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Expansion of an existing power system - a study

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EXPANSION OF AN EXISTING POWER SYSTEM - A STUDY

BY

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ABSTRACT

An existing paper mill is being expanded to increase its installed capacity. Concurrent expansions will be increasing the electrical demand by 40 - 50 MVA. The expansion also includes the addition of DC drives. The existing system has to be used effectively while additional equipment may be added to cater the load increase.

Load flow study with various single line diagram configurations has been carried out to find the required solution. A harmonic analysis was also carried out on the suggested new system to install the required filters and capacitor banks.

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I. INTRODUCTION

A load flow and harmonic analysis study of the electrical distribution system has been conducted at Champion International Corporation, Bucksport, Maine.

Concurrent expansions in this paper manufacturing plant are expected to increase the demand on the 13.8 kV system from 82 to 124 MVA. The demand on the 7.2 kV buses (20 MVA) is not expected to change. The purpose of the study is to determine the electrical system's ability to reliably serve these loads.

Load flow calculations predict the voltage level on each major bus under normal load flow conditions and the initial voltage drop on each bus if a major source is suddenly removed from service. The calculations also show the flows of megawatts and megavars throughout the system.

This study addresses load flow situations on the 7.2 and 13.8 kV buses when the total electrical demand will be 135 MVA. Additional load flow situations are included for a new utility tie transformer, new capacitor banks, and various bus tie arrangements. Also included are load flow situations for three incremental increases in electrical demand. Load flow calculations on 480 and 2400 volt buses are excluded from the scope of this study.

Resonant conditions can occur when capacitor banks are used in a distribution system having dc drives or rectifier loads. Resonance by the rectifier generated harmonics can overload the capacitors and result in nuisance fuse operation. A harmonic analysis study was conducted to ascertain these harmonic resonant conditions and properly size the filter reactors and capacitor banks.

A harmonic analysis study models the distribution system on a digital computer, based on the system impedance, rectifier loads and calculated harmonic currents injected on the rectifier buses. The system's responses to harmonics from fundamental to 30th are calculated to determine the resonance conditions. Harmonic current flow analyses in the various elements of the distribution system, capacitor banks and filter reactors are then made. A number of switching conditions representative of the plant's normal operation and also operating conditions under a source outage are considered. The study was conducted with equal 5th and 7th harmonic filter banks, with one 5th harmonic filter, and with unequal 5th and 7th harmonic filters to ascertain the optimum loading on the filter banks and to limit the total harmonic distortion on the 115 kV and 13.8 kV buses.

II. STAGE-WISE MILL LOAD GROWTH

A. EXISTING MILL OPERATING LOADS

The existing mill operating loads have been estimated using meter readings and the utility company power bills. The data used represent the mill's typical operating conditions and reflect the maximum operating loads that can occur in the existing distribution system.

B. LOAD GROWTH ASSOCIATED WITH PLANT EXPANSIONS

The loads associated with projects currently in progress are estimated in three stages:

Stage 1:

-- TMP and groundwood modifications

-- New No. 3 turbine generator

-- No. 8 supercalender winder

Stage 2:

-- No. 6A and 6B supercalenders

-- Supercalender pulper

-- No. 6 supercalender winder

Stage 3:

-- No. 4 paper machine rebuild

-- Refiner motors added to bus D (10,000 HP)

Table I through Table IV show the stage-wise load growth of plant loads. Table V is a summary of this load development.

All of the load growth is taking place on systems served by the 13.8 kV buses. The existing plant load on the 13.8 kV buses is approximately 82 MVA. The stage wise cumulative increases are approximately as follows:

Stage 1: 17 MVA 21% increase over existing load

Stage 2: 23 MVA 28% increase over existing load

Stage 3: 42 MVA 51% increase over existing load

C. <u>NO. 4 PAPER MACHINE LOADS</u>

The following configurations for No. 4 paper machine loads have been considered:

-- If a new 115-13.8 kV utility transformer is not installed, the No. 4 paper machine loads will be divided on 13.8 kV buses B and G. The total No. 4 paper machine load cannot be shifted to bus G without overloading transformer C. Figure 1 shows the load distribution from the 13.8 kV buses.

-- If new 115-13.8 kV transformer G is installed, the total No. 4 paper machine load can be connected to bus G. Breaker G on bus B will become a spare. Figure 2 shows this load distribution.

Table I. LOAD FLOW STUDY STAGEWISE LOAD GROWTH ESTIMATE NO. 1

Bus No.	Breaker	Existing loads			Stage 1 loads		Stage 2 loads		Stage 3 load		
Voltage	No.	MW	MVAR	P.F.	MW	MVAR	MW	MVAR	MW	MVAR	P.F.
D	X and	15.00	8.55	0.87	18.28	10.41	18.28	10.41	25.58	14.65	0.87
13.8 kV	Y										
C	T	1.20	1.15	0.72	2.21	2.18	2.21	2.18	2.21	2.18	0.71
13.8 kV	S	0.65	0.66	0.70	0.65	0.66	0.65	0.66	0.65	0.66	0.70
	R	2.00	2.04	0.70	2.00	2.04	2.00	2.04	2.00	2.04	0.70
	Q	5.30	4.67	0.75	5.30	4.67	5.30	4.67	5.30	4.67	0.75
	P	4.2	-0.37	-0.99	5.10	0.26	5.10	0.26	5.10	0.26	0.998
Total		1.75	1.78	0.70	1.75	1.78	1.75	1.78	1.75	1.78	0.7
Bus C		15.10	9.93	0.84	17.01	11.59	17.01	11.59	17.01	11.59	0.83

Table II. LOAD FLOW STUDY STAGEWISE LOAD GROWTH ESTIMATE NO. 2

Bus No.	Breaker	Existing loads			Stage 1 loads		Stage 2 loads		Stage 3 loads		
Voltage	No.	MW	MVAR	P.F.	MW	MVAR	MW	MVAR	MW	MVAR	P.F.
A	B	5.0	4.15	0.77	5.0	4.15	5.0	4.15	4.05	3.49	0.76
13.8 kV	C	5.8	4.67	0.78	6.84	5.59	6.84	5.59	6.84	5.59	0.77
	D	6.2	5.10	0.77	8.42	5.71	8.42	5.71	8.42	5.71	0.83
Total		17.0	13.92	0.77	20.26	15.45	20.26	15.45	19.31	14.79	0.79
Bus A											
B	E	4.20	1.66	0.93	4.20	1.66	4.20	1.66	4.20	1.66	0.93
13.8 kV	F	5.48	3.31	0.86	8.68	5.71	8.86	5.71	8.86	5.71	0.84
	I	1.17	1.03	0.75	1.17	1.03	1.17	1.03	1.17	1.03	0.75
	L	0.35	0.26	0.80	0.35	0.26	0.35	0.26	0.35	0.26	0.80

Table III. LOAD FLOW STUDY STAGEWISE LOAD GROWTH ESTIMATE NO. 3

Bus No.	Breaker	Existing loads			Stage 1 loads		Stage 2 loads		Stage 3 loads		
Voltage	No.	MW	MVAR	P.F.	MW	MVAR	MW	MVAR	MW	MVAR	P.F.
B 13.8 kV	K	2.50	2.19	0.75	4.71	4.14	4.71	4.14	4.71	4.14	0.75
Total Bus B									19.11	12.80	0.83
	G	7.30	4.00	0.87	7.54	4.18	8.19	4.56	7.34	4.68	0.84
Total Bus G		21.00	12.45	0.86	26.65	16.98	27.30	17.36	26.45	17.48	0.84
New Bus G	Shifted Load								7.34	4.68	0.84

Table IV. LOAD FLOW STUDY STAGEWISE LOAD GROWTH ESTIMATE NO. 4

Bus No. Voltage	Breaker No.	Existing loads MW	MVAR	P.F.	Stage 1 loads MW	MVAR	Stage 2 loads MW	MVAR	Stage 3 loads MW	MVAR	P.F.
New Bus G	Shifted Load								1.33	1.35	0.70
							2.80	2.86	9.94	10.14	0.70
							1.05	1.07	1.05	1.07	0.70
Total							3.85	3.93	19.66	17.24	0.75
Bus G with new transformer											
without new transformer							3.85	3.93	12.32	12.56	0.70
E & F 7.2 kV	A,Z	18.00	-8.72	-0.9	18.00	-8.72	18.00	-8.72	18.00	-8.72	-0.9

Table V. LOAD FLOW STUDY SUMMARY OF LOAD GROWTH

Bus No.	Existing Loads		Stage 1 Loads		Stage 2 Loads		Stage 3 Loads			
							with new xfrmr		without new xfrmr	
	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR
D	15.00	8.55	18.28	10.41	18.28	10.41	25.58	14.65	25.58	14.65
C	15.10	9.93	17.01	11.59	17.01	11.59	17.01	11.59	17.01	11.59
A	17.00	13.92	20.26	15.45	20.26	15.45	19.31	14.79	19.31	14.79
B	21.00	12.45	26.65	16.98	27.30	17.36	19.11	12.80	26.45	17.48
G	--	--	--	--	3.85	3.43	19.66	17.24	12.32	12.56
E and F	18	-8.72	18	-8.72	18	-8.72	18	-8.72	18	-8.72
Total	86.10	36.13	100.20	45.71	104.70	50.02	118.67	62.35	118.67	62.35
Plant	MVA = 93.37		MVA = 110.13		MVA = 116.03		MVA = 134.05		MVA = 134.05	
Load	PF = 0.922		PF = 0.910		PF = 0.902		PF = 0.885		PF = 0.885	

