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Harmonic Resonance phenomena in lightly loaded MV network

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1 SUMMARY

This paper presents in detail a specific case of harmonic resonance that can occur in a very lightly loaded MV network with the potential to cause severe voltage distortions and in some cases run away effect of voltage rise, resulting in significant damage to end user equipment / appliances.

In this particular case study, a 132/22 kV Sub-Station with four Transformers of 60 MVA capacity, normally two operating in parallel, feeding an extensive 22kV distribution network comprising of twenty (20) loops, has been analyzed. Initial load was so low that the MVAR import to the 22 kV bus was higher than the MW export. The MVAR import was due to the capacitance effect of the lightly loaded long cable network of the 22 kV distribution feeders, which is a potential condition for harmonic resonance.

The order of natural resonant frequency between the system source reactance and the capacitance of the network at the interface is governed by the equation;

$h_r = \sqrt{\frac{MVA_{sc}}{MVAR_c}}$ where,

h_r = the order of natural frequency which is fr/50 for a 50 Hz system
MVA_{sc} = Source impedance in MVA
$MVAR_c$ = Capacitance of the network in MVAR

Therefore, during the planning stage, due diligence has to be done to minimize possibility of harmonic resonance occurrences in the network systems that are built for long-term load considerations in green field developments and are lightly loaded initially due to low utilization, followed up by gradual load ramp up.

KEYWORDS

Harmonic resonance, fifth harmonic resonance, MV network, lightly loaded MV network, parallel resonance, series resonance, PCC- point of common coupling

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2 Introduction:

Power system networks are planned for long-term requirements based on the area-wise load forecast in distribution geographies. However, in the initial few years after commissioning, networks are normally lightly loaded. Measurements carried out at one such sub-station revealed significant amount of current distortion due to harmonics, which in turn caused voltage distortions. The network under study was a very lightly loaded, newly commissioned 132/22 kV Sub Station with four 60 MVA, 132/22 kV Transformers (180 MVA Firm Capacity), operating under normal scenario as a combination of two sets of two parallel transformers (Figure-1). A large number of underground cables connected at the 22 kV distribution feeders were causing a net MVAR import (of around 20.0 MVAR) to the 22 kV bus, which far exceeded the small MW load (of around 2.0 MW), exported from the bus.

The Total Harmonic Distortions (THD) measured, varied based on the network configuration (Transformers parallel/independent combinations with combinations of load distribution) and was quite pronounced under certain network configurations.

