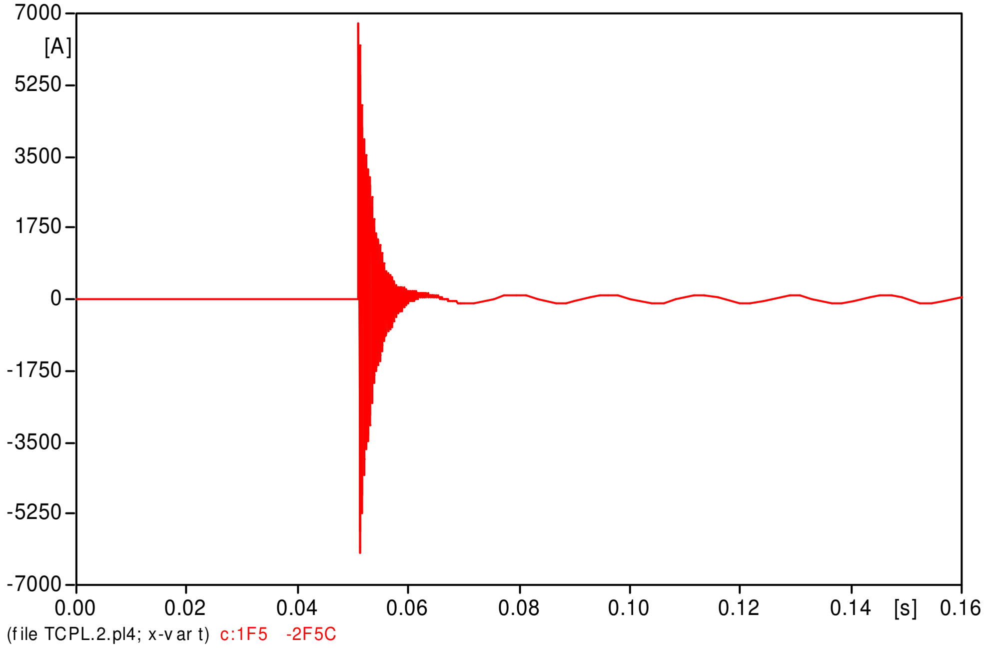
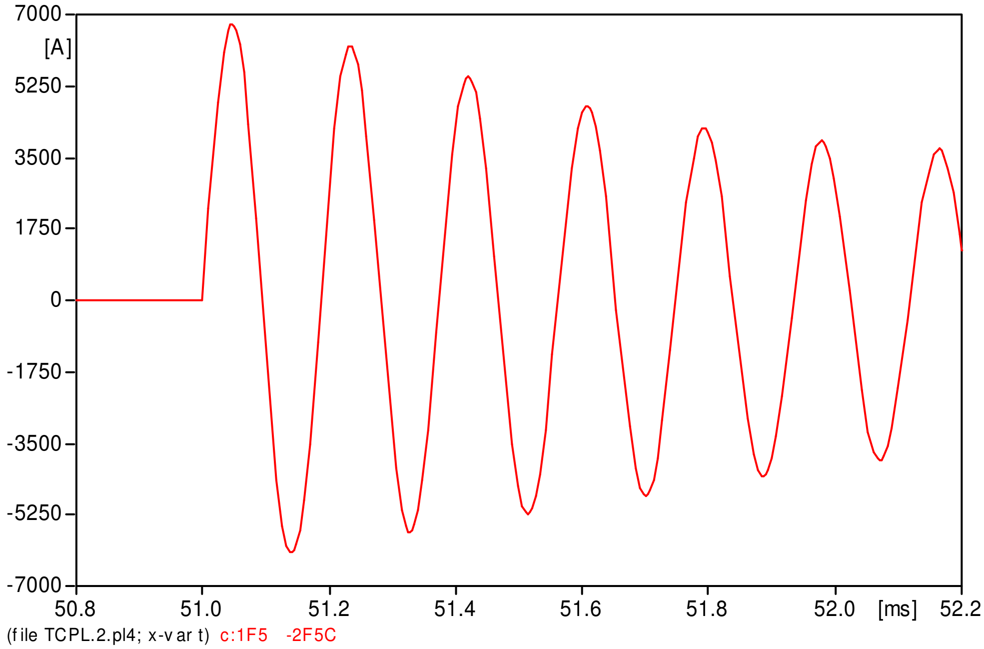
STEP 5 CAPACITOR CURRENT TRANSIENT:



