A Case Study of Resonance in 11kV Network in the Presence of Series Current Limiting Reactors, VSDs and Power Factor Improvement Capacitors

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***Abstract*—Presence of electrical network elements such as reactors, power factor capacitors along with harmonics injecting loads such as Variable Speed drives create an ideal situation for resonant conditions in an industrial electrical network. This paper attempts to identify various conditions that influence the resonance situation in the 11KV network of hydrocarbon industry and its sensitivity to influencing factors is assessed. Further, the effect of detuning reactor in the power factor capacitors on the THD values, harmonic frequency and other parameters is studied. Based on the case study, the impact of configuration of electrical network and variation of capacitance in the electrical network on the THD and harmonic frequency is established.**

***Index Terms*—harmonics, resonance, capacitors banks**

I. Introduction

Study of resonance in the electrical network is not routine activity for many electrical design engineers and plant operating engineers. Mostly the facilities of an oil field operate either in full throughput capacities or in part loads. Few of the operating facilities may be under shutdown that results in variation in power intake requirement from the utility undertaking.

Application of power factor capacitors and presence of harmonic injecting electrical loads along with long cables for power transfer create an ideal situation for electrical resonance conditions [1]. Electrical Engineers face the dilemma to proceed with electrical network modifications & expansions very often when the electrical network modifications consist of harmonic sources and capacitors. Although the awareness of harmonics is growing, yet the issues pertaining to the resonance are seen as complicated and facility design electrical engineers do not confer much attention.

A routinely used method to assess resonance frequency by multiplying the fundamental frequency with the square root of ratio of the system fault level to the capacitor size is an indicative method and cannot be considered, as reliable design tool as the estimation of fault current at the bus, is not an easy task. Fault current is function of source impedance, minimum & maximum fault current available from the utility, motor short circuit contribution, configuration of the electrical network etc. Inevitably, one has to use an established software to assess the resonance situation in the electrical network.

Electrical engineers planning for capacitor installations in the electrical network for addition or resizing, have to pass through the various design activities to have trouble free operation of capacitor banks. In the present context, intentionally introduced resonance that happens in the filtering circuits is not discussed.

A. Resonance

Resonance is a phenomenon of electrical networks when inductive impedance equals to capacitive impedance of the electrical network at certain frequencies. Under the resonant conditions, the electrical network behaves differently as the impedance of the electrical network varies in enormous way.

Electrical impedance is function of electrical network operating conditions. Resonance is function of harmonic frequencies and harmonic impedances. Under resonant conditions, the network impedance will change in a considerable degree and leads to increased currents which further leads to abnormal situations in the electrical network. It becomes exceedingly difficult for electrical engineers to establish the reasons of failure of the electrical network unless the aspects of resonance are studied.

Resonance can happen in electrical network either in the form of parallel resonance, series resonance and combination of both. In whatever fashion resonance happens in the electrical networks the ill effects of the resonance will be present. Resonance can also be partial resonance or full resonance.

When an electrical network has capacitors for the purpose of power factor improvement there is a possibility of occurrence of series and parallel resonance. Any resonant condition in the electrical network is detrimental as series resonance will result in high voltage conditions and parallel resonance will result in high currents & sometimes high voltages leading to damage of equipment.

- **Parallel resonance:** Parallel combination of network capacitance and network inductance equal in magnitude at a harmonic frequency. In this case, impedance seen by harmonic current source

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becomes infinite. The energy exchanges that take place between inductance and capacitance of the network leads to Parallel resonance. Parallel resonance results in High harmonic currents and distortion in the system.

- **Series resonance:** Series combination of network capacitance and network inductance equal in magnitude at harmonic frequency. In series resonance, impedance tends to become zero based on the network resistance. Series resonance results in high harmonic currents and high voltages.
- **Partial resonance:** If the natural frequency of the capacitor bank & power-system reactance combination is close to a particular harmonic, then partial resonance will occur.
- **Full resonance:** If the resonant frequency coincides with one of the harmonic frequency then it becomes a case of full resonance.

B. Brief Description of the Electrical Network

In the present resonance study, 11KV electrical network consisting of a source substation (X) and two distribution substations (Y&Z) loaded to 90% of installed capacity, is considered. Substation 'X' israted for 72MW at 11KV and feeds to Substation 'Y' and Substation 'Z'.

Substation 'X' is fed from Utility undertaking and consists of four 132KV/11KV transformers and 11KV switchboard. Substations 'Y' and 'Z' have 11KV switchboards and other voltage switchboards and receive power from Substation 'X' and distribute the same to facility loads. Substation 'X' feeds 11KV power to Substation 'Z' through four Series Current Limiting Reactors. For the electrical scheme details refer to Fig. 1.