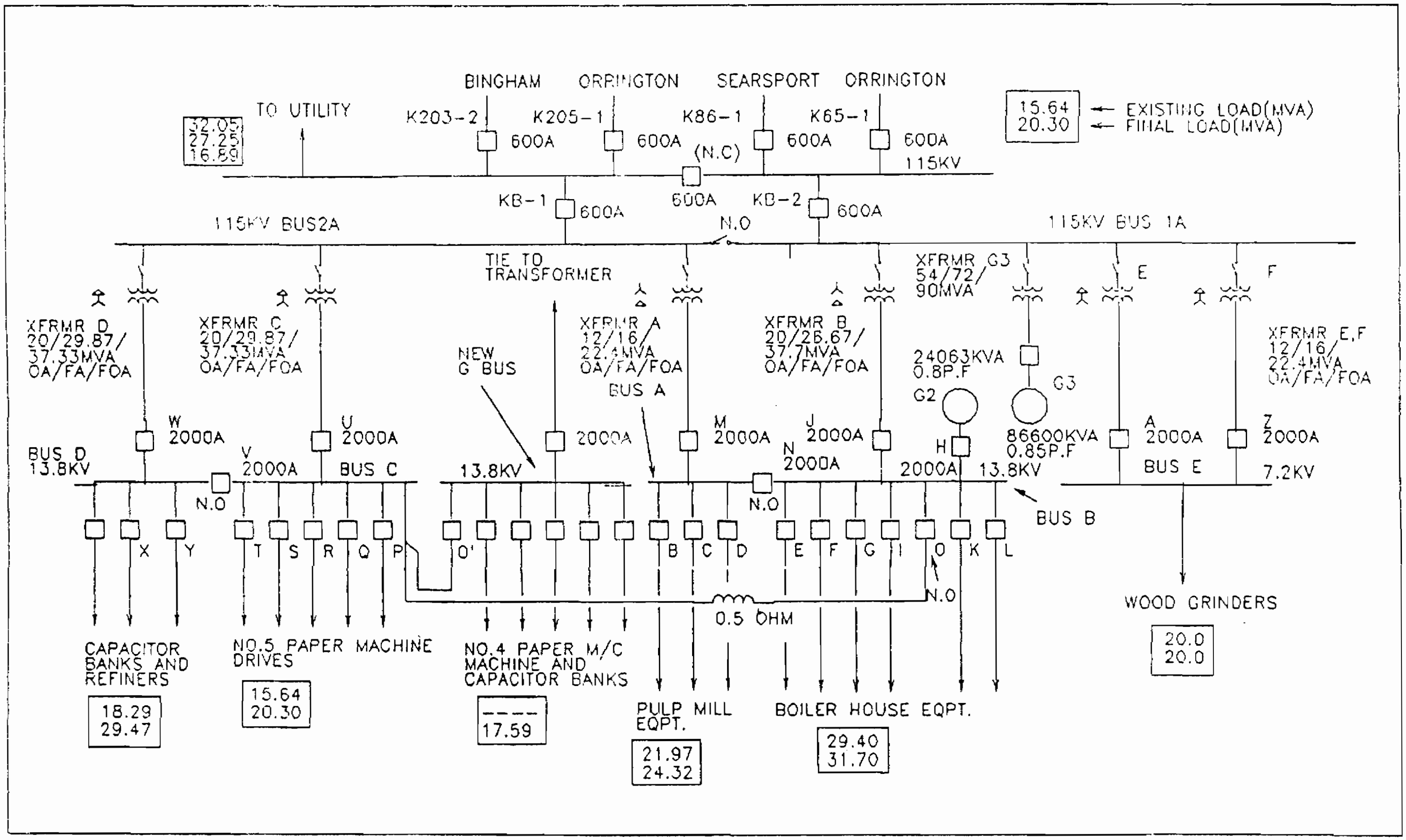

Figure 1. Single Line Diagram Without New Utility Tie Transformer

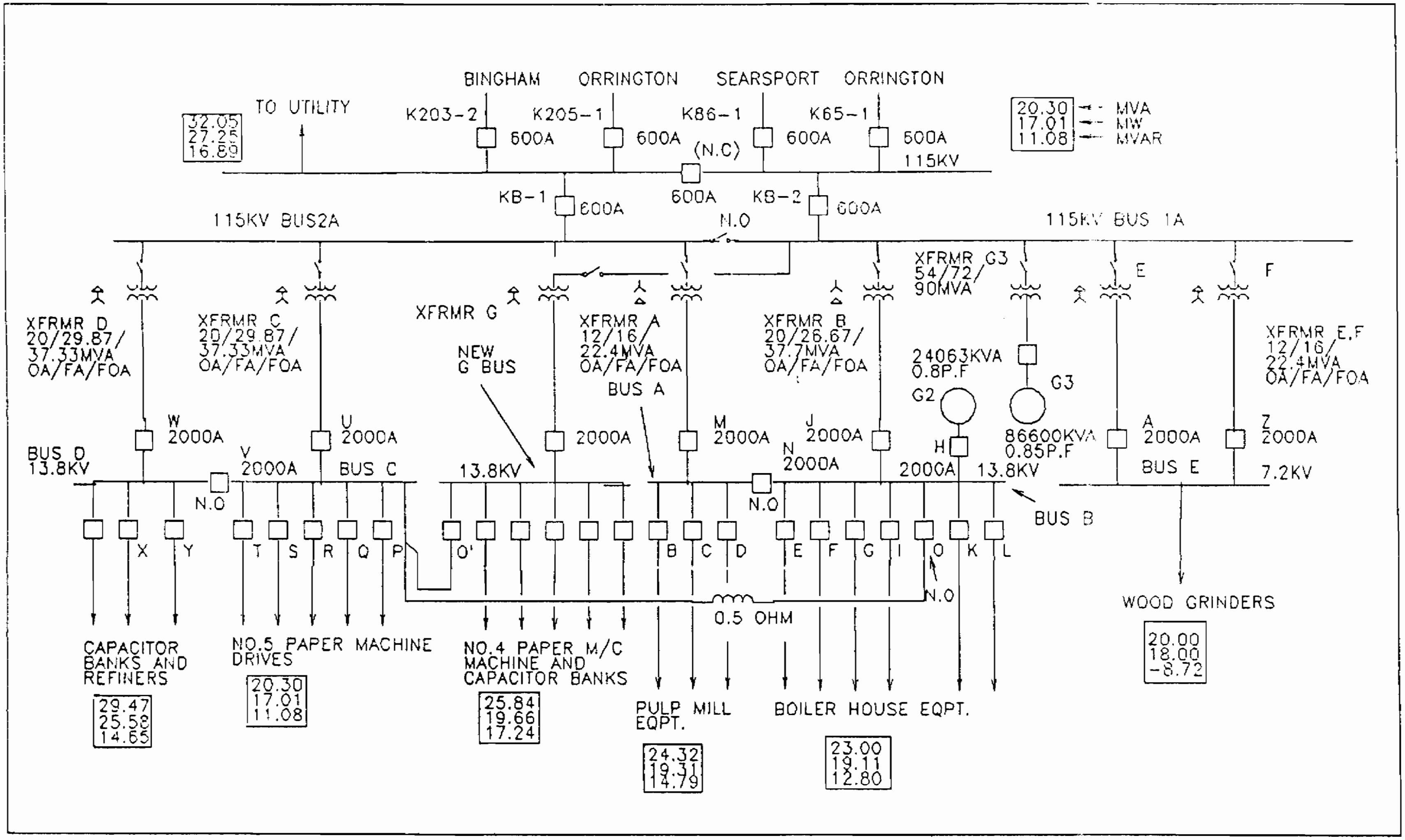

Figure 2. Single Line Diagram With New Utility Transformer

D. NEW NO. 3 TURBINE GENERATOR

The plant has contracted to supply 27.25 MW of power to the utility company upon commissioning of No. 3 generator. This commitment is shown as a load at 0.85 power factor connected to the 115 kV bus in the load flow diagrams.

E. ESTIMATED MVAR FLOW

The power factors assumed for the various type of loads for calculations of Mvar load flows are shown in Table VI. These are the actual power factors, as calculated from the operating conditions.

Table VI. ESTIMATED POWER FACTORS

Type of Load	Power Factor
Synchronous Motors	0.9 lead
5000 HP Refiner Motors	0.87 lag
Medium Voltage Motors Operating at 0.8 or Lower Load Factor	0.80 lag
480 Volt Motor Loads	0.75 lag
D.C. Drives	0.70 lag

III. LOAD FLOW STUDY

A. OBJECTIVES

The purpose of the load flow study is to determine active and reactive power flows and voltages at various 13.8 kV and 7.2 kV buses. The following system configurations were studied:

-- The existing distribution system.

-- The system at the completion of Stage 1 load growth.

-- The system at the completion of Stage 2 load growth.

-- The system at the completion of Stage 3 load growth.

-- Various system configurations and operating conditions after stage 3 load growth.

The load flow program calculates the voltages under normal load flow conditions and the initial voltage drop upon loss of a source.

The initial voltage drop should be limited to 10% of rated bus voltage to ensure continuous process operations during an upset condition like sudden outage of a source.

The active and reactive power flows demonstrate the system capabilities and limitations in serving the plant loads. Load flow calculations can be used to determine the changes necessary in a system to support increased load growth. A load flow analysis will also be helpful in planning power generation strategies, calculating system losses, and selecting the optimum taps on transformers.

The normal load flow situation should not overload any of the system components, such as transformers, circuit breakers or feeder cables. Upon an upset condition, it should be possible to revert to normal operations without excessive shutdowns and load shedding.

B. ASSUMPTIONS FOR THE LOAD FLOW STUDY

1. System Impedance Data. The system impedance data has been taken from the available short-circuit study and the plant single line diagrams. The three phase short circuit level and X/R ratio at the 115 kV utility system were obtained from the utility company. Figure 3 shows the system impedance data used for the load flow study.

2. 13.8 kV And 7.2 kV System Configurations. The operating configurations of the 13.8 and 7.2 kV systems are the same as the existing plant operating practices. In each of these configurations it is assumed that the short-circuit levels at 13.8 kV and 7.2 kV buses will be within the rated short circuit capabilities of the circuit breakers installed on these buses.

Two basic configurations of the 13.8 kV distribution system have been studied for Stage 3 load growth:

-- A new 115-13.8 kV, 20/37.33 MVA utility tie transformer is connected to bus G. This transformer will be normally operating in parallel with existing transformer C.

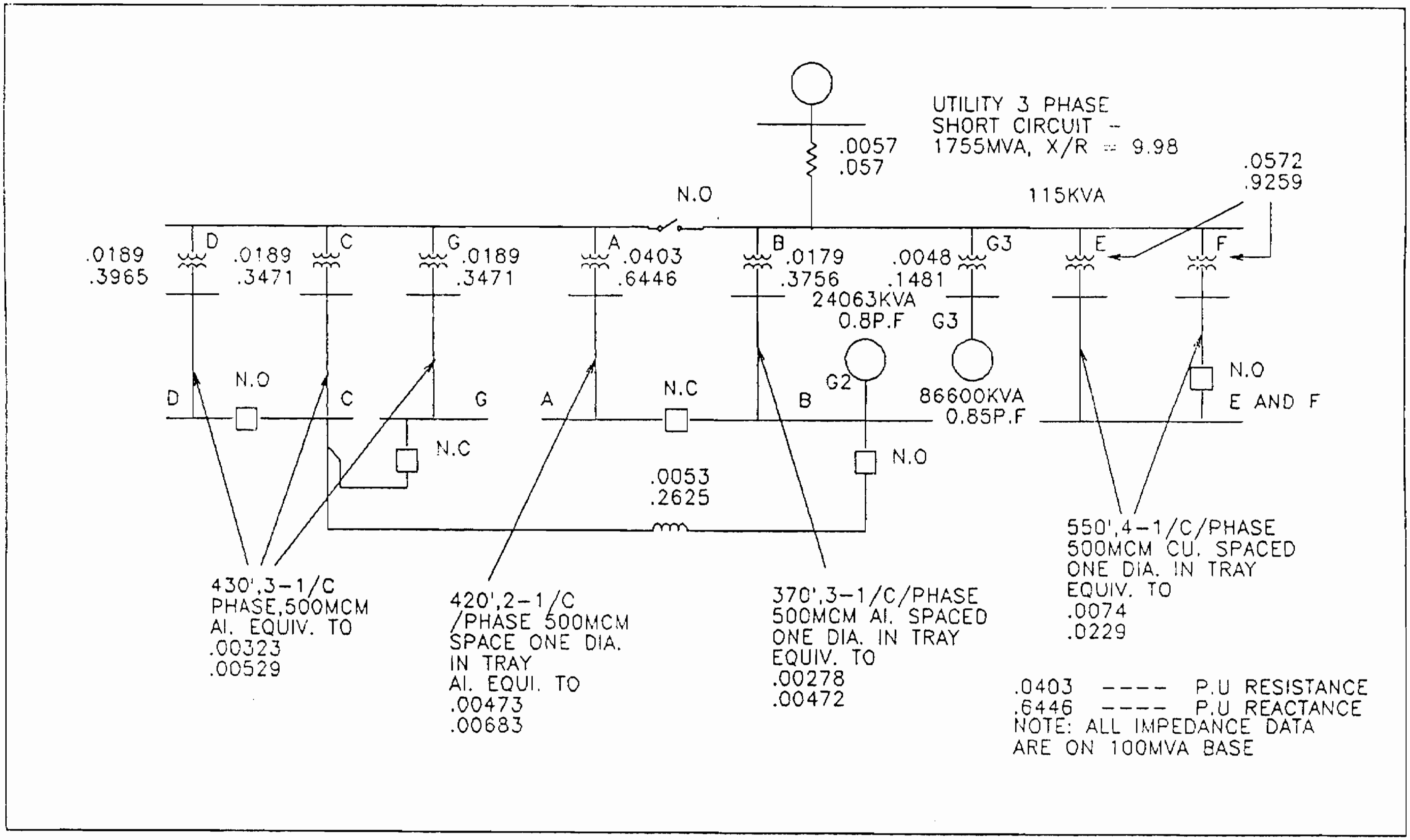

Figure 3. Load Flow Study - Impedance Data

-- A new 115-13.8 kV, 20/37.33 MVA transformer is not installed.

The existing operating practices for the 13.8 kV and 7.2 kV distribution systems shown in Figure 1 are as follows:

-- Only one of the transformers E or F is connected to supply the 7.2 kV loads on buses E and F.

-- Transformers A and B are operated in parallel, with bus tie breaker N between buses A and B normally closed. No. 2 generator is normally operated at its rated output. Reactor tie breaker O between buses C and B is normally open. In the present system, transferring load through the reactor tie is not required for normal operations.

-- Buses C and D are operated in isolation, with tie breaker V between buses C and D normally open.

3. Retrofit Of Cooling Equipment Of Transformer B. The load flow study assumes that cooling fans and oil circulating pumps are installed on transformer B. This equipment will permit transformer B to operate at its maximum rating. This equipment is not presently installed.

4. Sharing Of Loads Between Transformers A And B. The per unit impedance of transformers A and B, which operate in parallel, are not of equal magnitude and phase angle. A trial load flow program was run to ascertain the load sharing between these two transformers. The calculations demonstrate that transformer B will serve approximately 63% of the total load on buses A and B. Thus, load sharing is closely proportionate to the transformer ratings.

5. No. 2 Generator Reactive Capability Curve. A reactive capability curve shows the MW and Mvar output of a generator at different operating points. As No. 2 generator may be operating at a reduced output of 8.4 MW, its reactive power output will increase. As No. 2 generator reactive capability curve could not be obtained, it has been conservatively assumed to have a reactive output of 16 Mvar at 8.4 MW.

6. Utility Tie Transformer Taps. All utility tie transformers are provided with two 2-1/2% taps above and below rated primary side voltage. The tap changers are off-load type.

C. DETAILED ANALYSIS OF LOAD FLOW CASES

1. Case No. 1, Stage 3 Loads. Base load flow conditions:

-- New 115-13.8 kV transformer is not installed.

-- No. 2 generator operating at an output of 8.4 MW, 16 Mvar.

-- No. 3 generator operating at its rated output.

-- Tie breakers O and V open; tie breaker N closed.

The following sudden upset conditions were examined:

Case 1A: Transformer A out of service

Case 1B: Transformer B out of service

Case 1C: No. 2 generator out of service

Case 1D: No. 3 generator out of service

The voltage drops under normal load flow and upset conditions are shown in Table VII. The percent voltage drop under normal conditions is based on the rated voltage. The percent voltage drop upon loss of a transformer or a generator is based on the actual bus voltage. Also it should be noted that the voltage at bus E and F actually increased by 4.6% under normal operating conditions. A typical load flow digram for Base Case 1 is shown in Figure 4.

The following conclusions can be drawn from the load flow calculations:

-- Under normal load flow conditions there is a 10.1% voltage drop on buses C and G. The voltage on bus D is depressed by 5.4% and on buses A and B by 3%. These voltage levels are unacceptable for normal plant operations.

-- Transformer C is overloaded approximately 14% under normal operating conditions. 4 MVA of load on buses C and G is a transient load, occuring during start-up or sheet breakage. Even if this load is not considered under normal load flow conditions, transformer C may be slightly overloaded.

-- As the base load operating voltages are not satisfactory, a detailed analysis of upset conditions is unnecessary. It is, however, seen that failure of transformer B will impose a voltage drop of 15.46%. This voltage drop is in addition to the 3% drop under normal load flow conditions. This means bus A and B voltages will be depressed by approximately 18.46% below rated voltage.