MAGNIFIED STEP 5 CURRENT TRANSIENT:



3. Resonance Frequency

Pumping Stations in Canada - Data

NR	PUMP STN	S. MVA sc	TR. MVA	TR. Z%	HP	QTY	TR. MVA sc	MVA sc
1	PS5	150.00	15.00	6.00	5,000	6	250.00	93.75
2	PS6	281.00	15.00	7.50	5,000	5	200.00	116.84
3	PS7	592.00	15.00	8.50	5,000	5	176.47	135.95
4	PS8	562.00	15.00	8.50	5,000	5	176.47	134.30
5	PS9	685.00	15.00	8.50	5,000	4	176.47	140.32
6	PS10	440.00	10.00	10.50	4,000	3	95.24	78.29
7	PS11	89.00	10.00	8.50	4,000	3	117.65	50.67
8	PS12	400.00	7.50	9.50	4,000	2	78.95	65.93
9	PS13	475.00	7.50	9.00	4,000	2	83.33	70.90
10	PS14	507.00	7.50	7.00	4,000	2	107.14	88.45
11	PS15	762.00	10.00	9.50	4,000	3	105.26	92.49
12	PS16	1105.00	7.50	8.50	4,000	2	88.24	81.71
13	PS17	1300.00	10.00	9.50	4,000	3	105.26	97.38
14	PS18	1731.00	10.00	10.50	4,000	3	95.24	90.27
15	PS19	1006.00	7.50	9.50	4,000	2	78.95	73.20
16	PS20	1216.00	7.50	8.50	4,000	2	88.24	82.27
17	PS21	98.00	10.00	9.50	4,000	3	105.26	50.75
18	PS22	99.99	7.50	8.50	4,000	2	88.24	46.87
19	PS23	193.00	10.00	8.50	4,000	3	117.65	73.09
20	PS24	99.99	5.00	8.50	4,000	1	58.82	37.04
21	PS25	165.00	10.00	8.50	4,000	3	117.65	68.68
22	PS26	128.00	15.00	8.50	5,000	4	176.47	74.19
23	PS27	217.00	15.00	8.50	5,000	4	176.47	97.32

Resonance Frequency - Table 1

Shows the resonance harmonic order (HN) and resonance frequency (f0) running the pump motors 100% service factor:

MOTORS ON:		1	2	3	4	5	1	2	3	4	5
NR	PUMP STN	HN	HN	HN	HN	HN	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]
3	PS7	17.57	13.39	11.67	10.71	10.08	1054.38	803.50	700.17	642.31	604.93
6	PS10	15.24	12.05	10.78			914.20	722.90	646.68		
8	PS12	14.31	11.46				858.43	687.87			
9	PS13	14.69	11.70				881.24	702.14			
11	PS15	16.24	12.69	11.26			974.33	761.16	675.32		
13	PS17	16.57	12.90	11.42			994.21	773.91	684.91		
15	PS19	14.86	11.81				891.65	708.68			
17	PS21	13.07	10.70	9.79			784.49	642.20	587.16		
18	PS22	12.74	10.50				764.46	630.01			
19	PS23	14.85	11.81	10.60			891.16	708.37	635.87		
20	PS24	11.85					711.13				
21	PS25	14.52	11.60	10.44			871.12	695.80	626.55		
22	PS26	14.27	11.53	10.46	9.88		856.21	691.91	627.66	592.93	
23	PS27	15.74	12.45	11.14	10.42		944.32	747.04	668.46	625.48	

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Pumping Stations in USA - Data