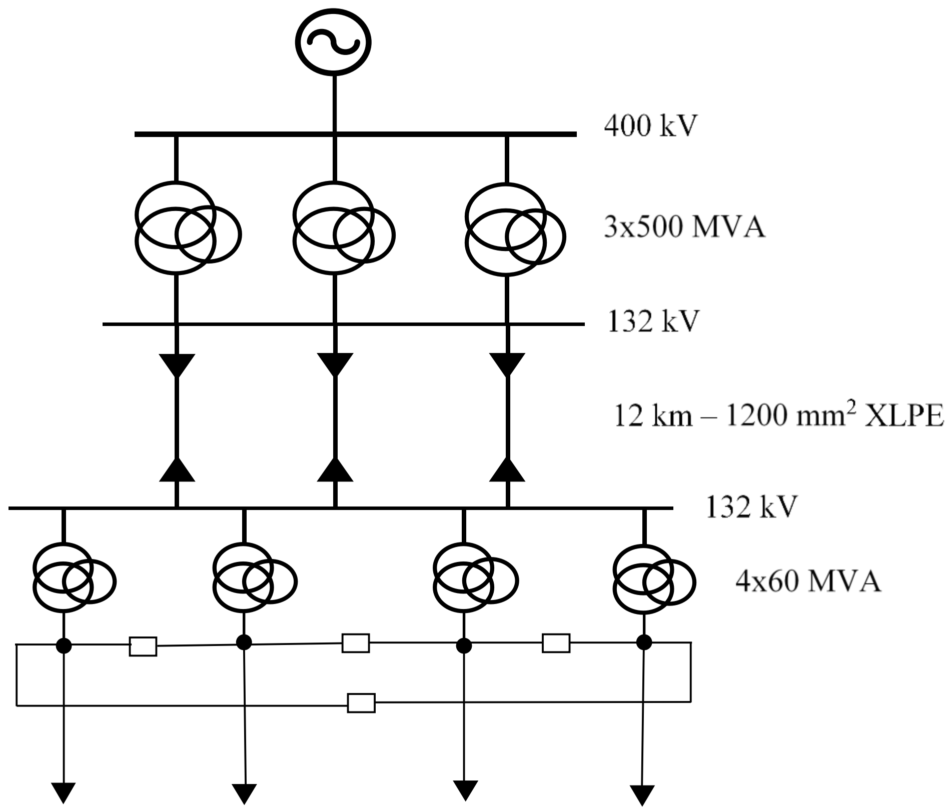

Figure 1: Simplified representation of the system under consideration

3 Measurement and Analysis:

As a root cause analysis of this incident, systematic power quality measurements were carried out both on 22 kV and 132 kV side of the Sub-Station under all possible network operating configurations. This incident resulted in severe damage to a large number of tariff meters at the consumer end. Records of voltage and current during the incident revealed a steep rise in voltage within a short span of time (Figure-2). This disproportional rise has been attributed to harmonic resonance and in this particular case to fifth harmonic, as validated through distortion analysis.

In order to simulate the condition in the field, a network configuration on the day of the incident with one transformer out of service was recreated with due care to avoid runaway conditions by monitoring the voltage/ limiting the transformer taps. Equivalent network models was also created using software tools through third party consultants and compared with the measurement findings. Key parameters such as current, active/ reactive power, total harmonic distortion were compared and accuracy was well within tolerable limits.

Snapshot of values captured on the Fault Monitoring System (FMS) at the time of incident at one of the Transformers' 22 kV side, showing sharp increase in voltage under fifth harmonic resonant condition, is shown in Table-1 and the difference between fundamental and true rms values is significant.

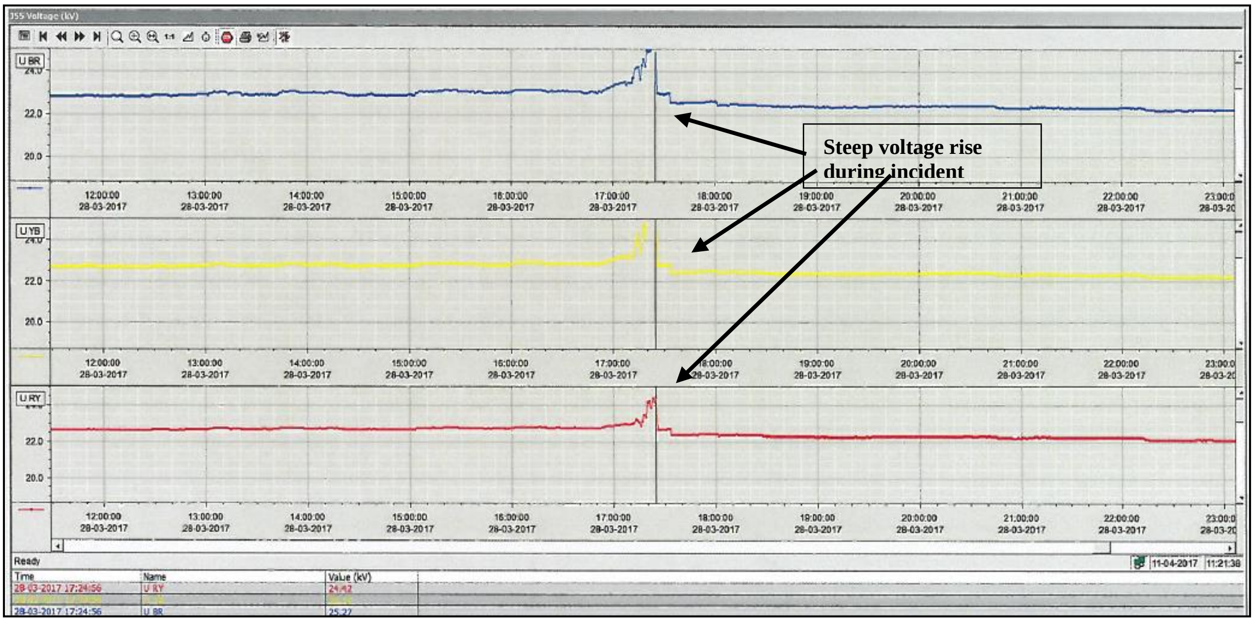

Figure 2: SCMS voltage trend of 22 kV bus that captured steep rise in voltage at the time of incident