Table VII. BASE CASE 1 CHANGE CASES 1A TO 1D

Bus No.	Per Unit Voltage and % drop normal conditions		% Initial voltage drop on loss of: XFRMR A Case 1A	XFRMR B Case 1B	G2 Case 1C	G3 Case 1D
115 kV buses 1A and 2A	0.968	3.2	0.21	0.72	1.45	3.10
13.8 kV bus D	0.946	5.4	0.32	0.95	1.80	3.70
13.8 kV buses C and G	0.899	10.1	0.33	1.11	2.0	4.23
13.8 kV buses A and B	0.970	3.0	3.92	15.46	6.7	3.5
7.2 kV bus E and F	1.046	up by 4.6	0.20	0.76	1.34	2.86

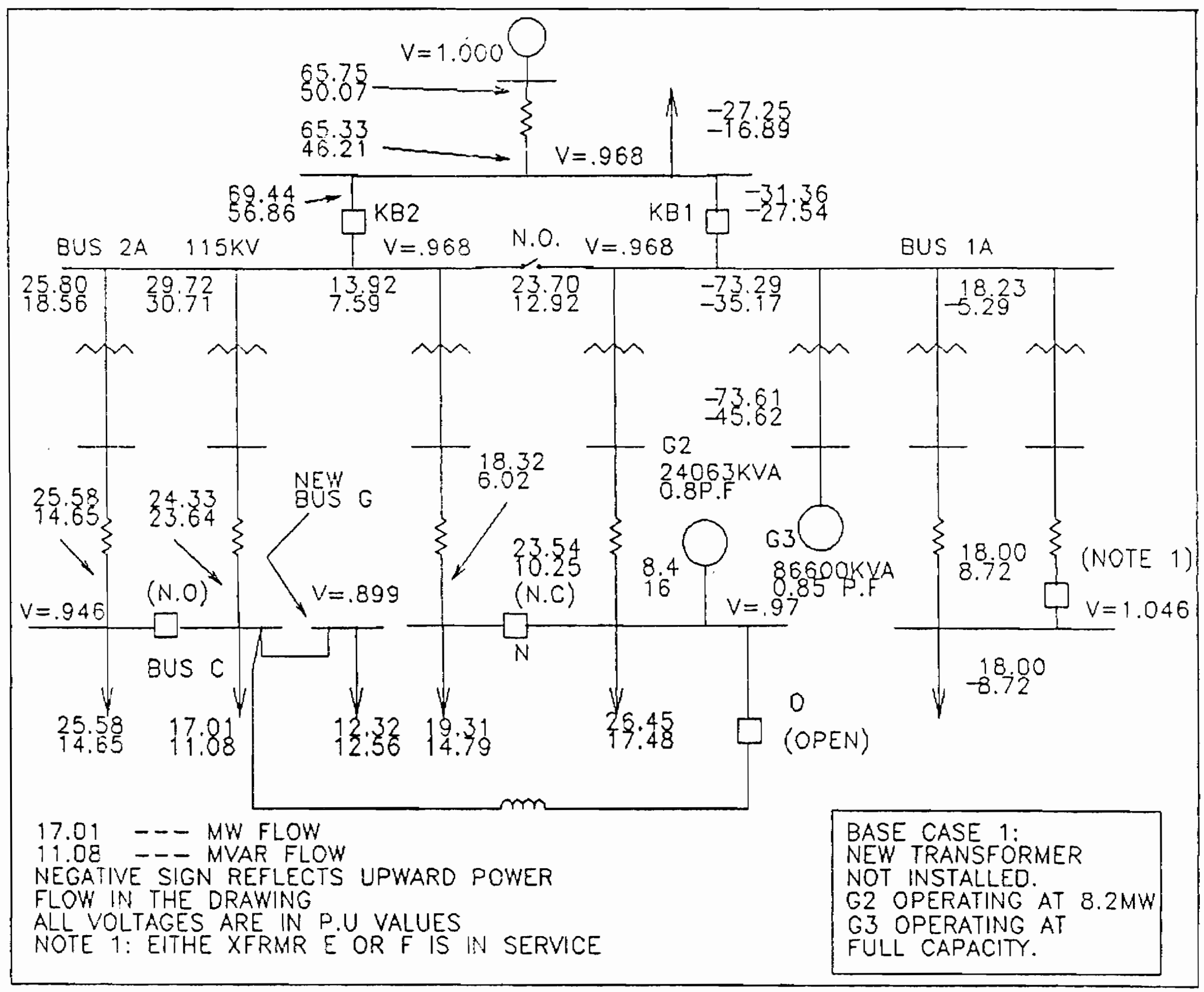

Figure 4. Load Flow Diagram - Base Case I

Wide spread process interruptions on buses A and B can be expected. Since the mill's boiler complex is fed from these buses, the extent of process interruptionsmay increase. Even 115 kV utility breaker KB2 will be overloaded under this condition.

The Stage 3 load growth cannot be served by the present distribution system, even with No. 3 generator operating at rated output.

2. Case No. 2, Stage 3 Loads. Base load flow conditions:

-- New 115-13.8 kV transformer is not installed.

-- No. 3 generator operating at its rated output.

-- No. 2 generator out of service.

-- Tie breakers O and V open, tie breaker N closed.

The following sudden upset conditions were examined:

Case 2A: Transformer A out of service

Case 2B: Transformer B out of service

Case 2C: No. 3 generator out of service

The voltage drops under normal load flow and upset conditions are shown in Table VIII.

The following conclusions can be drawn from the load flow calculations:

-- Under normal load flow conditions, the voltage levels at buses A, B, C, and D are worse than the voltage levels in Case 1. The voltage on buses A and B is depressed by 9.5% under normal load flow conditions.

Table VIII. BASE CASE 2 CHANGE CASES 2A TO 2C

Bus No.	Per Unit Voltage and % drop normal conditions	% Initial voltage drop XFRMR A Case 2A	XFRMR G Case 2C
115 kV buses 1A and 2A	0.954 4.6	0.63	3.35
13.8 kV bus D	0.929 7.1	0.65	3.98
13.8 kV buses C and G	0.881 11.9	0.79	4.54
13.8 kV buses A and B	0.905 9.5	9.94	4.31
7.2 kV buses E and F	1.032 up by 3.2	0.58	3.10

-- The computer run did not converge upon loss of transformer B, and no meaningful results could be obtained. This indicates that there will be excessive voltage drops, and the plant operations cannot be sustained.

Without No. 2 generator in service, the normal voltage levels on buses A and B will be 9.5% below rated voltage. This case demonstrates the necessity of keeping No.2 generator in operation, to reduce voltage drops on 13.8 kV buses A and B and to prevent overloading of transformers A and B.

3. Case No. 3, Stage 3 Loads. Base load flow conditions:

-- New 115-13.8 kV transformer is not installed.

--No. 2 and 3 generators out of service.

--Tie breakers O and V open, tie breaker N closed.

The following sudden upset conditions were examined.

Case 3A: Transformer A out of service

Case 3B: Transformer B out of service

The voltage drops under normal load flow and upset conditions are shown in Table IX.

The following conclusions can be drawn from the load flow calculations:

--Excessive voltage drops occur on all 13.8 kV load buses.

--Transformers A, B, and C are overloaded.

A lack of convergence of the computer program upon outage of transformer B indicates that there will be excessive voltage drops on most 13.8 kV buses.

Stage 3 load growth cannot be sustained by the distribution system in any of the configurations from case 1 through case 3.

Table IX. BASE CASE 3 CHANGE CASES 3A AND 3B

Bus No.	P.U. Voltage and % drop normal conditions	% Initial voltage drop on loss of Trans. A Case 3A
115 kv buses 1A and 2A	0.937 6.3	0.64
13.8 kv bus D	0.910 9.0	0.88
13.8 kv buses C and G	0.860 14.	0.93
13.8 kv buses A and B	0.885 11.5	10.84
7.2 kv buses E and F	1.015 up by 1.5	0.59

4. <u>Case No.4, Stage 3 Loads</u>. Base load conditions:

--- New 115-13.8 kV transformer is not installed.

--- No.3 generator out of service.

--- No.2 generator operating at its rated output of 19.25 MW -14 Mvar.

--- Tie breakers O and V open; tie breaker N closed.

The following sudden upset conditions were examined.

Case 4A: Transformer A out of service.

Case 4B: Transformer B out of service.

Case 4C: No.2 generator out of service.

The voltage drops under normal load flow and upset conditions are shown in Table X.

The following conclusions can be drawn from the load flow calculations:

--- This case represents the existing operating configuration of the 13.8 kV buses with stage 3 loads added. Excessive voltage drops occur on most of the 13.8 kV buses under normal load conditions.

The stage 3 load growth cannot be served by the present distribution system.

5. Case No.5, Stage 3 Loads. Base load conditions:

---New 115-13.8 kV transformer is installed. It is connected to bus G

and operated in parallel with the existing transformer C.

---All paper machine No.4 loads are connected to bus G.

---No.2 and No.3 generators out of service.

---Tie breakers O and V open, tie breaker N closed.

The following sudden upset conditions were examined:

Case 5A: Transformer A out of service

Case 5B: Transformer B out of service

Case 5C: Transformer C out of service

The voltage drops under normal load flow and upset conditions are shown in Table XI. The following conclusions can be drawn from the load flow calculations:

---The voltage on 13.8 kV buses A, B, C, D and G will be depressed from 7.8% to 9.3% under normal load flow conditions.

---The overloading of transformers A, B, and C observed in cases 2 and 3 is removed, even with No.2 generator out of service. This is due to shifting of all No.4 paper machine loads to bus G and the addition of transformer G.

Addition of a new utility tie transformer solves the problem of overloading of transformers under normal load flow conditions. However 13.8 kV bus voltages are too low for normal plant operations when both generators are out of service. This is primarily due to losses in the utility company's system. Plant operations will be limited when No.2 and 3 generators are out of service. No.2 generator has a major impact on bus voltages.

Table X. BASE CASE 4 CHANGE CASES 4A TO 4C

Bus No.	P.U. Voltage and % drop normal conditions	% Initial voltage drop on loss of: Transf. A Case 4A	Transf. B Case 4B	Gen. 2 Case 4C
115 kv buses 1A and 2A	0.953 4.7	0.10	0.52	1.68
13.8 kv bus D	0.928 7.2	0.11	0.54	1.94
13.8 kv buses C and G	0.880 12.	0.23	0.68	2.27
13.8 kv buses A and B	0.951 4.9	3.89	13.99	6.94
7.2 kv bus E and F	1.031 up by 3.1	0.09	0.48	1.55

6. <u>Case No. 6, Stage 3 Loads</u>. Base Load Conditions

---New 115-13.8 kV transformer is not installed.

---9.5 Mvar capacitor banks are connected to buses G and B.

---No. 2 and 3 generators are out of service.

---Tie breakers O and V open, tie breaker N closed.

The following sudden upset conditions were examined:

Case 6A: Transformer A out of service.

Case 6B: Transformer B out of service.

The voltage drops under normal load flow and upset condition are shown in Table XII.

The following conclusions can be drawn from the load flow calculations:

---The purpose of this study was to ascertain the effects of capacitor banks on bus voltage and transformer loadings when No.2 and 3 generators are out of service. It is seen that the provision of 9.5 Mvar capacitor banks on buses B and G will relieve the overloads on transformers A, B, and C, which occured in cases 2 and 3 The The voltage levels on the 13.8 kV buses, however, still remain depressed by 7.5 to 8.3%. This is unacceptable for normal plant operations.

Table XI. BASE CASE 5 CHANGE CASES 5A TO 5C

Bus No.	Per Unit Voltage and % drop normal conditions	% Initial voltage drop XFRMR A Case 5A	XFRMR G Case 5C
115 kV buses 1A and 2A	0.941 5.9	0.43	0.64
13.8 kV bus D	0.914 8.6	0.44	0.77
13.8 kV buses C and G	0.922 7.8	0.54	12.03
13.8 kV buses A and B	0.907 9.3	7.6	0.77
7.2 kV buses E and F	1.019 up by 1.9	0.39	0.59

Table XII. BASE CASE 6 CHANGE CASES 6A AND 6B

Bus No.	P.U. Voltage and % drop normal conditions	% Initial voltage drop on loss of Transf.A Case 6A
115 kv buses 1A and 2A	0.951 4.9	0.63
13.8 kv bus D	0.925 7.5	0.65
13.8 kv buses C and G	0.917 8.3	0.76
13.8 kv buses A and B	0.925 7.5	8.10
7.2 kv buses E and F	1.029 up by 2.9	0.58

The addition of capacitor banks will not provide adequate voltage levels on the 13.8 kV buses when No.2 and 3 generators are out of service. Plant operations will be limited when No.2 and 3 generators are out of service.

7. Case No.7, Stage 3 Loads. Base load conditions:

---New 115-13.8 kV transformer is not installed.

---A 14 Mvar capacitor bank is connected to bus G and a 7 Mvar capacitor bank is connected to bus D.

---No.2 generator operating at a minimum output of 8.4 MW - 16 Mvar.

---No.3 generator operating at its rated output.

---Tie breakers O and V open; tie breaker N closed.

The following sudden upset conditions were examined:

Case 7A: Transformer A out of service.

Case 7B: Transformer B out of service.

Case 7C: No.2 generator out of service.

Case 7D: No.3 generator out of service.

The voltage drops under normal load and upset conditions are shown in Table XIII.

Table XIII. BASE CASE 7 CHANGE CASES 7A TO 7D

Bus No.	Per Unit Voltage and % drop normal conditions	% Initial voltage drop on loss of: XFRMR A Case 7A	XFRMR B Case 7B	G2 Case 7C	G3 Case 7D
115 kV buses 1A and 2A	0.983 1.7	0.2	0.71	1.42	3.05
13.8 kV bus D	0.993 0.7	0.2	0.91	1.71	3.63
13.8 kV buses C and G	0.980 2.0	0.31	0.92	1.84	4.08
13.8 kV buses A and B	0.986 1.4	3.75	14.5	6.39	3.45
7.2 kV bus E and F	1.036 up by 3.6	0.19	0.68	1.25	2.80

Table XIV shows the percent transformer loadings based on their maximum ratings, under normal load flow and upset conditions based on FOA ratings. Generator outputs are shown in MW/Mvar.

The following conclusions can be drawn from the load flow calculations:

Under normal load flow conditions, the voltages on 13.8kV buses C and G will be depressed by 2% of rated voltage. The voltage on buses A and B will be lower by 1.4% and on bus D by 0.7%. Table XIV shows that none of the transformers are overloaded during normal load flow conditions. The base case, therefore, represents a normal operating configuration capable of supporting Stage 3 loads.

Upon loss of transformer A, an initial voltage drop of 3.75% occurs on buses A and B. Transformer B, however, is loaded to 117.6% of its maximum rating. By operating No. 2 generator at its rated output of 19.25 MW - 14Mvar, transformer B loading can be reduced to 94%. Thus plant operations can be sustained upon loss of transformer A.