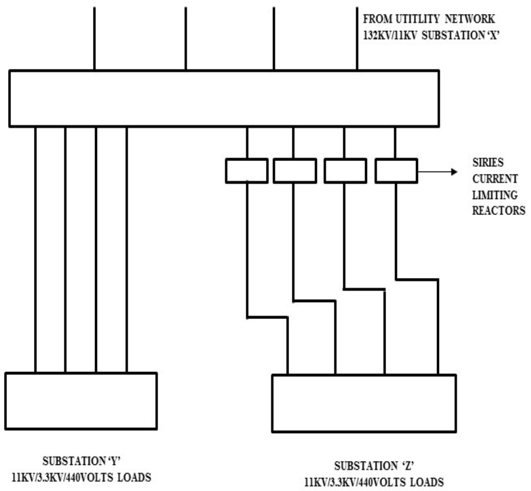

Figure 1. Overall electrical network.

C. Type and Nature of the Connected Load

Total maximum demand of Substation 'Y' is 55MW. Non-linear loads to the extent of 36MW operate on Substation 'Y' 11KV bus. Substation 'Z' has maximum demand of 12MW consisting of motors and power factor improvement capacitors at 11KV level.

For limiting fault current that is at the level of 40KA at Substation 'X' to the level of 25KA at Substation 'Z' a reactor value of 0.3 ohm is considered. The purpose of this reactor is to limit the short circuit current at Substation 'Z'.

The other load composition consists of induction motors of various sizes connected to 3.3KV and 440 volt level along with associated transformers. Lighting loads and small nonlinear loads such as battery chargers, UPS systems, Computers and Switch Mode Power Supplies (SMPS) are connected at the 440 volts level.

D. Presence of Harmonics and Harmonic Related Information

As the nonlinear loads operate at Substation 'Y', harmonic pollution is present in the network. The main contribution of harmonics is from 11KV Variable Speed Drives. The Variable Speed Drives are of voltage source type with high pulse rectifiers.

The capacity of UPS systems & Battery Charger(s) is much less than 15% of the corresponding transformer capacity at the 440 volt level. Hence the harmonic presence at 440 volts is ignored.

E. Capacitor Banks

Physically capacitor banks for power factor improvement can be installed at Substation X and Substation 'Z' keeping in view the space requirement and feeder availability. Two numbers capacitor banks 2100KVAr & 1800KVAr are proposed to be installed at substation 'Z'.

II. ETAP System Studies

The ETAP software is used to develop the electrical network described above and conducted the resonance related studies. The variations in the configurations of the electrical network and parameters are considered keeping in view the operation of the facility is very vital to avoid production loss. The objective of the resonance study is to identify the occurrence of resonance under various network configurations and parameter variation as indicated hereunder [2]:

- Capacitor Variation Under Minimum fault current and Maximum fault current conditions
- Number of Reactors, Numbers of Transformers and Number of VSD's variation
- Normal operating and Abnormal Operating configurations
- Source X/R variation

Keeping the power factor capacitors constant in the electrical network, resonant frequency directly varies with the square root of available short circuit in the network. Short circuit current is function of network configuration and load variation. Hence, various configurations are studied by varying the (i) number of transformers at source substation X, (ii) reactors between source substation X and distribution substation Z, (iii) capacitor banks at substation Z, (iv) number of harmonic sources at substation Y etc. In the first stage ETAP study is carried out without considering the detuning reactors in the capacitor circuits.

A. Harmonic Load Flow Study

Harmonic Load flow Study is carried out, for assessing Total Harmonic Distortion and quantifying individual harmonic currents. These calculated values are compared with recommended values indicated in the International standards to determine the acceptability of Harmonic content.

B. Frequency Scan Study

Frequency Scan study is carried out, for identifying the resonant frequency and harmonic impedance related information.

III. RESULTS

A. Capacitor Variation under Minimum Source Fault Current Contribution with 4 Transformers and 4 Reactors

As the capacitance is introduced, in the substation 'Z', two different peaks of parallel resonance and minimum one series resonance trough is noticed.

As the capacitance increases in the network in all the substations, Parallel Resonant impedance decreases from 24.37 ohms to 11.15 ohms and Resonant Frequency reduced from 1100Hz to 450Hz. (Harmonic order from 22 to 9). Same trend applies to Series resonant impedance and Series resonance frequency.

The quantum of capacitance in the electrical network influences the resonant frequency.

B. Capacitor Variation under Maximum Source Fault Current Contribution with 4 Transformers and 4 Reactors

The trend indicated above is equally applicable when the source fault level increases from 1851 MVA to 2789 MVA. The expected variation in the source fault level is due to operational variations at Utility side. However, there is no major difference in the harmonic impedance due to increase in source fault level.

C. Series Current Limiting Reactor Variation under Maximum Source Fault Condition with 4 Transformers and All Capacitors Included in the Network at Substation 'Z'

With the reduction of series current limiting reactors from 4 (four) to 3 (three), the harmonic impedance is expected to increase. However, from 4 Reactors to 3 Reactors variation, the harmonic impedance is reduced from 21.28 ohms to 18.07 ohms for Substation Z. The reduction in impedance is attributed to harmonic angles. Further, reduction of three (3) Reactors to two (2) Reactors variation the harmonic impedance has increased from 18.07 ohms to 27.08 ohms. In addition, the harmonic frequency decreased from 450Hz to 400Hz (Harmonic order from 9 to 8).

From the above, it is noted that Series Current Limiting Reactor variation has pronounced impact on the harmonic impedance.