NR	PUMP STN	S. MVA sc	TR. MVA	TR. Z%	HP	QTY	TR. MVA sc	MVA sc
1	PS15	99.99	15.00	6.00	4,000	5	250.00	71.42
2	PS16	99.99	15.00	6.00	4,000	5	250.00	71.42
3	PS17	99.99	15.00	6.00	5,000	4	250.00	71.42
4	PS18	215.00	15.00	7.00	5,000	4	214.29	107.32
5	PS19	386.00	20.00	8.50	5,000	4	235.29	146.18
6	PS20	923.00	15.00	9.50	5,000	4	157.89	134.83
7	PS21	323.00	15.00	8.50	5,000	4	176.47	114.12
8	PS22	444.00	15.00	9.50	5,000	4	157.89	116.47
9	PS23	458.00	15.00	8.50	5,000	4	176.47	127.39
10	PS24	99.00	15.00	8.00	5,000	4	187.50	64.79
11	PS25	137.00	15.00	8.50	5,000	4	176.47	77.13
12	PS26	88.00	15.00	8.50	5,000	4	176.47	58.72
13	PS27	107.00	12.00	8.50	5,000	3	141.18	60.87
14	PS28	99.99	15.00	8.00	5,000	4	187.50	65.21
15	PS29	731.00	15.00	9.50	5,000	4	157.89	129.85
16	PS30	628.00	15.00	9.50	5,000	4	157.89	126.17
17	PS31	1834.00	15.00	8.50	5,000	4	176.47	160.98
18	PS32	138.00	12.00	8.50	5,000	3	141.18	69.79
19	PS33	131.00	15.00	8.50	5,000	4	176.47	75.19
20	PS34	519.00	12.00	7.80	4,000	4	153.85	118.67
21	PS35	99.99	12.00	7.80	4,000	4	153.85	60.60
22	PS36	4075.00	15.00	8.70	5,000	4	172.41	165.42
23	PS37	99.99	15.00	8.00	5,000	4	187.50	65.21
24	PS38	99.99	15.00	8.00	5,000	3	187.50	65.21

Resonance Frequency - Table 2

Shows the resonance harmonic order (HN) and resonance frequency (f0) running the pump motors 100% service factor:

MOTORS ON:		1	2	3	4	5	1	2	3	4	5
NR	PUMP STN	HN	HN	HN	HN	HN	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]
1	PS15	14.73	11.73	10.54	9.89	9.48	883.64	703.65	632.37	593.52	568.95
2	PS16	14.73	11.73	10.54	9.89	9.48	883.64	703.65	632.37	593.52	568.95
3	PS17	14.08	11.42	10.38	9.82		845.07	685.03	622.60	588.92	
5	PS19	18.46	14.20	12.46	11.49		1107.61	851.81	747.34	689.19	
7	PS21	16.72	13.08	11.61	10.80		1003.46	784.64	696.58	648.09	
8	PS22	16.86	13.16	11.67	10.85		1011.47	789.76	700.43	651.19	
10	PS24	13.63	11.14	10.17	9.65		817.72	668.22	610.31	579.18	
11	PS25	14.46	11.65	10.55	9.95		867.89	699.15	632.98	597.16	
12	PS26	13.20	10.87	9.98	9.50		791.85	652.46	598.83	570.13	
13	PS27	13.35	10.97	10.05			801.10	658.08	602.92		
14	PS28	13.66	11.16	10.18	9.66		819.49	669.31	611.10	579.81	
20	PS34	17.94	13.79	12.09	11.14		1076.47	827.10	725.17	668.40	
21	PS35	13.89	11.20	10.15	9.58		833.21	672.19	609.12	575.00	
22	PS36	19.10	14.40	12.45	11.34		1146.20	864.09	746.72	680.50	
23	PS37	13.19	10.58	9.55	9.00		791.63	634.90	573.21	539.72	
24	PS38	13.66	11.16	10.18			819.49	669.31	611.10		

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Resonance Frequency - Table 3

Shows the resonance harmonic order (HN) and resonance frequency (f0) running the pump motors 50% service factor:

MOTORS ON:		1	2	3	4	5	1	2	3	4	5
NR	PUMP STN	HN	HN	HN	HN	HN	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]
1	PS15	13.70	10.41	9.05	8.29	7.80	822.25	624.82	543.30	497.55	467.96
2	PS16	13.70	10.41	9.05	8.29	7.80	822.25	624.82	543.30	497.55	467.96
3	PS17	12.93	9.96	8.75	8.07		775.86	597.55	524.83	484.39	
5	PS19	17.60	13.05	11.13	10.04		1055.75	783.20	668.08	602.32	
7	PS21	15.77	11.83	10.18	9.25		945.90	709.55	610.77	554.82	
8	PS22	15.91	11.92	10.25	9.31		954.40	715.21	615.16	558.45	
10	PS24	12.43	9.64	8.50	7.88		745.97	578.21	510.18	472.50	
11	PS25	13.34	10.23	8.95	8.24		800.66	613.69	537.10	494.37	
12	PS26	11.96	9.33	8.27	7.69		717.52	559.92	496.39	461.36	
13	PS27	12.13	9.44	8.36			727.71	566.46	501.31		
14	PS28	12.47	9.66	8.52	7.89		747.91	579.46	511.13	473.27	
20	PS34	17.11	12.69	10.82	9.75		1026.68	761.18	648.97	584.85	
21	PS35	12.80	9.82	8.60	7.92		767.81	589.17	516.06	475.31	
22	PS36	18.44	13.51	11.40	10.18		1106.36	810.49	683.99	611.00	
23	PS37	12.21	9.33	8.14	7.48		732.75	559.77	488.68	448.94	
24	PS38	12.47	9.66	8.52			747.91	579.46	511.13		

Resonance Frequency - Table 4

Shows the resonance harmonic order (HN) and resonance frequency (f0) running the pump motors 25% service factor:

MOTORS ON:		1	2	3	4	5	1	2	3	4	5
NR	PUMP STN	HN	HN	HN	HN	HN	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]	f 0 [Hz]
1	PS15	13.16	9.69	8.21	7.36	6.80	789.77	581.42	492.77	441.82	408.21
2	PS16	13.16	9.69	8.21	7.36	6.80	789.77	581.42	492.77	441.82	408.21
3	PS17	12.31	9.14	7.81	7.04		738.82	548.61	468.35	422.53	
5	PS19	17.15	12.44	10.41	9.23		1028.84	746.52	624.68	553.80	
7	PS21	15.26	11.15	9.38	8.36		915.77	668.85	562.98	501.73	
8	PS22	15.41	11.25	9.46	8.43		924.54	674.86	567.73	505.73	
10	PS24	11.79	8.79	7.53	6.81		707.37	527.48	451.87	408.86	
11	PS25	12.75	9.44	8.03	7.23		764.82	566.15	482.06	433.95	
12	PS26	11.29	8.46	7.27	6.60		677.30	507.36	436.25	395.92	
13	PS27	11.47	8.58	7.36			688.09	514.57	441.84		
14	PS28	11.82	8.81	7.55	6.83		709.42	528.85	452.94	409.74	
20	PS34	16.68	12.10	10.12	8.97		1000.85	725.97	607.29	538.23	
21	PS35	12.22	9.05	7.71	6.94		732.92	542.92	462.56	416.61	
22	PS36	18.10	13.04	10.84	9.55		1085.89	782.31	650.36	573.10	
23	PS37	11.69	8.64	7.34	6.60		701.46	518.14	440.38	395.82	
24	PS38	11.82	8.81	7.55			709.42	528.85	452.94		

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Source MVAsc in grey are assumed values when missing measured Source MVAsc data. Potentially critical resonance frequencies below n = 9 are shown in red. Potentially critical resonance frequencies do not necessarily imply problematic operation, as no information about harmonic current injection is available at this point in time. The criticality of these points can be investigated individually if harmonic injection levels from non-linear loads are measured and properly recorded and the correspondent harmonic current amplification factors are calculated. Harmonic current amplification factors could be calculated based on case by case simulations using ETAP software, but the large number of stations should be considered before undertaking such extended task. We have opted selecting one “worst case” station instead.

Note the resonance frequency does depend on the motor loading (Service Factor): lower motor service factor implies lower resonance frequency! The load Power Factor also affects the resonance frequency!