Upon loss of transformer B, the initial voltage drop on buses A and B will be 14.5%, and transformer A will be loaded to approximately 222% of its rating. Widespread shutdowns in the areas served by buses A and B can be expected. This may cause mill wide process disruptions, since the boiler complex is fed from bus B.

Upon loss of No. 2 generator, buses A and B experience a initial voltage drop of 6.39%, and transformers A and B are slightly overloaded. Load shedding of 3-4 MVA will relieve transformers A and B of their overloads.

Table XIV. PERCENTAGE TRANSFORMER LOADINGS FOR NORMAL AND UPSET CONDITIONS NO. 1

XFRMR OR GEN. NO.	CASE 7 BASE CASE	CASE 7A XFRMR A OUT OF SERVICE	CASE 7B XFRMR B OUT OF SERVICE	CASE 7C G2 OUT OF SERVICE	CASE 7D G3 OUT OF SERVICE
XFRMR A	70.70	--	221.7	102.3	70.9
XFRMR B	71.5	117.6	--	103.5	71.7
XFRMR C	87.9	87.9	87.9	87.9	89.8
XFRMR D	74.7	74.7	74.7	74.7	75.4
G2	8.4/16	8.4/16	8.4/16	--	8.4/16
G3	76.61/45.62	73.61/45.62	73.61/45.62	73.61/45.62	--

Bus D and buses C and G are operated as islands. A total shutdown will occur in the process areas served by these buses if the transformer serving each island is suddenly lost. Under normal running conditions transformer C has a spare capacity of approximately 4.5 MVA, and transformer D has a spare capacity of approximately 9 MVA. Thus, a maximum of 9 MVA of load on bus C can be supplied from transformer D when transformer C is out of service. Thus, after a shutdown caused by failure of transformer C or D, there is no available spare capacity to restore the process to rated production. Extensive load shedding will be required.

Stage 3 loads can be supported under normal load flow conditions with capacitor banks added to buses D and G. However, widespread shutdown will occur upon failure of transformers B, C or D. The process cannot be restored at rated capacity with the loss of one of these sources.

8. Case No. 8, Stage 3 Loads. Base Load Conditions:

New 115-13.8 kV transformer is installed and connected to bus G. This transformer is operated in parallel with existing transformer C.

No. 2 generator operating at 8.4MW - 16 Mvar output.

No.3 generator operating at its rated output.

Tie breakers O and V open; tie breaker N closed.

The following sudden upset conditions were examined:

Case 8A: Transformer A out of service

Case 8B: Transformer B out of service

Case 8C: Transformer G or C out of service

Case 8D: No. 2 generator out of service

Case 8E: No. 3 generator out of service

Case 8F: This is an independent case. This examines the load flow conditions when transformer D is out of service and bus tie breaker V between buses C and D is closed.

The voltage drops under load flow and upset conditions are shown in Table XV and XVI.

Table XVII shows the percentage transformer loadings based on their maximum ratings under normal load flow and upset conditions. The generator outputs are shown in MW/Mvar.

The following conclusions can be drawn from the load flow calculations: The 13.8 kV bus voltages are within +0.2% to -0.5% of rated voltage under normal load flow conditions. A maximum initial voltage drop of 8.68% occurs on buses A and B upon loss of transformer B.

Table XVII shows that transformer A or No. 2 or 3 generators can be removed from service without overloading any of the other sources.

Table XV. BASE CASE 8 CHANGE CASES 8A TO 8E

Bus No.	P.u. Voltage and % drop normal conditions	% Initial voltage drop on loss of: Transf. A Case 8A	Transf. B Case 8B	transf. G Case 8C	Gen. 2 Case 8D	Gen. 3 Case 8E
115 kv buses 1A and 2A	0.985 1.5	0.10	0.30	0.30	1.32	3.05
13.8 kv bus D	0.995 0.5	0.10	0.40	0.40	1.51	3.52
13.8 kv buses C and G	1.002 0.2	0.10	0.40	5.59	1.50	3.49
13.8 kv buses A and B	1.002 0.2	2.40	8.68	0.30	5.89	3.19
7.2 kv bus E and F	1.038 3.8	0.10	0.30	0.30	1.25	2.79

Table XVI. BASE CASE 8F

Bus No.	Per Unit Voltage and % Drop for Normal Load Flow Conditions	
115 kV buses 1A and 2A	0.983	1.7
13.8 kV bus D	0.972	2.8
13.8 kV buses C and G	0.972	2.8
13.8 kV buses A and B	0.998	0.2
7.2 kV buses E and F	1.036	up by 3.6

Table XVII. PERCENTAGE TRANSFORMER LOADING NORMAL AND UPSET CONDITIONS NO. 2

XFRMR or GEN	8 BASE CASE	8A XFRMR A Out of Service	8B XFRMR B Out of Service	8C XFRMR G Out of Service	8D G2 Out of Service	8E G3 Out of Service	8F XFRMR D Out of Service
A	55	--	162	55	84.8	55.1	40.3
B	55.6	90.4	--	55.6	84.8	55.7	40.7
G	54.5	54.5	54.5	--	54.5	55.3	94.7
C	54.5	54.5	54.5	116.8	54.5	55.3	94.7
GEN	8.4/	8.4/	8.4/	8.4/	--	8.4/	19.25
G2	16	16	16	16		16	14
GEN	73.61/	73.61/	73.61/	73.61/	73.61	--	73.61/
G3	45.62	45.62	45.62	45.62	45.62		45.62
XFRMR D	74.6	74.6	74.6	74.6	74.6	75.4	--

If transformer B is removed from service, transformer A will experience a 62% overload. If the output of No. 2 generator is increased to 19.25 MW and 14 Mvar, this overload decreases to 32%. This overload can be removed by closing tie reactor breaker O and transferring power from bus to bus B. Case 15 covers this in detail.

If transformer C is suddenly removed from service, transformer G will experience a 16.7% overload. If the tie breaker between buses C and D is closed, this overload will be removed. A similar situation will occur if transformer G suddenly is removed from service, because transformers C and G will operate in parallel. The impact of large motor starting voltage drops when in one of these two system configurations is not known.

As bus D is being operated as an island, a sudden removal of transformer D will result in a complete shutdown of the process areas from this bus. The process can, however, be restored by closing tie breaker V between buses C, D and G can be fed from any two of the three transformers, without overloading any of these units. The impact of large motor starting voltage drops when this configuration is not known.

A planned outage of transformer D can be made without major load loss by opening tie breaker O′ between buses C and G. Thereafter tie breaker V between buses C and D can be closed, and transformer D can be taken out of service. Transformer C will supply loads on buses C and D and will be momentarily loaded to 130% of its maximum rating. The tie breaker O′ between buses C and G can be reclosed, relieving transformer C of its overload. This operation prevents paralleling of transformers D, C, and G. The voltage levels when only transformer C is supplying buses D and C have not been calculated. Some load reduction may be required.

The addition of a new utility tie transformer and capacitor banks will support the stage 3 loads. Loss of transformer A, No. 2 generator or No. 3 generator can be tolerated without process interruptions. Loss of other sources may result in overloading of transformers in service or cause process interruptions. However, appropriate switching operations may restore normal plant operations.

9. Case No. 9, Stage 3 Loads. This case has similar operating conditions as case No. 7 except that a third 7 Mvar capacitor bank was added to buses A and B. This further improves the normal operating bus voltages and limits the initial voltage drop upon loss of transformer B on buses A and B to 8.4%, as compared to 14.5% in 7. In all other respects the conclusions drawn from the study of case 7 apply.

10. Case No. 11, Existing Loads. Base load Conditions:

This case studies the load flow on 13.8 and 7.2 kV buses with existing plant loads.

11. Case No. 12, Stage 1 Loads. This case studies the load flow on 13.8 and 7.2 kV buses when stage 1 loads are applied to the distribution system without any modifications.

12. Case No. 14, Stage 2 Loads. This case studies the load flow on 13.8 and 7.2 kV buses when stage 2 loads are applied to the distribution system without any modifications. Now 13.8 kV bus G is in operation and is connected to bus G through a tie breaker.

The voltage drops under normal load flow conditions are shown in Table XXVIII.

The following conclusions can be drawn from the load flow calculations:

Stage 1 load growth results in a maximum voltage drop of 3.4% on 13.8 kV buses C and G. This increases to 5.8% when stage 2 loads are applied. The voltage drop on other 13.8 kV buses is limited to a maximum of 3.1% with stage 1 loads applied, increasing to 3.7% when stage 2 loads are applied. Though these voltage levels are slightly depressed, it may be possible to sustain plant operations, without modifications through stage 2 load growth. No. 2 generator has been assumed to be operating at its rated output and No. 3 generator out of service. The commissioning of No. 3 generator by the time stage 1 loads become operational will improve 13.8 kV bus voltages by approximately 2%. A further improvement of the voltage level is possible if the utility company can maintain rated voltage at the 115 kV buses under normal load flow conditions.

Change cases have not been considered in these configurations. However, during normal load flow conditions none of the sources are overloaded.

13. Case No. 15, Stage 3 Loads. Base Load Conditions:

This case was examined to ascertain the load flow through the tie reactor between buses C and B, when transformer B is out of service.

Table XVIII. BASE CASE 11, 12 AND 14

Bus No.	P.U. Voltage and % Drop Normal load flow conditions		
115 kv buses 1A and 2A	0.978 2.2	0.970 3.0	0.966 3.4
13.8 kv bus D	0.990 1.0	0.971 2.9	0.966 3.4
13.8 kv buses C and G	0.984 1.6	0.966 3.4	0.942 5.8
13.8 kv buses A and B	0.996 0.4	0.969 3.1	0.963 3.7
7.2 kv buses E and F	1.056 up by 5.6	1.048 up by 4.8	1.044 up by 4.4

Before closing tie-reactor breaker O, bus C is isolated from buses D and G.

The voltage drops under this condition are shown in Table XIX.

The following conclusions can be drawn from the study result:

5.52 MVA of load is transferred through the tie reactor. This relieves transformer A of its overload.

None of the sources are overloaded.

This configuration can be adopted to support load on buses A and B when No. 2 generator or transformer B is out of service. However, a short-circuit study of this configuration should be made to ascertain that none of the circuit breakers are exposed to short circuit duties exceeding their ratings.

D. GENERAL CONCLUSIONS DRAWN FROM THE LOAD FLOW CALCULATIONS

There are no voltage drop or load flow problems on 7.2 kV buses E and F in any of the load flow cases. The load on these buses consists of 4200HP synchronous grinder motors operating at a leading power factor of 0.9. Approximately 5.3 leading Mvar is supplied to 115 kV bus 1A through transformer E. Only one of transformers E and F is kept in service at any time. Failure of the operating unit will shutdown the loads, however, the process can be restored by switching in the standby transformer.

Utility tie transformers A, B, C, D, and new transformer G must be operated on their lowest tap of 0.95 to provide a 5% voltage boost on the 13.8 kV side. No problems are anticipated in controlling the generation voltage of new No. 3 turbine generator or the voltage levels on 7.2 kV buses E and F. Transformer G3 can be set on the 13.8 kV tap.

Table XIX. BASE CASE 15

Bus No.	P.U. Voltage and % Drop Normal load flow conditions	
115 kv buses 1A and 2A	0.984	1.6
13.8 kv bus D	0.994	0.6
13.8 kv bus C	0.966	3.4
13.8 kv bus G	1.017	up by 1.7
13.8 kv buses A and B	0.956	4.4
7.2 kv buses E and F	1.037	up by 3.7

A sudden loss of No. 3 generator will cause a voltage drop of approximately 3% to 4.7% on the 115kV buses. This drop is mainly due to increased load flow through the utility tie transmission line impedance.

The voltage drop on the 115 kV utility bus under maximum load flow conditions could approach approximately 6.3% to 8% when No. 2 and 3 generators are out of operation and capacitor banks are not provided on 13.8 kV buses D and G. This drop occurs in the utility transmission line and source impedances. The utility 115 kV bus voltage regulating capabilities are not known. The presence of capacitor banks on 13.8 kV buses will compensate for a portion of the lagging kvar and reduce the voltage drop in the utility's system under normal load flow and upset conditions. It is, however, desirable that the utility maintains rated voltage on the 115 kV buses under normal load flow conditions.

Two alternatives, as shown in Figure 5, for the primary side connections of new utility tie transformer G have been considered:

-- Primary connections can be made to 115 kV bus 1A.

-- Primary connections can be made to 115 kV bus 2A.

A primary connection of transformer G to115 kV bus 1A is preferred. This will ensure availability of power at 13.8 kV buses C, G and D even if one of 115 kV buses 1A or 2A is out of service. Since No. 3 generator is also connected to bus 1A, there is a direct flow of power from No. 3 generator to transformer G.

If a primary connection of transformer G is made to 115 kV bus 2A a total shutdown will occur on bus C, G, and D on a failure of 115 kV bus 2A.