D. Transformer & Series Current Limiting Reactor Variation under Source Maximum Fault Condition with All Capacitors at Substation 'Z'

Under 4TR and 2R conditions, harmonic impedance is about 27.8 ohms and harmonic frequency at which resonance likely to take place is at 400 Hz (Harmonic order 8).

The possibility of network with two (2) reactors is very remote as this kind of operation will not deliver the required power. However, under emergency conditions this configuration may be used for running few of the equipment.

E. Number of VSD's Variation under 4 TR, 4R and Bus Tie Opening at Substation 'Z' 11KV Bus Bar

Number of VSD's variation (from 8 to 6 VSD's) does not have major influence on the harmonic impedance and resonant frequency.

However opening the bus tie at Substation 'Z' 11kV has increased harmonic impedance to 30.89 ohms and increased the parallel resonance peaks to 3 (three) at Substation X and Substation Y.

This kind of operating conditions is not normal and this configuration affects reliability of power availability hence not recommended for facility operations. Resonance frequency at substation Z 11kV bus will be at harmonic order 8 or 9.

TABLE I. VTHD VALUES UNDER NORMAL-OPERATING CONDITIONS (THE FOLLOWING ARE MOST COMMON OPERATING CONDITIONS OF ELECTRICAL NETWORK TO OPERATE THE FACILITIES)

Configuration	% THD(Voltage)				PF at X-11kV-Bus	Remark
	Substation X-11kV-Bus	Substation Y-11kV-Bus	Substation Z-11kV-Bus	Substation Z-440V-Bus		
LF1-MAX-3TR	1.46	1.49	1.69	1.47	97.9	Sometimes this operation is possible
LF2-MAX-4TR	0.97	0.99	1.21	1.03	97.9	Most common method of operation
LF4-3TR-3R	1.51	1.56	1.71	1.48	97.9	This operation is possible in the network
LF6-4TR-3R	1.17	1.21	1.37	1.18	97.9	This operation is possible in the network
LF-4TR-3R2CMIN (MIN SOURCE FAULT)	1.34	1.39	1.53	1.29		This operation is possible in the network whenever Utility changes their mode of operation, both the capacitor banks & one reactor has failed or taken for maintenance

LF: Harmonic Load Flow.
TR: Number of Transformers in operation at Source Substation X.
R: Number of Current Limiting Reactors in operation between Substation X and Substation Z.
C: Capacitors in the electrical network.
PF: Power Factor

F. Voltage THD Values under Normal Operating Conditions

Any operational mode of electrical network that delivers power to facilities (for partial and full throughput capacity) reliably, without endangering life of operators and facility is Normal Operating condition. Under normal operating conditions, THD values at various substations are in the acceptable range while maintaining the power factor at source substation X. Refer to Table I for results.

G. Voltage THD Values under Abnormal Operating Conditions

Under most of the abnormal operating conditions, THD values at various substations have increased and when the capacitor values goes down to 1300 kVAR, the THD values will cross 5% at substation Z.

Under certain abnormal operating conditions, THD values may remain within the acceptable limits. However current flow through the series current limiting reactors will cross their rated capacities that would cause destruction of the equipment itself. Refer to Table II for simulation results.

TABLE II. VTHD VALUES UNDER ABNORMAL OPERATING CONDITIONS (THE ELECTRICAL NETWORK CAN ALSO BE OPERATED IN THE FOLLOWING CONFIGURATIONS UNDER CERTAIN EQUIPMENT FAILURE CONDITIONS)

Configuration	% THD (Voltage)				Remark
	Substation X-11kV-Bus	Substation Y-11kV-Bus	Substation Z-11KV-Bus	Substation Z-440V-Bus	
LF-4TR-3R1C (Max Source Fault)	3.26	3.29	4.33	3.52	This mode of operation is possible when one capacitor bank is in operation and other capacitor bank fails. Maximum source fault at utility is available. 1800 KVAR Capacitor is on.
LF-4TR-3R1CMIN (Min Source Fault)	3.52	3.55	4.6	3.76	This mode of operation is possible when one capacitor bank is in operation and other capacitor bank fails. Minimum source fault at utility is available. 1800 KVAR Capacitor is on.
LF-4TR-3R0CMIN (Min Source Fault)	3.08	3.13	3.12	2.12	NO CAPACITOR. This represents case of failure of both capacitors.
LF-4TR-3R1CMIN (Min Source Fault)	4.07	4.11	5.25	4.22	1400 KVAR CAPACITOR (Partial capacitor switched on)
LF-4TR-3R1CMIN (Min Source Fault)	3.76	3.79	4.91	3.95	1500 KVAR CAPACITOR(Partial capacitor switched on)
LF-4TR-3R1CMIN (Min Source Fault)	4.19	4.23	5.3	4.25	1300 KVAR CAPACITOR(Partial capacitor switched on)
LF-4TR-4R1C (Max Source Fault)	3.38	3.41	4.28	3.47	1800 KVAR CAPACITOR ON
LF-4TR-4R1CMIN (Min Source Fault)	3.57	3.6	4.45	3.63	1800 KVAR CAPACITOR ON
LF-4TR-3R1C (Max Source Fault)	3.26	3.29	4.33	3.52	1800 KVAR CAPACITOR ON
LF3-MIN (Min Source Fault, 3TR, 1 Incomer Open In All Substations)	1.64	1.69	1.84	1.47	Although this configuration delivers the required power, this configuration is not used normally due to the reasons of low reliability. However, under rare situations, this configuration may be used to operate the facility.