450 KVAR capacitors are considered connected to 4,000 HP motors and 525 KVAR capacitors to 5,000 HP motors.

Resonance Order Number Calculation – Formulas

Following formulas were used for calculating the resonance frequencies and order numbers:

n = Number of Motors On
MW motor = (0.74569987 / 1000) x HP
MVA motor = MW motor / PF motor
PF motor = 0.93
XL motor = V^2 x Sin (ArcCos (PF)) / MVA motor / 3 [Ohms]
MVAR motors = n x V^2 / XL motor = n / [Sin (ArcCos (PF)) / MVA motor / 3]
MVA sc transformer = 100 x MVA transformer / Z transformer [%]
MVA sc = MVA sc utility // MVA sc transformer
MVA sc = MVA sc utility x MVA sc transformer / (MVA utility + MVA sc transformer)
MVAR inductive total = MVAR utility // MVAR transformer + MVAR motors
≈ MVA sc + MVAR motors, for Utility X / R > 2 !

Finally:

$$HN = \sqrt{\text{MVAR inductive total / (n x MVAR caps)}}$$

$$HN \approx \sqrt{\text{(MVAR sc + MVAR motors) / (n x MVAR caps)}}$$

f0 = 60 x HN

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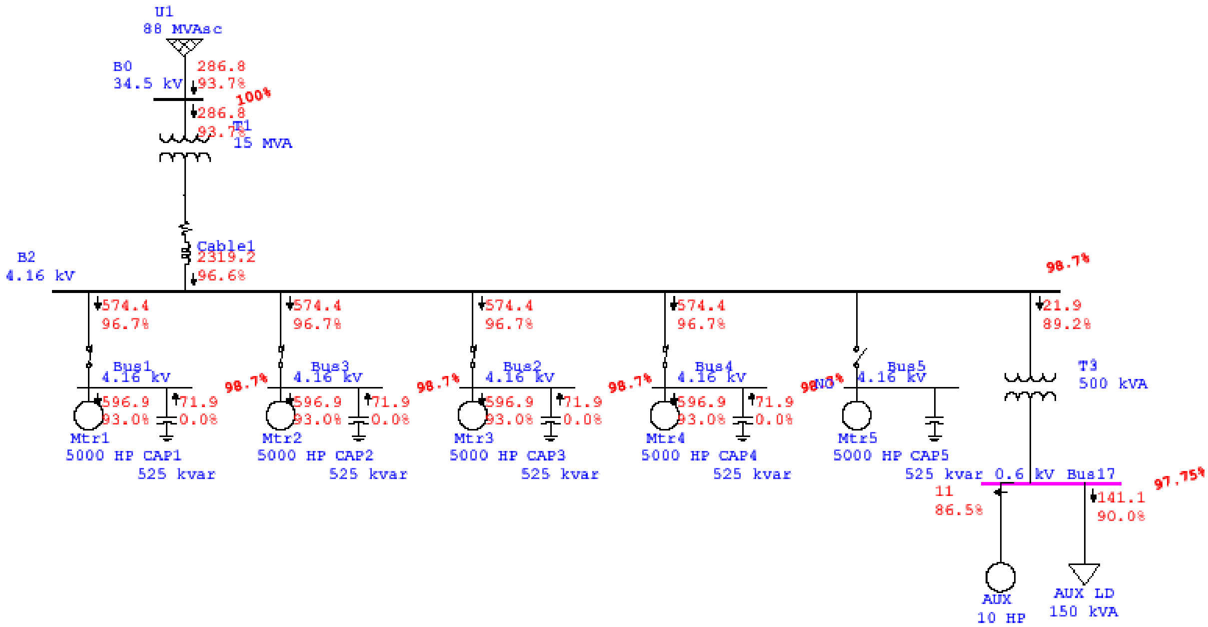
4. ETAP Simulation

The most critical pumping station as far as resonance is concerned (Pumping Station PS26 in USA) has been chosen for this simulation. The one-line and load flow diagram, MV bus frequency scan (impedance amplitude and phase angle) and the harmonic current amplification factor at the source are presented next. The current amplification chart should be carefully considered if important non-linear loads such as ac or dc drives are expected.