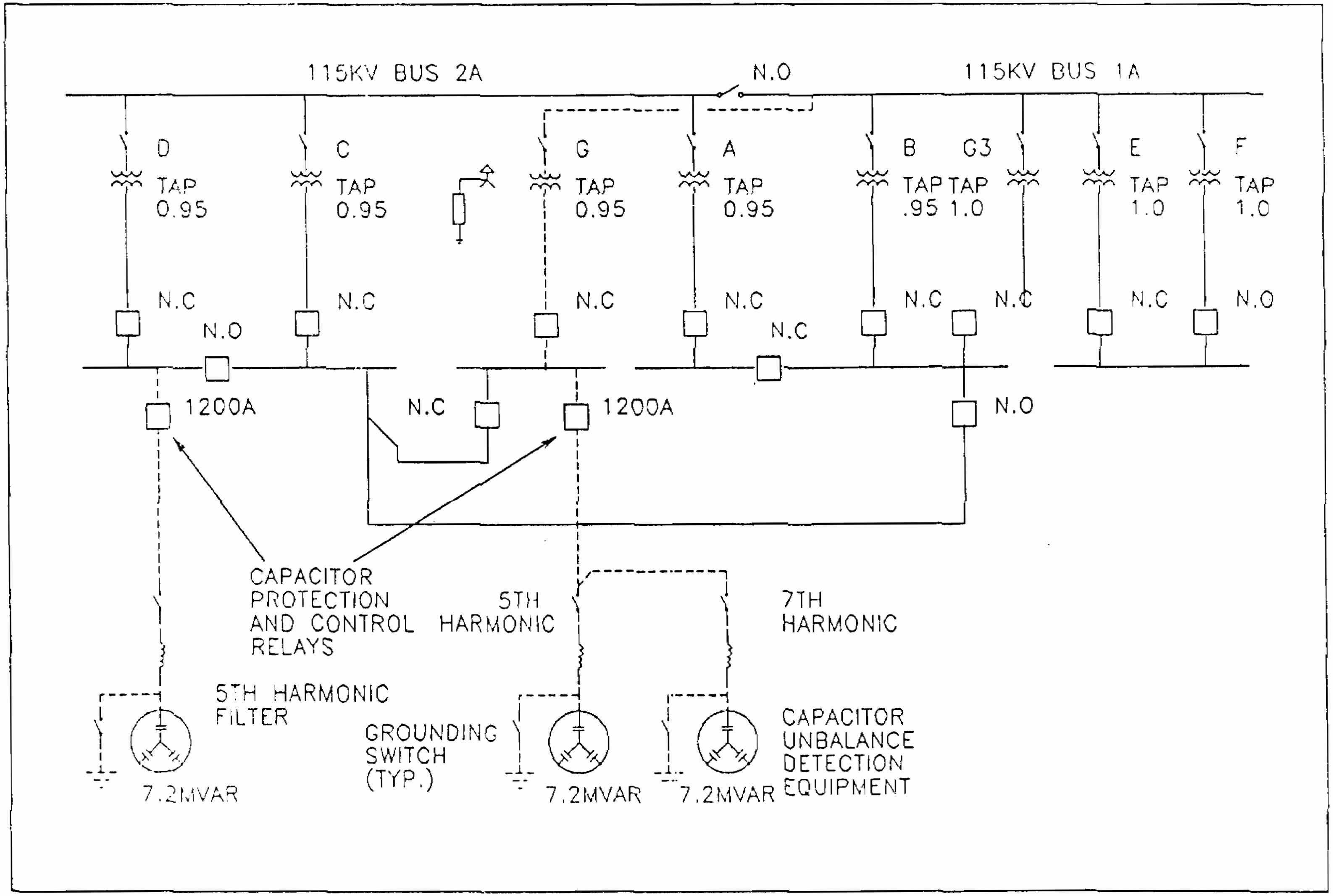

Figure 5. Location of Tie Transformer G And Filters

IV. HARMONIC ANALYSIS STUDY

A. INTRODUCTION

Installation of capacitor banks in a distribution system can achieve the following objectives:

---Improve the system operating power factor.

---Improve the load flow situation and the operating voltage level on load buses.

---Reduce the initial voltage drop upon loss of a major source.

---Improve the useful energy availability from generators and transformers.

---Reduce loading of cables, bus bars and other distribution system components.

---Reduce system losses.

---Reduce voltage and current distortions on various buses when capacitors are used with harmonic filter reactors.

Capacitors are needed on 13.8 kV bus G to support an acceptable operating voltage level and to reduce the Mvar loading of transformer C.

B. HARMONICS DUE TO RECTIFIERS LOADS AND RESONANCES

The No. 4 paper machine dc drive loads will be connected to 13.8 kV bus G. Thyristor drive systems produce alternating harmonic currents. The harmonic currents generated will depend upon the following factors:

---The circuit configuration and whether any of the rectifier units are phase-displaced from the others.

---System parameters, which determine the flow of harmonic currents in the various elements of the distribution system.

---KVA output of the rectifier units.

---Phase retard angle of the rectifiers.

Application of capacitors in conjunction with harmonic current generating equipment can cause resonant conditions.

There are two forms of resonances that can occur. These are series and parallel resonances. In a series resonant circuit, the total impedance at a resonant frequency reduces to a resistance component only. high currents can flow at the resonant frequency. A parallel resonant circuit has high impedance at the resonant frequency. However, high resonant currents can circulate through the capacitor and system reactance combinations, though the exciting source current may be small. This can overload the capacitor banks and result in nuisance operation of the capacitor bank fuses.

Excessive harmonic currents can also cause the following undesirable effects:

---Telephone interference

---Produce rotor overheating in turbine generators

---Increase system losses

---Affect operation of protective devices

---Distort voltage and current waveforms

C. SIX-PULSE RECTIFIERS

The mill's dc drive systems have six-pulse rectifiers. They produce six pulses superimposed on the dc output for every cycle of the ac supply.

Harmonic currents in an ac supply system are given by the expression:

$$h = kp \pm 1 \tag{1}$$

where

$$\begin{aligned} h &= \text{order of the harmonic} \\ p &= \text{number of pulses produced by the rectifier} \\ k &= \text{any integer} \end{aligned} \tag{2}$$

Thus a six-pulse rectifier will produce 5th, 7th, 9th, 11th, 17th, 19th, etc. The maximum magnitude of each harmonic current is given by:

$$I_h = I/h \quad \text{p.u. of the fundamental} \tag{3}$$

where I_h = harmonic current and h = order of the harmonic. Thus a 5th harmonic can theoretically produce a current equal to 1/5th or 20% of the fundamental current.

IEEE 399-1980 recommends that the following factors be included when modeling a power system for a harmonic analysis study:

HCF : harmonic cancellation factor. This factor depends upon the rectifier-transformer configuration. In the plant where study was conducted, transformers are delta-wye connected and have a HCF = 1.

CRF : Commutating reactance factor. The commutating reactance will affect the magnitude of harmonic currents.

LDF : Unit loading factor. Harmonic current output will be reduced if the rectifier is not delivering rated output. Since the rectifiers have phase retard control, this loading factor is not necessarily proportional to the kVA output of the rectifiers. when these factors are included in the analysis, equation (2) is modified as follows:

$$I_h = \frac{(HCF)(CRF)(LDF)}{h} \quad \text{p.u. of the fundamental} \tag{4}$$

The harmonic current magnitude are shown in Table XX.

D. FILTER REACTORS

Figure 6 shows a basic system configuration utilizing capacitors on a rectifier bus. The equivalent impedance diagram is also shown in this drawing. The transformer and source impedance are in parallel with the filter impedance. Referring to this drawing:

$$Z_s = \frac{(Z_t + Z_1)Z_m}{Z_t + Z_1 + Z_m} \tag{5}$$

$$I_h = I_s + I_f \ , \tag{6}$$

and

$$(I_f)(Z_f) = (I_s)(Z_s) \quad (7)$$

where

I_h = total harmonic current injected

I_s = harmonic current in system elements

I_f = harmonic current in filter (8)

Z_f = filter impedance

Z_s = equivalent source impedance

Table XX. HARMONIC CURRENT IN STATIC CONVERTER INPUT PER UNIT OF FUNDAMENTAL CURRENT

Harmonic Order	Frequency (Hertz)	Harmonic current in per unit of fundamental frequency
5	300	0.175
7	420	0.110
11	660	0.045
13	780	0.029
17	1020	0.015
19	1140	0.010
23	1380	0.009
25	1500	0.008

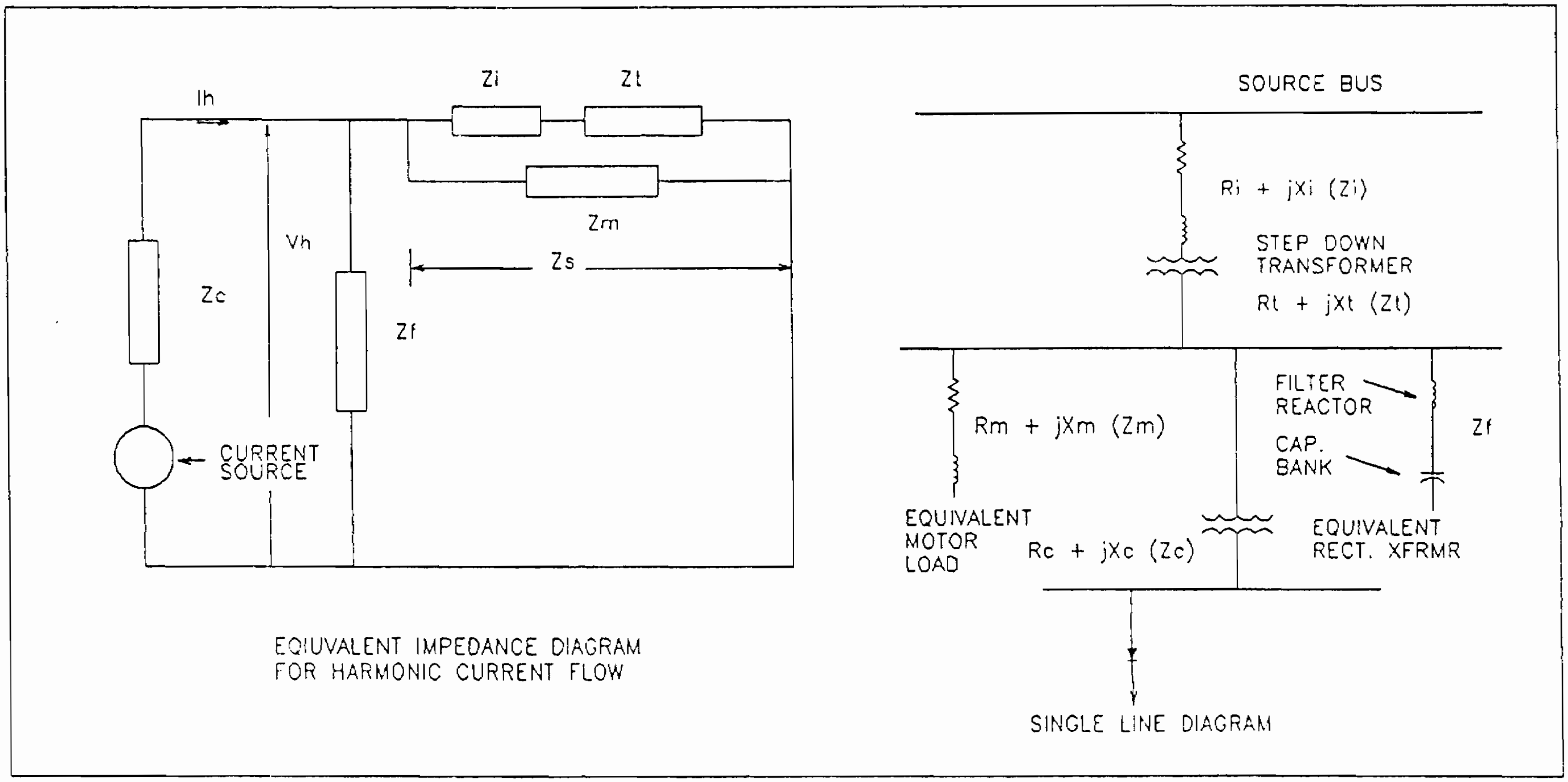

Figure 6. Equivalent Circuit for Harmonic Analysis

The harmonic voltage across the filter impedance equals that of the total source impedance. This gives

$$I_s = \frac{Z_f}{Z_f + Z_s} I_h \qquad (9)$$
$$= (P_s)(I_h)$$

and

$$I_f = \frac{Z_s}{Z_f + Z_s} I_h \qquad (10)$$
$$= (P_f)(I_h)$$

where

$$P_s = \frac{Z_f}{Z_f + Z_s} \quad , \quad P_f = \frac{Z_s}{Z_f + Z_s} \quad \text{both are complex quantities.} \qquad (11)$$

Ratios P_s and P_f are called "harmonic current distribution factors" or RHO factors. A good filter will have a P_f of very close to unity for a current at its tuned frequency. P_f will be typically around 0.995, and the corresponding P_s for the power system will be around 0.05.

For a series resonant filter, the impedance angles of P_s and P_f will be approximately $-81°$ and $+2.6°$ respectively.

E. CAPACITOR RATINGS

Capacitor banks in the filter circuit are subjected to harmonic current flows. Capacitors can fail either due to harmonic current overloading or due to the overvoltages caused by these harmonics.

The recommendations of IEEE 519-1981 and IEEE 18-1980 have been followed to provide a normal life expectancy for the capacitor banks. These recommendations impose the following limits on capacitor loading:

-- Total rms current of the capacitor banks, including all harmonics, should not exceed 180% of its rated current, i.e.

$$IRSS = \sqrt{I_f^2 + \sum_{h=2}^{h=max} I_h^2} \leq 180 \times I_f \tag{12}$$

where

$$\begin{aligned} IRSS &= \text{total current (rms)} \\ I_f &= \text{fundamental current} \\ I_h &= \text{harmonic current.} \end{aligned} \tag{13}$$

It should be noted that if the capacitor bank is loaded with only one harmonic current, it could take 150% of the rated fundamental current at that harmonic.

-- The total kvar loading of the capacitor bank should not exceed 135% of the nameplate rating, including loading due to all harmonics:

$$\text{Total kvar} = \sqrt{I_f^2 + \sum_{h=2}^{h=max} I_h^2} \leq 180 \times I_f \tag{14}$$

-- The rms voltage, including all harmonics, but but excluding transients should not exceed 110% of the rated voltage.

$$VRSS = \sqrt{V^2 + \sum_{h=2}^{h=max} V_h^2} \tag{15}$$

$$\leq 110 \times V_f$$

-- The crest voltage should not exceed 120% of the rms voltage times $\sqrt{2}$. The harmonic voltages are arithmetically summated and added to the fundamental for this evaluation

$$VSUM = V_f + \sum_{h=2}^{h=max} V_f \tag{16}$$

Values of IRSS, VRSS, total kvar and VSUM are calculated. The selection of capacitor banks has been made so that none of these parameters exceed the recommended limits under any of the modeled operating conditions of the distribution system.