LF: Harmonic Load Flow.
TR: Number of Transformers in operation at Source Substation X.
R: Number of Current Limiting Reactors in operation between Substation X and Substation Z.
C: Capacitors in the electrical network.
1C represents 1800 KVAR capacitor

TABLE III. CAPACITOR & REACTOR CURRENT & THD VALUES UNDER NORMAL OPERATING CONDITIONS

Configuration	VTHD Substation Z	2100KV AR Capacitor Current in Amps/Current THD	1800KV AR Capacitor Current in Amps/Current THD	Reactor Current in Amps	Reactor THD
LF1 – Max – 3TR	1.69%	137.9 / 14.41%	118.2 / 14.41%	208.5	3.7%
LF2 – Max – 4TR	1.21%	137.9 / 11.87%	118.2 / 11.87%	207.6	3.26%
LF4 – 3TR – 3R	1.71%	137.4 / 14.46%	117.7 / 14.46%	284.0	3.52%
LF6 – 4TR – 3R	1.37%	136.7 / 13.19%	117.2 / 13.19%	280.6	3.44%
LF3 – Min	1.84%	137.5 / 15.02%	117.9 / 15.02%	276.7	3.69%
LF-4TR-3R2CMIN	1.53%	137.1 /15.33%	117.5 / 15.33%	371.0	2.92%

TABLE IV. CAPACITOR & REACTOR CURRENT & THD VALUES UNDER VARIOUS ABNORMAL-OPERATING CONDITIONS

Configuration	VTHD at 11kV Bus Substation Z	2100KV AR Capacitor Current in Amps /CTHD	1800KVAR Capacitor Current in Amps/CTHD	Reactor Current in Amps	Reactor CTHD
LF – 4TR – 3R1C (Max)	4.33%	-	131.5 / 52.02%	386.5	4.05%
LF – 4TR-3R1C (Min)	4.6%	-	132.7 /54.27%	386.5	4.15%
LF – 4TR – 3ROC (No Capacitor)	3.12%	-	-	408.1	0.71%
LF – 4TR – 3R1C Min (1400KVAR)	5.25%	-	109.2 / 67.40%	391.1	3.97%
LF – 4TR – 3R1C Min (1500KVAR)	4.91%	-	114.3 / 62.16%	389.9	3.97%
LF – 4TR – 3R1C Min (1300KVAR)	5.3%	-	101.9 / 68.55%	392.2	3.68%
LF – 4TR – 4R1C (Max)	4.28%	-	132.1 / 51.39%	287.9	4.34%
LF – 4TR – 4R1C (Min)	4.45%	-	132.6 / 52.89%	287.9	4.34%
LF – 4TR – 3R1C (Max)	4.33%	-	131.5 / 52.02%	386.5	4.05%
LF5 – 3TR – 2R	1.82%	136.8 / 14.91%	117.2 / 14.91%	422.7	3.49%
LF7 – 4TR – 2R	1.33%	137.4 / 12.14%	118.2 / 12.14%	416.7	3.10%
LF7-3TR-3RBTO	2,14%	138.3 /16.49%	118.5 /16.49%	258.4	6.61%

H. Capacitor & Reactor Current & THD Values under Normal Operation Conditions

Both VTHD values are within the range. However, CTHD values are close to 15 %, which is the limit as per IEEE 519. Refer to Table III for simulation results.

I. Capacitor & Reactor Currents & THD Values under Abnormal Operation Conditions

In general, there is an increase of VTHD and enormous increase in CTHD values for Capacitor currents [3]. Few of the operating conditions, in which the VTHD & CTHD are low, are not acceptable due to existing practice of operations & for reliability related aspects. Refer to Table IV for simulation results.

J. Harmonic Currents Passing through Reactors under Various Operating Conditions

The harmonic currents that pass through the reactors for various operating conditions are in the specified limits of IEEE 519. For various configurations, the third harmonic currents (zero sequence currents) are zero. Some even harmonic currents are expected to flow in the network but the values of the even harmonics are within 25% of odd harmonics as required by IEEE 519. The harmonics currents will result in more heat in the reactors [4]. However, as the harmonic currents are within the acceptable range, the reactor thermal circuit is expected to have the capability to withstand this additional heat. Refer to Table V for simulation results.