Signal	R.M.S.	Phase	Fundamental	DC	2nd harm.	3rd harm.	5th harm.
VR	16.164 kV	36.3°	12.873 kV	-0.20%	0.10%	0.90%	**73.90%**
VY	17.492 kV	-83.7°	12.815 kV	-0.10%	0.10%	2.70%	**90.70%**
VB	18.211 kV	156.5°	12.836 kV	0.30%	0.00%	2.90%	**98.60%**
IR A	0.7524 kA	-97.8°	0.1059 kA	-1.10%	1.10%	13.90%	**692.30%**
IY B	0.9036 kA	127.9°	0.1023 kA	-0.70%	0.60%	45.40%	**866.30%**
IB C	0.9867 kA	17.2°	0.08127 kA	2.40%	1.80%	63.70%	**1196.80%**

Table 1: Snapshot of values captured on the Fault Monitoring System (FMS).

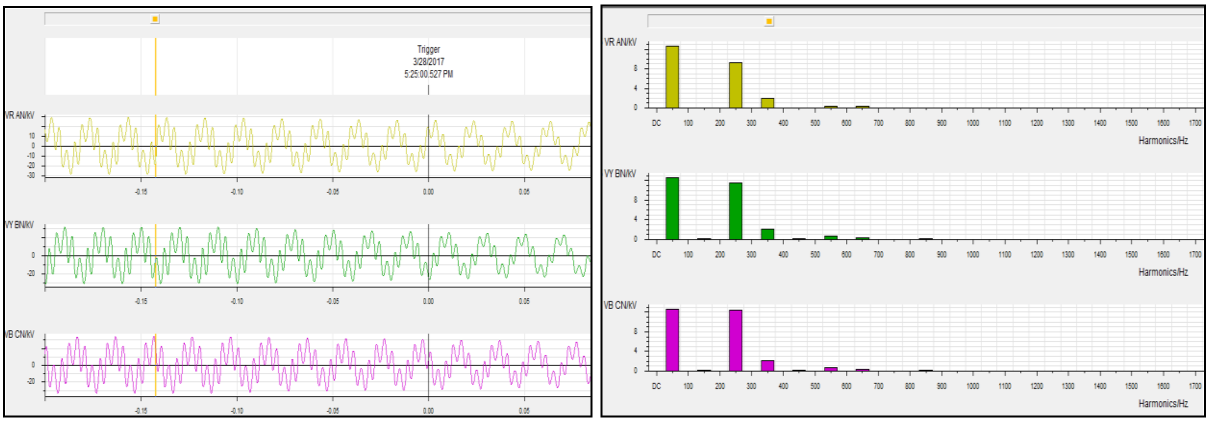

Figure-3 Snapshot of voltage waveforms along with harmonic contribution

Further, foot print of voltage and current waveform, extracted from FMS records along with harmonic contribution on a bar chart are shown in Fig-3 and Fig-4 respectively.