V. SYSTEM MODELING FOR HARMONIC ANALYSIS STUDY

A. IMPEDANCE DIAGRAM

Figure 7 shows the impedance diagram of the distribution system at the fundamental frequency for the harmonic analysis study.

The plant rectifier loads are connected to 13.8 kV buses A, B, C, and G. There are no rectifier loads connected to 13.8 kV bus D or 7.2 kV buses E and F.

The projected dc drive loads for No.4 paper machine and the existing rectifier loads are represented as equivalent rectifier loads:

Buses A and B: 9750 KVA, 480 Volt. This load is shown as Bus 3 load in Figure 7.

Buses C and G: 26,000 KVA, 480 Volt. This load is shown as Bus 2 load in Figure 7.

1250 KVA, 550 Volt: This load is shown as Bus 1 load in Figure 7.

To simulate the worst harmonic loading conditions, the rectifier load estimates throughout the distribution system have been made based upon the naturally cooled rating the connected transformers.

The rectifier load injection buses are connected to the 13.8 kV buses A and B and C and G through rectifier transformers of equivalent impedances.

The motor loads on each of the 13.8 kV buses are represented as equivalent impedances M1, M2, M3 and M4.

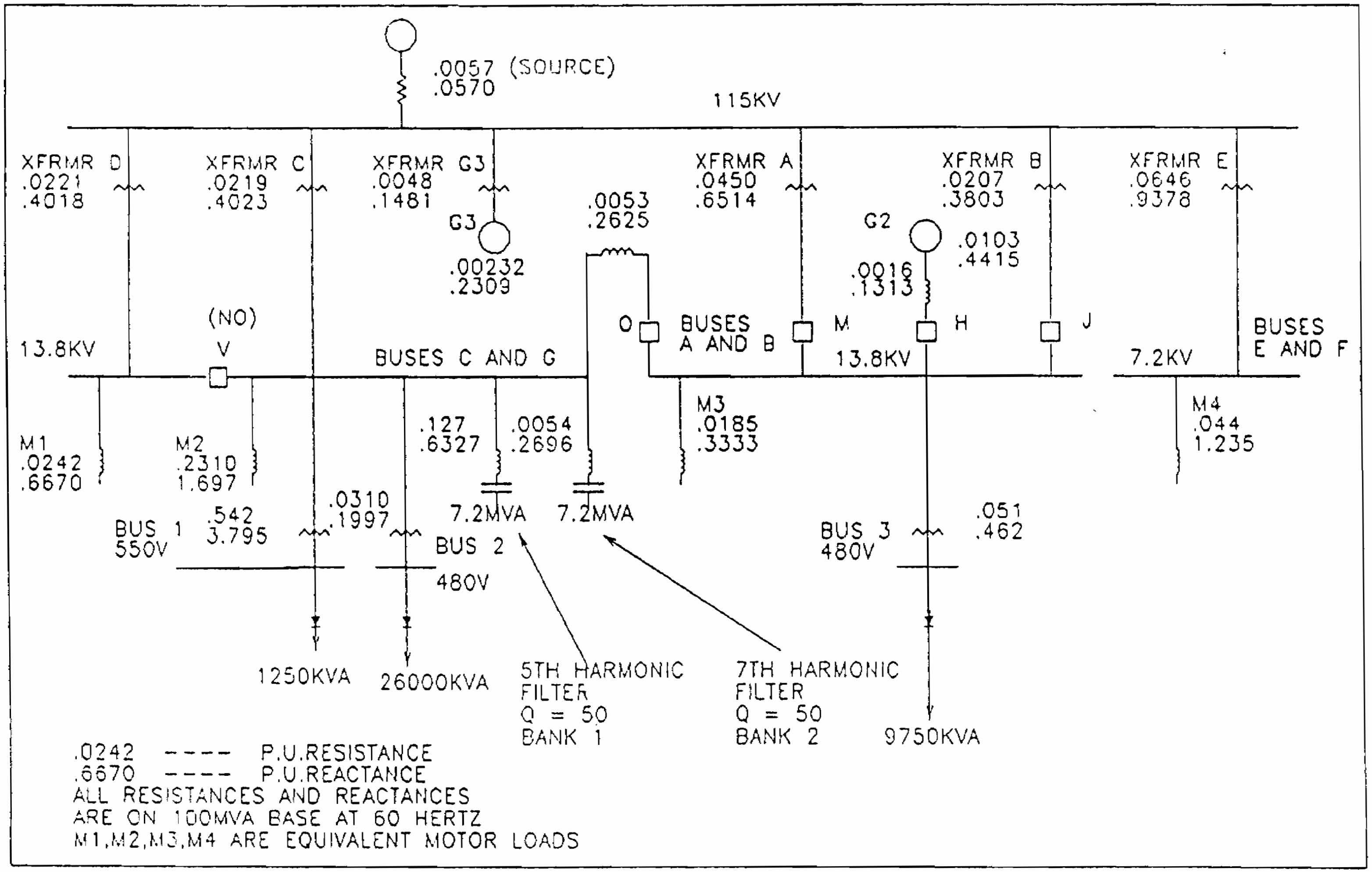

Figure 7. Impedance Diagram with Equal 5th and 7th Filters

B. SWITCHING CONDITIONS

The switching conditions shown in Table XXI were initially identified for the harmonic analysis study. The following symbols are to be noted:

C - closed In - in service

O - open Out - out of service

These switching conditions did not consider installation of a new utility transformer on Bus G. As the study progressed, it became evident that it will not be necessary to study all the conditions initially identified in Table XXI. The effect of adding a new tie transformer to bus G was included in the study. Each of the switching conditions studied, and the study results, are described in detail in Chapter 6.

C. DETAILS OF THE DIGITAL COMPUTER HARMONIC STUDY

The computer program used conducts the harmonic analysis in two parts:

1. Part-I. A rectifier is assumed to be a harmonic current generator which 'injects' higher frequency currents into the system. Current is injected one frequency at a time to find the system response. Then currents at all other frequencies are injected. This identifies the resonant conditions in the system at a particular frequency. A graph of frequencies and the corresponding harmonic current distribution factors are obtained. These data are also shown in tabular form.

Table XXI. SWITCHING CONDITONS WITHOUT NEW UTILITY TRANSFORMER

Case No.	Capacitor Banks		G2	G3	Breakers			
	5th	7th			V	J	M	O
1	IN	IN	IN	IN	O	C	C	O
2	IN	IN	IN	OUT	O	C	C	O
3	IN	IN	OUT	OUT	O	C	C	O
4	IN	IN	IN	IN	O	C	O	O
5	IN	IN	IN	IN	O	O	C	C
6	IN	IN	OUT	IN	O	C	C	C
7	OUT	IN	IN	IN	O	C	C	O
8	IN	OUT	IN	IN	O	C	C	O

2. Part-II. Harmonic currents and voltages in the selected system configurations are calculated for the injected harmonic currents. The magnitude of harmonic current and voltage distribution on each of the 13.8 kV buses, capacitor banks, and utility system are calculated.

The resulting VSUM, total capacitor Kvar loadings, VRSS, IRSS, and total harmonic distortion are calculated to evaluate the harmonic duties on the capacitors and effectiveness of the filter reactors.

The computer calculations include the following:

---A listing of the circuit elements along with impedance values, tolerances, load currents and voltages.

---A tabulation and graphical representation of the harmonic distribution factors and phase angles.

---A tabulation of the harmonic currents and voltages in the identified buses.

---Totalized quantities of VSUM, THD, VRSS, IRSS and Kvar loading on the identified buses.

VI. DISCUSSION OF THE STUDY RESULTS

A. FREQUENCY SCAN

A frequency scan is made from 60 Hz to 1,800 Hz (fundamental to 30th harmonic) to identify the location of resonant frequencies. The per unit harmonic impedances of the major components of the distribution system are also calculated.

The switching conditions considered for frequency scan are shown in Table XXII and XXIII.

A brief summary of the resonant frequencies and the distribution factors is shown in Table XXIV and XXV.

The following conclusions can be drawn from the study results:

---The resonant conditions of cases 1AF, 1BF, 1CF show that the system response is identical whether the harmonic injection source is placed at rectifier group 1, 2 or 3. Thus the rest of the study was conducted with harmonic injection only at rectifier group 1.

---Cases 1AF, 2AF, 3AF show that harmonic distribution factors are high at 5th and 7th harmonics. Tuning reactors are necessry to reduce RHO factors at these rectifier generated frequencies.

---Resonances at frequencies higher than 7th harmonic do not occur in the distribution system.

---The capacitor banks should not be operated with the 5th harmonic filter out of service,though they can be operated without the 7th harmonic filter.

Table XXII. SUMMARY OF FREQUENCY SCAN CASES NO. 1

CASE NO.	HARMONIC INJECTION AT		SWITCHING CONDITIONS				5TH HARMONIC FILTER AND CAP.	7TH HARMONIC FILTER AND CAP.
		BRKR V	BRKR H	NO.2 GEN REACTOR	BRKR O	XFRMR G		
1AF	RECT 1	OPEN	CLOSE	OUT	OPEN	NO	---NO REACTOR	
1BF	RECT 2	OPEN	CLOSE	OUT	OPEN	NO	---7.2MVAR	
1CF	RECT 3	OPEN	CLOSE	OUT	OPEN	YES		
2AF	RECT 1	OPEN	CLOSE	OUT	OPEN	YES	NO REACTOR/7.2MVAR	
3AF	RECT 1	OPEN	CLOSE	OUT	OPEN	YES	7.2MVAR	NO
4AF	RECT 1	OPEN	CLOSE	OUT	OPEN	YES	RT 4.7	RT 7.2
							7.2MVAR	7.2MVAR

Table XXIII. SUMMARY OF FREQUENCY SCAN CASES NO. 2

CASE NO.	HARMONIC INJECTION AT	SWITCHING CONDITIONS BRKR V	BRKR H	NO.2 GEN REACTOR	BRKR O	XFRMR G	5TH HARMONIC FILTER AND CAP.	7TH HARMONIC FILTER AND CAP.
5AF	RECT 1	OPEN	CLOSE	OUT	OPEN	NO	RT 4.7 7.2MVAR	RT 7.2 7.2MVAR
6AF	RECT 1	OPEN	CLOSE	OUT	OPEN	NO	NO	RT 7.2 7.2MVAR
7AF	RECT 1	OPEN	CLOSE	OUT	OPEN	YES	RT 4.7 7.2MVAR	NO
8AF	RECT 1	OPEN	OPEN	OUT	CLOSE	NO	RT 4.7 7.2MVAR	RT 7.2 7.2MVAR

Table XXIV. FREQUENCY SCAN CASES RESONANT HARMONIC FREQUENCIES IN MULTIPLES OF FUNDAMENTAL RHO FACTORS NO. 1

CASE NO.	RECT. BUS AT	CAP 1 5th HARMONIC	CAP 2 7th HARMONIC	XFRMR C	XFRMR G3
1AF	RECT 1	4.5/9.159	4.5/9.159	4.4/14.344	4.4/1.584
		5/2.315	5/2.315	5/2.894	5/9.320
		(NO FILTER)	(NO FILTER)		
1BF	RECT 2	4.5/9.159	4.5/9.159	4.4/14.344	4.4/1.584
		5/2.669	5/2.669	5/2.894	5/0.320
		(NO FILTER)	(NO FILTER)		
1CF	RECT 3	4.5/0.381	4.5/0.381	4.5/0.608	4.4/0.097
		(NO FILTER)	(NO FILTER)		
2AF	RECT 1	5.7/10.691	5.7/10.691	5.7/18.802	5.7/2.076
		5/1.615	5/1.615	5/3.691	5/0.408
		(NO FILTER)	(NO FILTER)		
3AF	RECT 1	8.1/20.978	REMOVED	8.1/18.273	8.1/2.018
		7/2.961		7/3.454	7/0.381
		(NO FILTER)			

Table XXV. FREQUENCY SCAN CASES RESONANT HARMONIC FREQUENCIES IN MULTIPLES OF FUNDAMENTAL RHO FACTORS NO. 2 &part2. &part3.

CASE NO.	RECT. BUS AT	CAP 1 5th HARMONIC	CAP 2 7th HARMONIC	XFRMR C	XFRMR G3
4AF	RECT 1	3.7/7.903	6/11.237	3.8/10.705	3.8/1.183
		5/0.924	7/1.200	5/0.292	5/0.032
		(5th FILTER)	(7th FILTER)	7/0.068	7/0.008
5AF	RECT 1	3.4/10.042	5.7/9.805	3.4/12.852	3.4/1.420
		5/1.051	7/1.084	5/0.184	5/0.020
		(5th FILTER)	(7th FILTER)	7/0.036	7/0.004
6AF	RECT 1	REMOVED	4.7/15.802	4.7/12.772	4.7/1.411
			5/5.095	5/3.279	5/0.362
			(7th FILTER)		
7AF	RECT 1	4.1/7.878	REMOVED	4/6.866	4/0.758
		5/0.733		5/0.234	5/0.026
		(5th FILTER)			
8AF	RECT 1	3.9/10.106	6/10.168	3.9/6.005	3.9/1.104
		5/0.896	7/1.119	5/0.147	5/0.027

---The 5th harmonic filter alone is adequate to control the resonant conditions in the distribution system. The use of a 7th harmonic filter is mainly to control total harmonic distribution (THD).

B. TOLERANCES ON CAPACITORS AND REACTORS

The computer program calculates harmonic loading under various combinations of tolerances on the capacitor banks and the filter reactors The computer also calculates the currents calculated for each harmonic under the worst combination of tolerances.

The following tolerances were considered:

Capacitor banks -0 to $+7.5\%$Reactors $\pm 3\%$

The specified tolerances for reactors are $\pm 2\%$. However, the harmonic current flow study was conducted with $\pm 3\%$ tolerance to allow for variations due to installation, cable connections and manufacturing.