TABLE V. HARMONIC CURRENTS AND ITS PERCENTAGE THROUGH REACTORS UNDER VARIOUS OPERATING CONDITIONS

Configuration	2nd Harmonic	3rd Harmonic	5th Harmonic	8th Harmonic	11th Harmonic	14th Harmonic
LF1 – Max – 3TR	0.2 / 0.1%	0%	1.1 / 0.5%	1.1 / 0.5%	4.8 / 2.3%	0.7 / 0.3%
LF2 – Max – 4TR	0.1 / 0.1%	0%	0.7 / 0.3%	0.7 / 0.3%	4.8 / 2.3%	0.6 / 0.3%
LF3 – Min	0.3 / 0.1%	0%	1.6 / 0.6%	1.5 / 0.5%	5.8 / 2.1%	0.9 / 0.3%
LF4 – 3TR – 3R	0.3 / 0.1%	0%	1.4 / 0.5%	1.4 / 0.5%	5.9 / 2.1%	0.9 / 0.3%
LF5 – 3TR – 2R	0.4 / 0.1%	0%	2.0 / 0.5%	1.6 / 0.4%	7.7 / 1.8%	1.2 / 0.3%
LF6 – 4TR – 3R	0.2 / 0.1%	0%	1.1 / 0.4%	1.2 / 0.4%	6.5 / 2.3%	0.9 / 0.3%
LF7 – 4TR – 2R	0.3 / 0.1%	0%	1.5 / 0.4%	2.2 / 0.5%	7.8 / 1.9%	1.1 / 0.3%
LF7-3TR-3RBTO	0.2 / 0.1%	0%	3.8 / 1.5%	1.4 / 0.5%	7.4 / 2.9%	1.2 / 0.5%
LF-4TR-3R2CMIN	0.3 / 0.1%	0%	0.4 / 0.1%	1.1 / 1.3%	7.3 / 2.0%	1.0 / 0.3%
LF – 4TR – 3R1C	0.3 / 0.1%	0%	1.2 / 0.3%	0.1 / 0.0%	9.6 / 2.5%	1.6 / 0.4%
LF – 4TR-3R1C	0.3 / 0.1%	0%	1.2 / 0.3%	0.1 / 0.0%	11.1 / 2.9%	1.5 / 0.4%
LF – 4TR – 3ROC (1800 KV AR)	0.4 / 0.1%	0%	2.1 / 0.5%	0.1 / 0.5%	1.1 / 0.3%	0.2 / 0.0%
LF – 4TR – 3R1C Min (1400KV AR)	0.3 / 0.1%	0%	1.4 / 0.4%	0 / 0	4.5 / 1.1%	2.1 / 0.5%
LF – 4TR – 3R1C Min (1500KV AR)	0.3 / 0.1%	0%	1.4 / 04%	0 / 0	5.6 / 1.4%	1.9 / 0.5%
LF – 4TR – 3RIC Min (1300KV AR)	0.3 / 0.1%	0%	1.5 / 0.4%	0 / 0	3.5 / 0.9%	2.3 / 0.6%
LF – 4TR – 4R1C (Max)	0.2 / 0.1%	0%	0.8 / 0.3%	0 / 0	7.0 / 2.4%	1.4 / 0.5%
LF – 4TR – 4R1C (Min)	0.1 / 0.1%	0%	0.9 / 0.3%	0.1 / 0	8.1 / 2.8%	1.3 / 0.4%
LF – 4TR – 3R1C (Max)	0.3 / 0.1%	0%	1.2 / 0.3%	0.1 / 0	9.6 / 2.5%	1.6 / 0.4%

K. Harmonic Current Passing through the Capacitor under Various Operating Conditions

Based on the mode of configuration, the current through the capacitors vary and corresponding Current THD varies. When both the capacitor banks are in the network, then the current values are in acceptable range and current THD values are in the range of close to 15%. The acceptable THD value is less than 15% as the I_{sc}/I_L ratio is more than 100 and less than 1000 as per IEEE519 [5].

However when only 1800 KVAR capacitor is in the circuit, then the current flow and Current THD values increased to very high ranges. In addition, when the capacitance value varies to 1400KVAR and 1500KVAR, the current THD values further increase to 67.40% and 62.10% respectively. Refer to Table VI for results.

TABLE VI. HARMONIC CURRENTS AND ITS PERCENTAGE THROUGH CAPACITORS UNDER VARIOUS OPERATING CONDITIONS

Configuration	Parallel Resonance			Series Resonance		
	Frequency	Harmonic Order	Harmonic Imp in ohms	Frequency	Harmonic Order	Harmonic Imp in ohms
LF1-Max-3TR	400	8	21.06	2150	43	0.43
LF2-Max-4TR	450	9	16.45	2200	44	0.43
LF3-Min	400	8	24.57	2150	43	0.46
LF4-3TR-3R	400	8	22.37	2000	40	0.5
LF- 4TR-3R1C (Max)	600	12	25.67	1850	37	0.9
LF- 4TR-3R1C (Min)	600	12	24.89	1850	37	0.88
LF- 4TR-3ROC (Min)	1100	22	23.05	1900	38	1.36
LF- 4TR-3R1C Min,1400kVAR	650	13	25.99	1850	37	0.98
LF- 4TR-3R1C Min,1500kVAR	650	13	24.06	1850	37	0.96