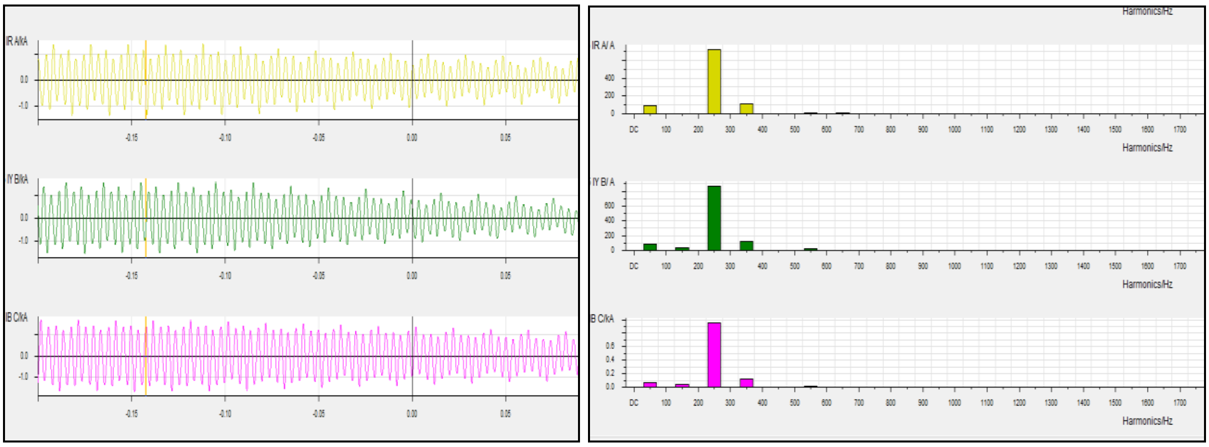

Figure-4 Snapshot of current waveforms along with harmonic contribution

These trends clearly show that 5th harmonic increased at the same time 22 kV voltage exponentially, which suggests that system resonance that has caused voltage rise at the consumer side was caused by the 5th harmonic.

4 Theoretical basis and analysis:

This section focuses on the fundamentals of harmonic resonances phenomena in electrical networks. There is the possibility of either series or parallel resonance, depending on the network configuration and system operating conditions. Based on these parallel and series resonances, the harmonic voltages and currents are amplified and can damage system elements especially on LV network.

The charging capacitance associated with the HV/MV cables and shunt capacitors, if any, are normally seen as an equivalent capacitance C in parallel with the system, while the network series line, generator and transformer impedances, normally inductive, are seen as an equivalent series reactance L. The load and resistance of the line, transformers and cables are seen as the equivalent R or damping element in the system.