ETAP One Line / Load Flow Diagram



Note:
Red horizontal values are currents (A)
Red inclined % values are voltages in % of nominal values
Red horizontal % values are Power Factor values in %
Blue horizontal indications are names and nominal load values (HP and KVAR)

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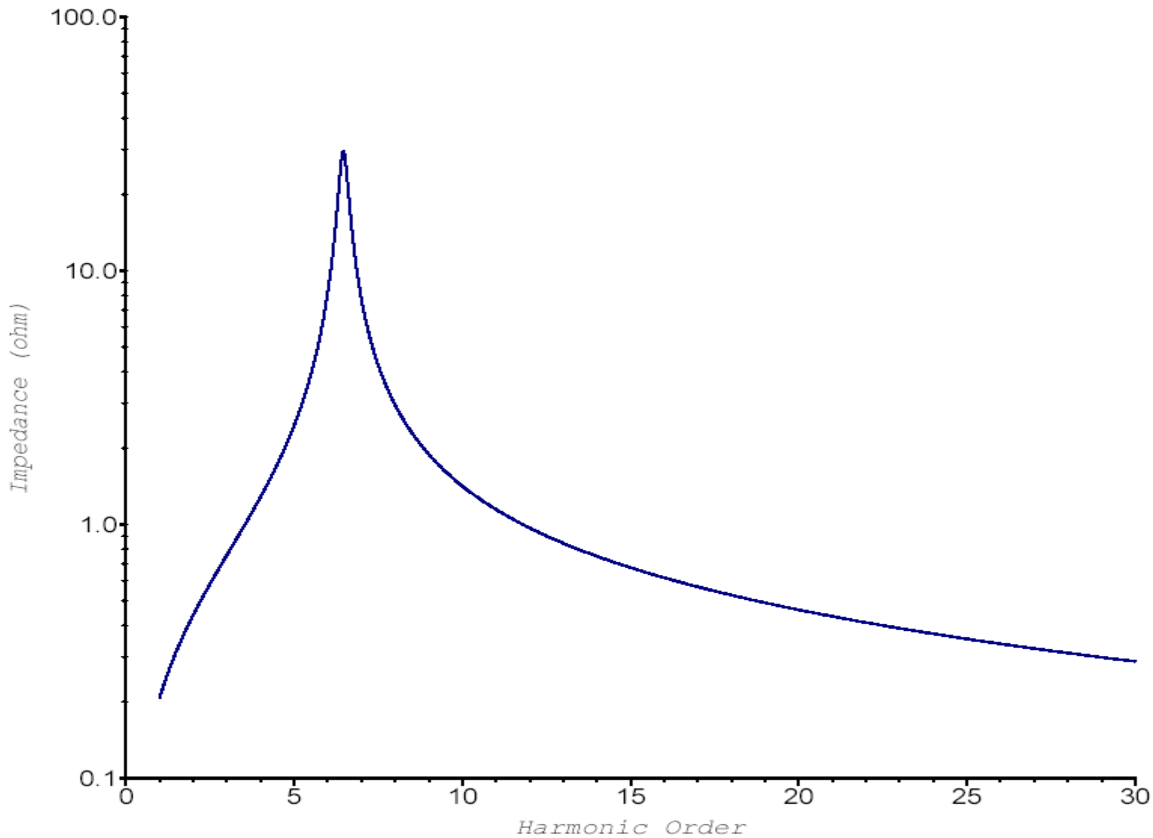
4.16 KV Bus Frequency Scan

Following chart presents the 4.16 kV Bus impedance (Ohms) for a 25% Service Factor of the ac loads. The bus impedance amplitude indicate clearly strong resonance at about NH = 6 to 7. To asses with better precision the harmonic current amplification magnitude, it is necessary to calculate the harmonic current amplification factor.