Configuration	2100 KVAR			1800KVAR		
	Total Current (CTHD)	Parallel Resonant Current	Series Resonant Current	Total Current (CTHD)	Parallel Resonant Current	Series Resonant Current
LF1-Max-3TR	137.9 (14.41%)	3.1(2.2%)	0.7 (0.5%)	118.2 (14.4%)	2.6 (2.2%)	0.6 (0.5%)
LF2-Max-4TR	137.9 (11.89%)	0%	0	1182 (11.87%)	0%	0
LF3-Min	137.5 (15.02%)	3.1 (2.3%)	0.8 (0.6%)	117.9 (15.2%)	2.7 (2.3%)	0.7 (0.6%)
LF4-3TR-3R	137.4 (14.46%)	2.9 (2.2%)	2.2 (1.6%)	117.7A	2.5 (2.2%)	0%
LF- 4TR-3R1C (Max)	-	-	-	131.5 (52.02%)	0	4.8 (4.1%)
LF- 4TR-3R1C (Min)	-	-	-	132.7 (54.27%)	-	5.0 (4.3%)
LF- 4TR-3ROC (Min)	-	-	-	-	-	-
LF- 4TR-3R1C Min,1400kVAR	-	-	-	109.2 (67.40%)	54.6 (60.3)	4.4 (4.8%)
LF- 4TR-3R1C Min,1500kVAR	-	-	-	114.3 (62.16%)	51.7 (53.3)	4.5 (4.7%)

IV. SENSITIVITY ANALYSIS

It is noted that configuration of the network and variation of the power factor capacitors has big influence on the harmonic impedance, resonance and VTHD. Further, the CTHD values for capacitors circuits rapidly increase to unacceptable levels with the capacitor value variation [6]. Resonance frequency reduces with the increase of capacitance in the electrical network.

The 11KV bus (Substation 'Z') to which power factor capacitors are connected is more sensitive and has higher VTHD values.

The configurations with only 2R (two reactors) in circuit cannot deliver required power at Substation 'Z' and reactor current crosses the rated value.

On comparison, it is noted, that variation of maximum fault & minimum fault current has little impact on the various values, although that under maximum source fault situations the slightly better values of VTHD are noted. This is consistent with the basic principle that the higher the short circuit of electrical network, better the current harmonic absorption and lesser the Current THD values.

With 1800 KVAR capacitor in the circuit:

- Variation in source X/R ratio has negligible effect on VTHD at various buses.
- Variation in minimum source fault level has significant effect on the VTHD at various buses. (For example decrease in minimum three phase

Fault level at source from 8.1KA to 4KA resulted in increase in the VTHD from 4.63% to 5.43% at Substation 'Z' 11KV bus)

- It resulted in marginal increase in the Current THD from 1.82% to 1.98% at one of the buses.

V. Introduction of Detuning Reactors for Capacitor Bank Circuits

In order to avoid passing through of harmonic currents and to limit inrush current through capacitor banks, detuned reactors are inserted in the capacitor bank circuits and ETAP studies are re-conducted [7].

Table VII indicates the effect of variation of detuned reactor impedance (X_L) as a percentage of capacitor impedance (X_C). It can be seen, that as the percentage impedance of X_L increases the current through the capacitor increases (this is due to the reason that the overall reactance of X_C-X_L decreases) and there is no much variation in the harmonic impedance, parallel and series resonance frequency, THD values at all the substations.

TABLE VII. Variation of Detuned Reactor Values for 1800KVAR Capacitor

X_L of Reactor Ohms (%)	VTHD of X S/s 11kV Bus %	VTHD of Y S/s 11kV Bus %	VTHD of Z S/s 11kV Bus %	Current Through Capacitor Amp	CTHD of Through Capacitor %	Parallel Resonance Frequency (HO)	Harmonic Impedance Ohms	Series Resonance Frequency (HO)	Harmonic Impedance Ohms	Series Limiting Reactor Current Amp	CTHD through Reactor %
3.3611 (5%)	3.15	3.21	3.09	124.7	5.21	150 (3) 1150 (23)	1.04 21.66	200 (4) 1900 (38)	0.16 1.36	384	1.05
3.811 (5.67%)	3.14	3.19	3.09	125.7	3.74	150 (3) 1150 (23)	1.07 21.67	200 (4) 1900 (38)	0.74 1.36	384.6	0.97
4.034 (6%)	3.14	3.19	3.10	126.3	3.37	150 (3) 1150 (23)	1.09 21.71	200 (4) 1900 (38)	0.85 1.36	384	0.94
4.71 (7%)	3.13	3.18	3.09	128	2.62	150 (3) 1100 (22)	1.21 21.79	200 (4) 1900 (38)	1.01 1.36	384.2	0.9
9.411 (14%)	3.08	3.13	3.08	141.7	1.04	1100 (22) 3800 (76)	22.54 14.67	1900 (38)	1.36	382	0.8
12.77 (18.9%)	3.06	3.11	3.07	153.4	1.98	100 (2) 1160 (22) 3800 (76)	1.06 22.7 14.66	150 (3) 1900 (38)	0.88 1.36	380.1	0.79

It can be noticed that for detuned reactor parameters for 6% and 18.9% are almost identical excepting for increased capacitor current for the later. Increase in the capacitor current is not acceptable above its rated capacity as this will destroy the capacitor. Hence, selection of 6% detuning reactor is prudent. Same logic is applicable for 2100 KVAR capacitor also.