C. TOTAL HARMONIC DISTORTION

The total harmonic voltage and current distortions are defined as:

$$\text{THD (voltage)} = \sqrt{\sum_{h=2}^{h=max} \frac{V_h^2}{V_f^2}} \qquad (17)$$

$$\text{THD (current)} = \sqrt{\sum_{h=2}^{h=max} \frac{I_h^2}{I_f^2}} \qquad (18)$$

where

$$v_h = I_h z_h \tag{19}$$

$$v_h = I_h z_h \tag{20}$$

$$I_h = \text{ harmonic current} \tag{21}$$

$Z_h =$ harmonic impedance

$I_f =$ fundamental frequency current (22)

$v_f =$ fundamental frequency voltage.

The distortion is a function of the amount of harmonic currents flowing through the system. IEEE 519-1981 gives the voltage distribution limits for medium and high voltage power systems. The following limits are specified in this standard.

System Voltage	Maximum Voltage Distortion
Medium Voltage systems:	
2.4 - 69 kv	5%
High voltage systems:	
115 kv and above	1.5%

The standard does not specify limits of current distortion. Table XXVI shows that total harmonic current distortion on the 115 kv system should be limited to 4% under normal mill operating conditions.

Table XXVI. MAXIMUM HARMONIC CURRENT DISTORTION IN PERCENTAGE OF FUNDAMENTAL

(r)	HARMONIC ORDER (FOR ODD)				
	0 TO 11	11 TO 17	17 TO 23	23 TO 35	THD
20	4.0	2.0	1.5	0.6	5.0
20 TO 50	7.0	3.5	2.5	1.0	8.0
50 TO 100	10.0	4.5	4.0	1.5	12.0
100 TO 1000	12.0	5.5	5.0	2.0	15.0

D. HARMONIC CURRENT FLOW

Harmonic current flow has been studied under a number of switching conditions with the following configurations:

---equal 5th and 7th harmonic filters, each with 7.2 Mvar capacitor banks.

---unequal 5th and 7th harmonic filters.

---a 5th harmonic filter only.

Table XXVII shows the harmonic current flow study cases with equal 5th and 7th harmonic filters. A summary of the study results with equal 5th and 7th harmonic filters is shown in Table XXVIII and XXIX. Harmonic current, and voltages up to 11th harmonic are only shown in this drawing.

The following conclusions can be drawn from the study results summarized in Table XXVIII and XXIX.

---Without harmonic filters connected to the distribution system, the voltage distortion on 13.8 kv buses C & G will be 13.5% and 7% on the 115 kv bus. This exceeds the permissible limits specified in IEEE 519-1981.

---The installation of 5th and 7th harmonic filters provides lower THD than a 5th harmonic filter alone.

---The computer program calculates a unit P.U. fundamental voltage in the presence of filter reactors. This is not correct,as the presence of a filter reactor in series with a capacitor will raise the fundamental voltage on the capacitor banks. This discrepancy in the computer program was corrected for some of the calculations. The computer calculations which do not allow for the rise in fundamental frequency voltage have been identified in Table XXVIII and XXIX.

Table XXVII.DESCRIPTION OF STUDY CASES FOR TWO EQUAL 5TH AND 7TH HARMONIC FILTERS

CASE NO.	5TH HARMONIC FILTER	7TH HARMONIC FILTER	FILTERS TURNING FREQ.	WITH XFRMR G	BREAKER STATUS O	V	M	H	J	No. 2 GEN REACTOR
1AR	IN	IN	4.7/7.2	NO	O	O	C	C	C	OUT
2AR	IN	IN	4.7/7.2	NO	O	O	C	C	C	IN
2BR	IN	IN	4.7/7.2	NO	O	O	C	C	C	IN
3AR	IN	OUT	4.7/--	NO	O	O	C	C	C	IN
4AR	IN	OUT	4.7/--	YES	O	O	C	C	C	IN
5AR	IN	IN	4.7/7.2	YES	O	O	C	C	C	IN
6AR	OUT	OUT	--/--	NO	O	O	C	C	C	IN
7AR	IN	IN	4.7/7.2	NO	C	O	C	O	C	OUT
8AR	IN	OUT	4.7/--	YES	C	O	C	O	C	OUT

Table XXVIIISUMMARY OF CAPACITOR BANK LOADINGS EQUAL 5TH AND 7TH HARMONIC FILTERS NO. 1

5TH HARMONIC FILTER

CASE NO.	HARMONIC CURRENTS FD	5	7	11	HARMONIC VOLTAGES FD	5	7	11	RSS (V)	SUM (V)	RSS	KVAR
1AR	312.9	248.9	9.8	9.8	1	.155	.005	.003	1.012	1.165	1.279	8248
2AR	312.9	259	13.1	10.2	1	.16	.006	.003	1.013	1.172	1.299	8507
2BR	318.7	265.4	10.1	9.3	1.05	.168	.005	.003	1.063	1.229	1.302	9126
3AR	312.9	173.5	65.7	21.6	1	.115	.031	.006	1.007	1.159	1.166	7991
4AR	312.9	160.5	50.5	15.8	1	.106	.024	.005	1.006	1.14	1.137	7903
5AR	312.9	199.1	10.4	8.4	1	.132	.005	.003	1.009	1.142	1.186	8087
6AR	----OUT OF SERVICE-----											
7AR	312.9	218	11.6	9.2	1	.145	.006	.003	1.01	1.156	1.22	8207
8AR	312.9	165.3	45.3	13.7	1	.11	.021	.004	1.006	1.139	1.141	7921

Table XXIX. SUMMARY OF CAPACITOR BANK LOADINGS EQUAL 5TH AND 7TH HARMONIC FILTERS NO. 2

CASE NO.	HARMONIC CURRENTS FD	5	7	11	5TH HARMONIC FILTER HARMONIC VOLTAGES FD	5	7	11	RSS (V)	SUM (V)	RSS	KVAR	THD 115KV I&V	THD BUSES C&G/V
1AR	312.9	144.2	145.5	30.9	1	.089	.069	.009	1.006	1.176	1.201	8037	.034/.007	.047
2AR	312.9	167.6	151.5	31.5	1	.103	.072	.009	1.008	1.193	1.24	8168	.037/.007	.052
2BR	309.6	198.3	147.2	31	1.02	.125	.073	.01	1.03	1.236	1.285	8436	.042/.008	.001
3AR	---------------OUT OF SERVICE-------												.034/.008	.065
4AR	---------------OUT OF SERVICE-------												.043/.011	.049
5AR	312.9	111.2	154.3	26.9	1	.068	.073	.008	1.005	1.157	1.175	7935	.043/.008	.037
6AR	---------------OUT OF SERVICE-------												.07/--	.135
7AR	312.9	119.4	172.9	29.3	1	.073	.082	.009	1.006	1.172	1.21	8031	.039/.008	.04
8AR	---------------OUT OF SERVICE-------												.047/.011	.043

---Case 2BR shows the effect of -0 to +10% tolerance for capacitors on the harmonic loadings. The increased tolerance detunes the filter and attracts more harmonic current. A tolerance smaller than -0 to +7.5% is therefore desirable. An investigation revealed that capacitor units with -0 to +5% tolerance can be supplied.

A study of harmonic current flow with unequal capacitor banks was also conducted. The purpose of this study was to optimize harmonic loadings on the capacitor banks without exceeding current and voltage total harmonic distortions on 13.8 and 115 kv buses. A tolerance of -0 to +5% for capacitor units was used for this study.

A summary of the study cases with unequal 5th and 7th harmonic filters is shown in Table XXX and the results of the study are shown in Table XXXI and XXXII. The Figure 8 shows the corresponding impedance diagram.

The following conclusions can be drawn from the study results:

---Case 2(1B) considers only a 5th harmonic filter with a 14.2 Mvar capacitor bank. However,the voltage distortion on 13.8 kv buses C and G is 4.7%.

---Case 2(GR) shows the effect of tuning frequency on the harmonic current loading of the 7th filter. Shifting the tuned frequency of 7th harmonic filter from 7.25 to 6.6 KHz reduces harmonic current loading. However, the THD on 13.8 kV buses C and G is increased to 4.2%, compared to 3.4% in case 2FR.

---The harmonic loadings on the capacitor banks in all the cases are well within the acceptable ratings of the filter banks.

Table XXX. DESCRIPTION OF STUDY CASES FOR TWO UNEQUAL 5TH AND 7TH HARMONIC FILTERS

CASE NO.	5TH HARMONIC FILTER	7TH HARMONIC FILTER	FILTERS TURNING FREQ.	WITH XFRMR G	BREAKER STATUS O	V	M	H	J	No. 2 GEN REACTOR
2(1B)	IN 14.2MVAR	OUT	4.7/--	NO	O	O	C	C	C	IN
5(2B)	IN 9.2MVAR	IN 4.6MVAR	4.6/7.25	NO	O	O	C	C	C	IN
2(6R)	IN 9.2MVAR	IN 4.6MVAR	4.6/6.6	NO	C	O	C	C	C	IN
2FR	IN 9.2MVAR	IN 4.6MVAR	4.6/7.25	NO	O	O	C	C	C	IN

Table XXXI. SUMMARY OF CAPACITOR BANK LOADINGS UNEQUAL 5TH AND 7TH HARMONIC FILTERS NO. 1

CASE NO.	HARMONIC CURRENTS FD	5	7	11	5TH HARMONIC FILTER HARMONIC VOLTAGES FD	5	7	11	(V)	RSS (V)	SUM	KVAR
2(1B)	608.6	180.9	83.7	29.4	1.05	.063	.021	.005	1.052	1.142	1.054	15239
2(FR)	415.2	198.2	27.4	13.9	1.05	.103	.01	.003	1.055	1.169	1.111	10907
5(2B)	415.2	179.9	31	11.7	1.05	.093	.011	.003	1,054	1.16	1.093	10824
2(GR)	415.2	211.3	26.8	15.6	1.05	.109	.01	.004	1.055	1.176	1.125	10971

Table XXXII.SUMMARY OF CAPACITOR BANK LOADINGS UNEQUAL 5TH AND 7TH HARMONIC FILTERS NO. 2

5TH HARMONIC FILTER

CASE NO.	HARMONIC CURRENTS FD	5	7	11	HARMONIC VOLTAGES FD	5	7	11	RSS (V)	SUM (V)	RSS I&V	KVAR C&G/V	THD 115KV	THD BUSES
2(1B)	---ONLY 5TH FILTER INSTALLED--												.007	.047
													.027	
2(FR)	201.7	56.6	174.6	24.5	1.02	.056	.129	.012	1.029	1.227	1.36	5532	.006	.039
													.026	
5(2B)	201.7	47.5	197.5	20.8	1.02	.047	.146	.01	1.031	1.231	1.425	5653	.007	.034
													.034	
2(GR)	202.4	78.6	102.4	20.4	1.023	.078	.076	.01	1.029	1.196	1.193	5293	.006	.042
													.029	

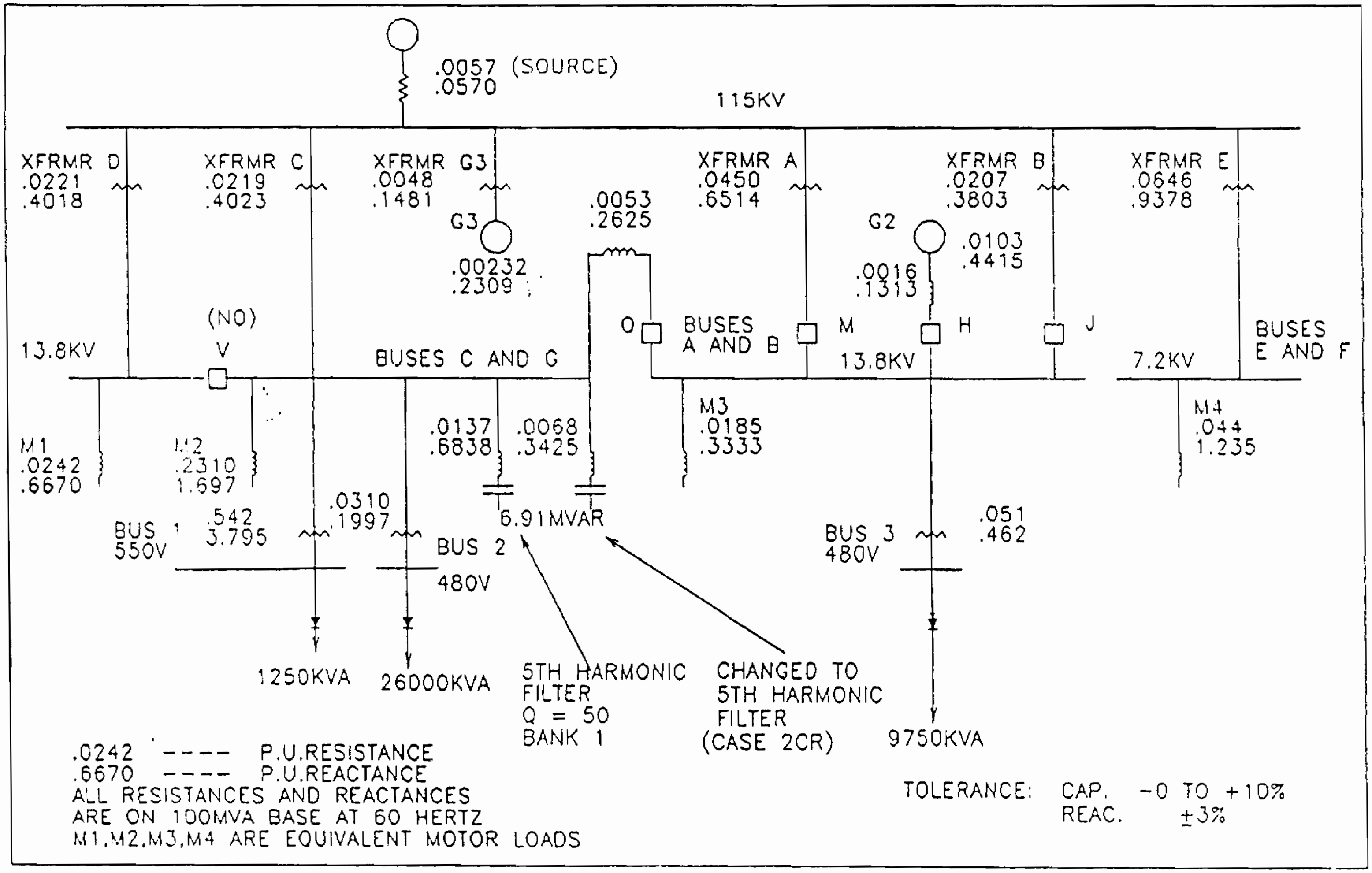

Figure 8. Impedance Diagram for Unequal 5th and 7th Filters

E. CONCLUSIONS

A 5th harmonic filter with a 9.2 Mvar capacitor bank and a 7th harmonic filter with a 4.6 Mvar capacitor bank provides acceptable bank loading. The harmonic voltage and current on the 13.8 and 115 kV buses under various switching conditions are below the limits specified in IEEE/ANSI standards.