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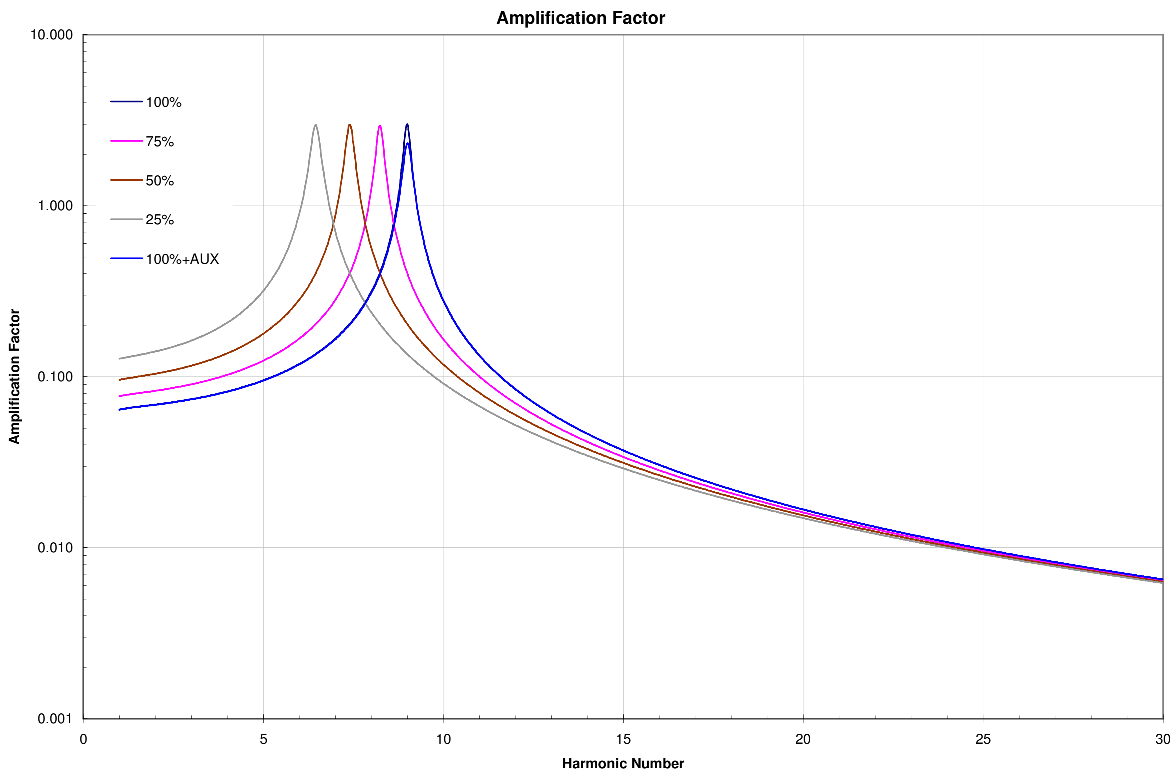
Harmonic Current Amplification at PCC Source Point

The harmonic current amplification magnitude can be calculated using the general formula: AF = HV / MV x |**Z** Bus / **Z** Utility|. Impedance values **Z** Bus and **Z** Utility resulting from the ETAP simulation. The factor HV / MV is 34.5 kV / 4.16 kV and serves for referring the Z Utility impedance to the 4.16 kV MV level.

Following chart shows the calculated current amplification factor for PS26 (USA) under different loading conditions (Service Factor = 100%, 75%, 50% and 25%).



Conclusions

This chart indicates strong resonance as predicted in Section 3. The resonance frequencies are basically in line with the calculated values as shown in Section 3. The Amplification Factor curves in the following chart indicate acute harmonic current amplification, almost factor 3, at resonance frequencies.

Special attention shall thus be paid if harmonic current injection from any expected non-linear loads. AC load variation affects the Amplification Factor resonance point (frequency) but not its amplitude. Lower loads cause lower resonance frequencies. The relationship between resonance frequency and load factor is not a simple square root function as the load impedance parallels to the series impedances of utility and power transformer. The Amplification Factor amplitude depends though on the load Power Factor and the number of capacitors (capacitive KVAR) on line.

The effect of the auxiliary loads can be neglected as shown in the chart, the blue and black curves are quite similar with the blue curve indicating slightly smaller amplification factor at resonance point.

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