Table VIII and Table IX indicate the effect of insertion of 6% detuning reactor for both capacitor banks, on THD values at various substations, on resonant frequencies, harmonic impedance for parallel/series resonance and on capacitor currents under various configurations.

TABLE VIII. Capacitor Current, THD Values and Resonance Frequencies under Various Configurations for 6% Detune Reactors for 1800KVAR & 2100KVAR Capacitor

Configuration	% THD at substations			2100KVAR & 1800 KVAR Capacitor			
	X %	Y %	Z %	Current through 2100 Capacitor Amp	Current THD of 2100 KVAR Capacitor %	Current through 1800 Capacitor Amp	Current THD of Capacitor %
LF1-MAX-3TR	2.75	2.79	2.74	148	3.15	126.8	3.15
LF2-MAX-4TR	2.43	2.47	2.47	148	2.39	127.1	2.39
LF4-3TR-3R	3.06	3.11	2.97	147.4	3.11	126.3	3.11
LF6-4TR-3R	2.86	2.91	2.81	146.9	2.67	125.9	2.68

Configuration	2100KVAR & 1800 KVAR Capacitor					
	Parallel Resonance			Series Resonance		
	Resonance Frequency	Harmonic Order	Harmonic Imp Ohm	Resonance Frequency	Harmonic Order	Harmonic Imp Ohm
LF1-MAX-3TR	150 1100	3 22	1.68 22.89	200 2300	4 46	0.66 1.05
LF2-MAX-4TR	150 1200	3 24	1.7 23.07	200 2400	4 48	0.62 1.16
LF4-3TR-3R	150 1150	3 23	1.62 22.48	200 2100	4 42	0.67 1.39
LF6-4TR-3R	150 1200	3 24	1.51 22.69	200 2150	4 43	0.64 1.49

TABLE IX. CAPACITOR CURRENT, THD VALUES AND RESONANCE FREQUENCIES UNDER VARIOUS CONFIGURATIONS FOR 6% DETUNE REACTORS FOR 1800KVAR CAPACITOR

Configuration	% THD at substations			Current Through Capacitor Amp	Current THD Through Capacitor %
	X %	Y %	Z %		
LF-4TR-3R1C (Max Source Fault)	3.13	3.19	3.10	126.2	3.25
LF-4TR-3R1CMIN (Min Source Fault)	3.25	3.31	3.10	125.8	3.0
LF-4TR-3R0CMIN (Min Source Fault)	3.08	3.13	3.12		
LF-4TR-3R1CMIN (Min Source Fault) 1400 KVAR	3.26	3.32	3.11	96.2	8.72
LF-4TR-3R1CMIN (Min Source Fault) 1500 KVAR	3.26	3.32	3.11	103.4	5.21
LF-4TR-3R1CMIN (Min Source Fault) 1300 KVAR	3.26	3.32	3.11	88.7	6.07
LF-4TR-4R1C (Max Source Fault)	3.13	3.19	3.22	126.8	3.34
LF-4TR-4R1CMIN (Min Source Fault)	3.15	3.21	3.47	126.8	3.47
LF-4TR-3R1C (MAX SOURCE FAULT)	3.13	3.19	3.10	126.3	3.25
LF3-MIN (MIN SOURCE FAULT, 3TR, 1 INC OPEN IN ALL SWBD)	4.08	4.16	4.01	126.4	3.47
LF5-3TR-2R-1C	3.26	3.32	2.95	125.7	2.95
LF7-4TR-2R-1C	2.86	2.92	2.64	125.2	2.48
LF-3TR-3RBTO-1C	3.05	3.11	2.86	126.8	2.98
LF-4TR-3R2CMIN (MIN SOURCE FAULT)	3.25	3.31	3.10	125.9	3.00

Configuration	Parallel Resonance			Series Resonance		
	Resonance Frequency	Harmonic Order	Harmonic Imp Ohm	Resonance Frequency	Harmonic Order	Harmonic Imp Ohm
LF-4TR-3R1C (Max Source Fault)	150 1150 3850	3 23 77	1.05 21.6 14.57	200 1950	4 39	0.33 1.43
LF-4TR-3R1CMIN (Min Source Fault)	150 1150	3 23	1.4 20.98	200 1900	4 38	0.62 1.36
LF-4TR-3R0CMIN (Min Source Fault)						
LF-4TR-3R1CMIN (Min Source Fault) 1400 KVAR	200 1150	4 23	2.28 20.96	250 1900	5 38	1.09 1.36
LF-4TR-3R1CMIN (Min Source Fault) 1500 KVAR	150 1150	3 23	1.28 20.97	200 1900	4 38	0.16 1.36
LF-4TR-3R1CMIN (Min Source Fault) 1300 KVAR	150 1150	3 23	1.24 20.96	250 1900	5 38	1.05 1.36
LF-4TR-4R1C (Max Source Fault)	150 1150	3 23	0.98 23.28	200 2350	4 47	0.8 1.13
LF-4TR-4R1CMIN (Min Source Fault)	150 1150	3 23	1.02 23.69	200 2300	4 46	0.82 1.06
LF-4TR-3R1C (MAX SOURCE FAULT)	150 1150	3 23	1.05 21.8	200 1950	4 39	0.83 1.43
LF3-MIN (MIN SOURCE FAULT, 3TR, 1 INC OPEN IN ALL SWBD)	150 1200	3 24	1.96 33.37	200 2250	4 45	0.69 1.37
LF5-3TR-2R-1C	150 1200	3 24	2.14 20.88	200 1850	4 37	0.7 2.12
LF7-4TR-2R-1C	150 1250	3 25	1.8 21.31	200 1900	4 38	0.67 2.31
LF-3TR-3RBTO-1C	150 1150	3 23	2.37 21.39	200 1750	4 35	0.72 2.2
LF-4TR-3R2CMIN (MIN SOURCE FAULT)	150 1150	3 23	1.4 20.98	200 1900	4 38	0.62 1.36