VII. CAPACITOR BANK CONTROL

A. INTRODUCTION

The selection of appropriate controls for the capacitor bank switching should be based upon ease of system operation, reliability and maintainability. The following types of controls can be considered :

---Voltage control : A simple voltage relay may be used to switch the capacitors 'on' if the voltage drops to a present level and switch the capacitors 'off' above a second present level.

---Current control : The capacitors are connected to the system during heavy load. This control is similar to the voltage control, except that current level sensing is adopted to switch the capacitors 'on' and 'off'.

---VAR Control : The control determines the Mvar loading at a given point in the system. The control is thus responsive to power factor of the load also.

---VAR control is recommended for control of the capacitor banks due to its obvious merits.

B. CONTROL STRATEGY

A logic diagram of the var control of the capacitor bank breaker is shown in Figure 9. The main features of this control are described below:

---The Mvar loading of bus G is converted into a 0-1 mA signal through a var transducer. A summation current transformer is used to add the input currents in the 2000 AMPS tie breaker and the future 2000 AMPS utility transformer tie breaker.

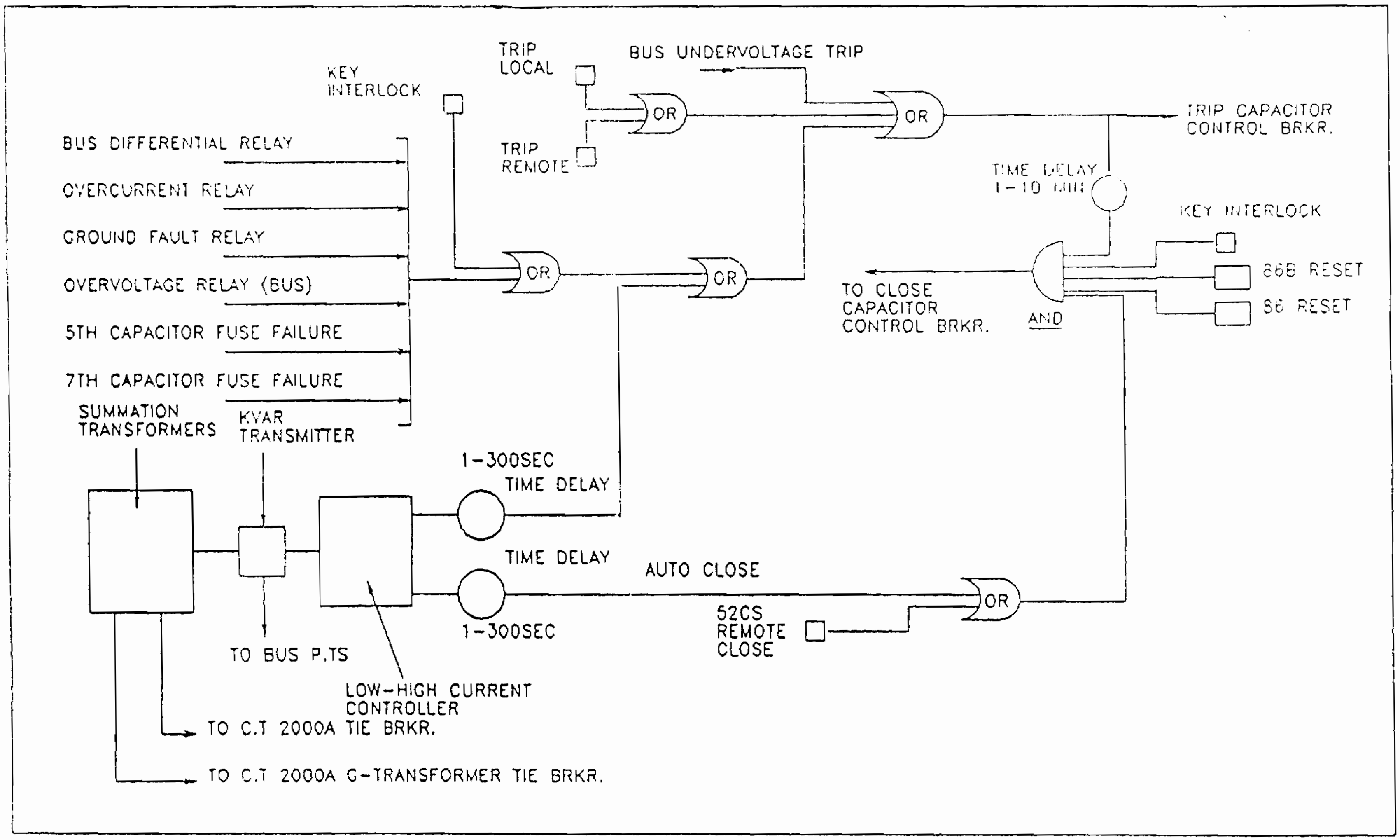

Figure 9. Capacitor Bank Breaker Control Logic Diagram

---A high-low current controller output activates two time-delays, adjustable 1-300 seconds, to prevent repeated switching of the capacitor banks on transient loads. The low set point, after a present time-delay, trips the capacitor breaker. Similarly, the high set point, after a present time-delay, closes the capacitor breaker.

The voltage on 13.8 kV Bus G rise approximately 5.6 % upon energizing the capacitor banks. The high set point will be controlled so that the voltage on 13.8 kV bus G is approximately 2% below rated voltage when the capacitors are energized. A time delay is provided to prevent the capacitor banks from being energized within 5 minutes of tripping.

The filter reactors introduce sufficient impedance in the capacitor bank circuit to limit the magnitude of switching currents. Abnormal notching in the 13.8 kV supply voltage upon energizing the capacitor banks is not expected.

C. INTERLOCKING REQUIREMENTS FOR 13.8 KV CIRCUIT BREAKERS

The installation of a new tie transformer will introduce additional interlocking requirement, to limit fault currents to levels within the short-circuit rating of the 13.8 kV circuit breakers. Though this is a matter of detailed design, these interlocks are briefly described as follows :

Transformer D, C, and G secondary tie breakers should be so interlocked that only two of these transformers can be operated in parallel at any time.

Interlocks should be provided to ensure that reactor-tie breaker 0 on bus B is closed only if:

---No. 2 generator or transformer B is out of service

---Tie breaker 0′ between buses C and G is open

---Tie breaker V between buses D and C is open

It is important to note that a detailed short-circuit study will be required to ensure that none of 13.8 kV circuit breakers are exposed to short circuit currents exceeding their ratings.

VIII. RESULTS

A. FINDINGS

The existing system will be able to serve a load growth of approximately 17 MVA associated with stage 1 of the plant expansions. However, the voltage taps on the primary side of the utility tie transformers serving the 13.8 kV load buses will have to be set to their lowest setting. Some of the unit substations served by the 13.8 kV buses may require primary side tap changes to compensate for below normal voltage levels. If No. 3 generator is operating at rated output concurrent with stage 1 load growth, tap changes on unit substations will be minimized.

The distribution system should be able to serve a further load growth of approximately 6 MVA associated with Stage 2 of the plant expansions. However, primary side tap changes on some unit substations may be required to compensate for below normal voltage levels. With No. 3 generator operating at rated output, the voltage on 13.8 kV buses C and G will be approximately 3.8 percent below rated voltage. The other 13.8 kV buses will be approximately 1.4 to 1.7 percent below rated voltage. The utility tie transformers will not be overloaded during normal operations.

The distribution system will not be able to serve the load growth associated with Stage 3 of the plant expansions. The normal voltage levels on the 13.8 kV buses will range from 3.0 to 10.1 percent below rated voltage, even with generator Nos. 2 and 3 in operation. These voltage levels are not appropriate for continuous plant operations.

It will be possible to serve the load growth of Stage 3 with the addition of a 7 Mvar capacitor bank to bus D and two 7 Mvar capacitor banks to bus G. The sizes of the capacitor banks will require a series reactor to form a filter for harmonic currents. The capacitor banks will improve the voltages on the 13.8 kV buses to acceptable levels and permit the mill to operate at the rated capacity. However, this system has serious limitations. Upon failure of a major source, like transformer B, C or D, widespread shutdowns will occur. The process cannot be restored to rated production due to lack of reserve capacity in the system.

A new 20/37.33 MVA utility tie transformer, connected to 13.8 kV bus G and operated in parallel with transformer C, will improve normal operating voltage levels on the 13.8 kV buses. However, the capacitor banks described above will still be required. They are needed to provide acceptable operating bus voltages and limit the initial voltage drops upon loss of a source. The addition of a new transformer offers the following advantages:

---The entire No. 4 paper machine load can be fed from 13.8 kV bus G. Without the new transformer, the No. 4 paper machine will be fed from buses B and G.

---A sudden loss of transformer A, or generator No. 2 or 3, should not cause a major process disruption. Loss of utility tie transformers B, C or G may result in overloading of other sources in service. However, appropriate switching operations may permit plant operations at the rated output.

---Since bus D is operated as an island, a sudden loss of transformer D will result in a shutdown of the loads served by this bus. The process can be restored by closing bus tie breaker V between buses C and D.

It will be necessary to operate No. 2 generator with an output of atleast 8.4 MW and 16 Mvar to support the load growth of Stages 1, 2 and 3. The load flow calculations demonstrate that excessive voltage drops will be experienced on 13.8 kV buses A and B when No. 2 generator is out of service.

There are no voltage problems associated with 7.2 kV buses E and F. The loads on these buses remain unchanged through Stage 3 load growth. These buses serve the grinders.

The results of the harmonic analysis study indicate that:

---Tuning reactors are required with the capacitor banks. Without tuning reactors the harmonic loadings on the capacitor banks will be excessive.

---Various switching conditions may result in resonance at the 5th and 7th harmonic frequencies.

---Resonance at frequencies higher than 7th harmonic does not occur.

---One 5th harmonic filter is adequate to control resonant conditions in the distributed system. However, the use of the 5th and 7th harmonic filters gives a lower total harmonic distortion (THD) on the 155 kV and 13.8 kV buses. With 5th and 7th filters the THD on these buses is within the specified limits in ANSI/IEEE Standard 519.

---Without the use of filters, the THD on 115 kV and 13.8 kV buses will exceed the specified limits in ANSI/IEEE Standard 519. Although the primary objective of installation of capacitor banks is to have an acceptable voltage level on load flow, the filter banks also limit the THD, both current and voltage, on 115 kV and 13.8 kV buses. Cleaner voltage and current waveforms will result in lower harmonic losses in the distribution system.

---Unequal 5th and 7th harmonic filters give optimum capacitor bank loadings.

The following additional power systems studies are required to confirm that the new utility tie transformer and the loads can be safely added to the distribution system and that the system will reliably serve the loads:

---Short-circuit study.

---Initial voltage drop due to large motor starting on selected buses.

---Load flow study extended to selected 480 and 2400 volt buses.

B. RECOMMENDATIONS

Contingent upon completion of the power system studies, the following are the possible solutions:

---Install a new 115-13.8 kV, 20/37.33 MVA utility tie transformer on 115 kV bus 1A. The transformer should be connected to 13.8 kV bus G and normally operated in parallel with transformer C.

---Install fans and oil circulating pumps on utility transformer B, to permit operation at its maximum MVA rating.

---Utility tie transformers A, B, C, D and G should be operated on their lowest primary tap. Transformers E and F should be operated on the +2.5% tap. Transformer G3 can be operated on the 13.8 kV tap.

---Operate No. 2 generator at 8.4 MW and 16 Mvar output and No. 3 generator at its rated output concurrent with Stage 1 load growth.

---Install 5th harmonic and 7th harmonic filters on the 13.8 kV buses C and G. The 5th harmonic filter should have a 9.2 Mvar capacitor bank. The 7th should have 4.6 Mvar capacitor bank. These filters will be controlled by a single circuit breaker on bus G.

---The distribution system can be operated without the 7th harmonic filter. The system should not be operated without the 5th harmonic filter. However, both filters should be operated during normal operations to provide reactive power for 13.8 kV buses C and G.

---Install interlocking on the utility tie transformer 13.8 kV circuit breakers and bus tie circuit breakers as outlined in chapter 5.3.

---Conduct a short-circuit study on each of the major 0.48, 2.4 and 13.8 kV buses. This study should compare the available fault currents with the short-circuit current ratings of the system's switching devices and cables.

---Conduct large motor starting studies on selected buses, to determine initial voltage drops for various system operating conditions.

---Conduct load flow studies on selected 480 and 2400 volt buses, where voltage drop problems are anticipated.

BIBLIOGRAPHY

1. "National Electric Code," - 1988

2. "IEEE Recommended Practice For Electric Power Distribution for Industrial Plants," STD 141-1976

3. Stagg and El-Abiad "Computer Methods In Power System Analysis," McGraw-Hill Book Company, 1968

4. John E. Harder and Elton L. Parker "Important Considerations For Capacitor Applications In The Pulp and Paper Industry," IEEE Transactions of Power Apparatus and Systems, Vol. 10, pp 32-43, 1982.

5. "American National Standard for Shunt Power Capacitors," ANSI C55.1, IEEE No.18.

6. D. D. Shipp "Harmonic Analysis For Power Systems Supplying DC Drives," IEEE/IAS Pulp and Paper Conference Vol. 7, pp 182-187, 1978.

VITA

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