On comparison, THD values for configurations without detuning reactors of Table I to Table VI with the values of THD of Table VIII and Table IX, with detuning reactors, the following are noted:

- With introduction of detuning reactors, THD values increase for normal operating configurations for all substations (in particular for substations 'Z'), for other abnormal operating conditions the THD values have marginally decreased.
- All the THD values are less than 4 % as against stipulated 5% in IEEE 519.
- Only in the LF3–MIN configuration, the THD values crossed 4%.
- In most of the cases, the parallel resonance frequency is at third Harmonic order.
- Introduction of detuning reactors, the THD values at all the three substations (X, Y and Z) have become numerically in the close range.

VI. Conclusion

In this paper, at the beginning, examined the resonance and its sensitivity for mode of operation (electrical configuration), X/R ratio, fault current, transformer, VSD, reactor and capacitor element variations without detuning reactors in the capacitor circuits (Refer Fig. 2). It is noted that configuration of electrical network and capacitor variation have pronounced effect on the harmonic impedance and resonant frequency. The case study results indicate that number of resonance modes is equal to number of physical capacitor installations.

With the introduction of detuning reactors for the capacitor banks (Refer Fig. 3), THD values changed substantially for all configurations. For normal configurations, the VTHD values have increased for all the substations and CTHD values have decreased for Capacitor circuits in the Substation Z. For Abnormal configurations both VTHD and CTHD, values have decreased. This leads to important conclusion that detuning reactors in the capacitor circuits influence all configurations of electrical operations and achieves balance between VTHD and CTHD values. Use of appropriate detuning reactors is very much necessary whenever power factor capacitors form part of electrical network.

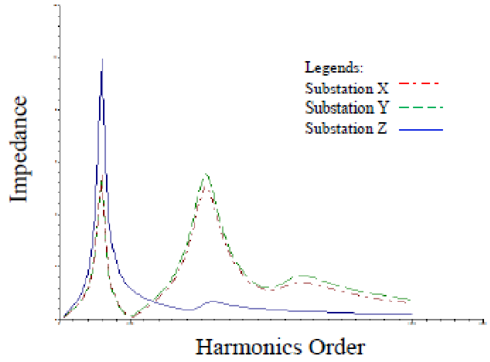

Figure 2. Impedance vs frequency without detuning reactors for capacitor circuits

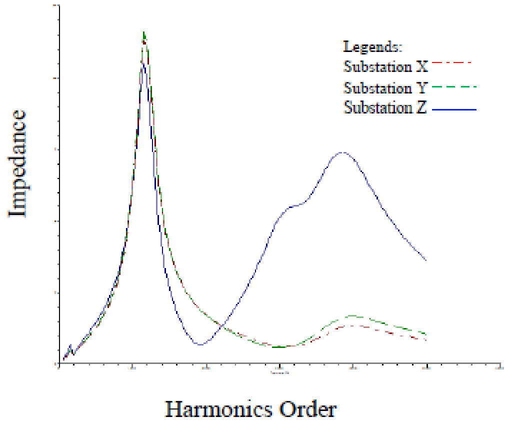

Figure 3. Impedance vs frequency with detuning reactors for capacitor circuits.

When an equipment or breaker fails or cable faults happen in the network, the electrical network operates in some other configuration other than the originally envisaged mode of operation. Under such circumstances, harmonic impedance and resonant conditions will change. It is advisable that the electrical engineers involved with design activities, study the various configurations and notify plant operators to avoid electrical configurations where conditions of resonance and high Voltage THD could arise.

As and when industrial electrical networks encounter the new situations of loading conditions, modifications, network additions and deletions, it is very important and essential that electrical system studies are repeated to reassess the harmonic impedance and resonant frequency. In addition, it is recommended to monitor the electrical parameters & measure the network harmonic distortion factors to compare with the theoretical results to verify the correctness of electrical model.

Monitoring Capacitor currents along with THD values will throw light on the detuning reactor's functioning in the capacitor network. In other words, the increased THD and capacitor currents indicate possible failure or improper selection of detuning reactors in the capacitor circuit.

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