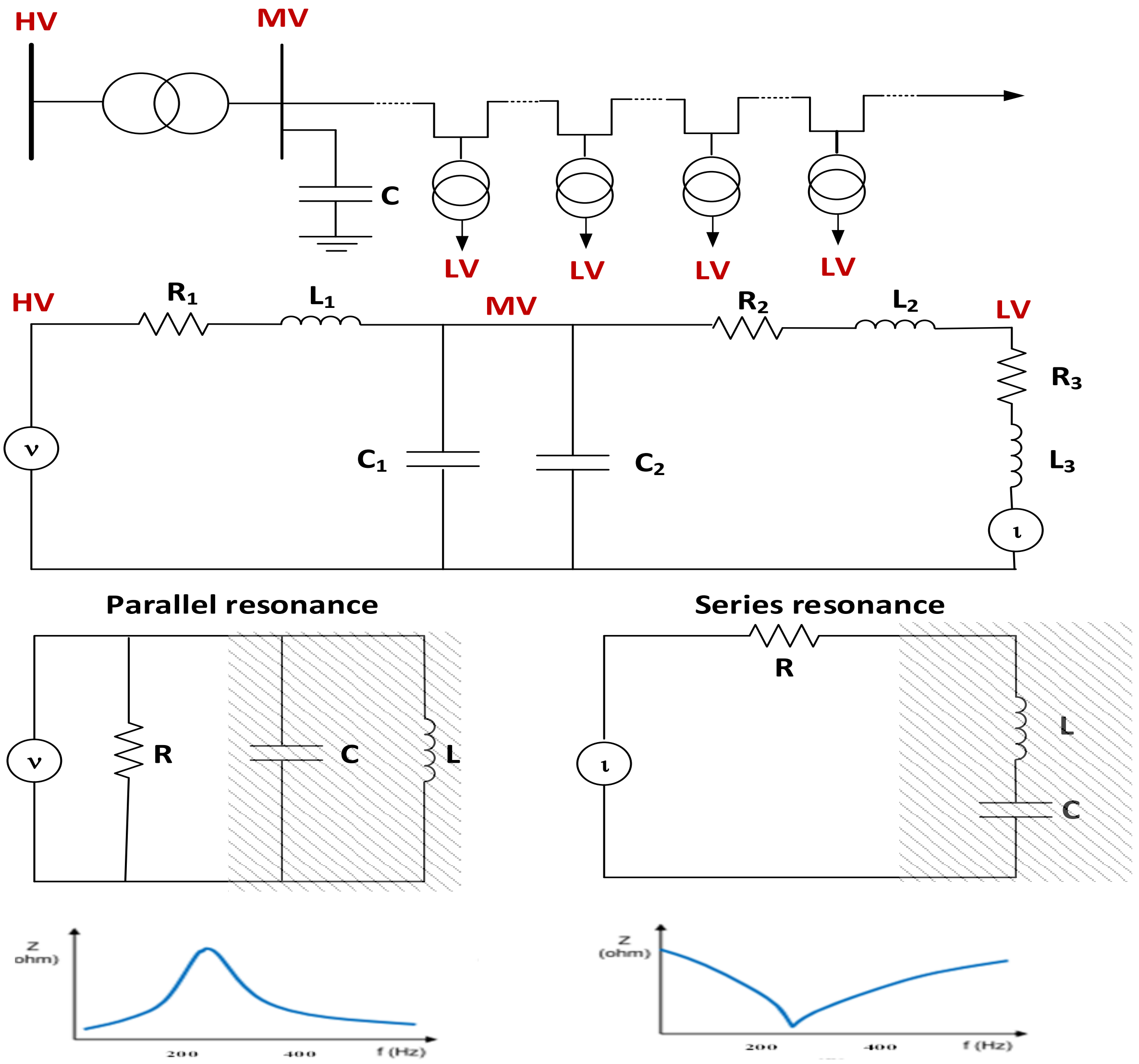

Figure 5: The combined effect of parallel and series resonance in a lightly loaded network at fifth harmonic resonant condition.

Resonance phenomena depicted in Figure-5, can be divided into parallel or series resonance. A parallel resonance is characterized as a high impedance to the flow of harmonic currents at the resonance frequency. In this case, the impedance at the resonance is high, resulting in higher voltage distortion at the Point of Common Coupling (PCC), or where the equipment and load is connected.

A series resonance is characterized as low impedance for harmonic currents at the resonance frequency. In such cases, the impedance at the resonance is low, resulting in higher current distortion through the load, cable capacitance or capacitor bank installations. In real life scenario these two phenomenons are linked in one circuit, resulting in both increased levels in the voltage, and current distortions.

System loading (active and reactive) can have a significant impact on the system frequency response, especially at lower frequency resonance points. At low frequencies, the transformer series reactance is small compared to the load impedance, but at higher frequencies, this reactance becomes large compared to the load, thus decoupling the load from the system impedance. The active portion of the system load affects mainly the system damping at lower resonance frequencies. The series and parallel resonance can be calculated at the frequency f_r, in the following equation:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

where, f_r is the resonance frequency, L and C the equivalent reactance and capacitance in the series or parallel network. If one of the existing harmonics in the network corresponds with the parallel resonance frequency, very high resonance voltages, damped only by the associated network and load resistances, will occur at PCC. This may have operational effects on the network and other equipment connected to the system. Harmonic impedance of the network is influenced by inductive line impedances and the charging capacitance of the cable networks/ capacitor banks. These two main reactive components (L and C) determine possible resonant points in the network. In the simplest form, the resonant frequency f_r is determined as shown in the following simple equation

$$f_r = f_1\sqrt{\frac{S_{sc}}{Q}} \qquad (2)$$

Where f_1 is the fundamental network frequency, S_{sc} the short-circuit power in MVA, at the point of connection, and Q the total amount of reactive power in MVAR of the cable network ($Q=1/2* CV^{\wedge 2}$). In this simple equation, there is no resistive network damping considered. In practical networks, resistive damping in the lines, transformers and loads, limits the resonance and harmonic impedance amplification above the characteristic network impedance. Figure-6 depicts the locus of resonant frequency based on system MVAR loading for S_{sc} = 274 MVA.

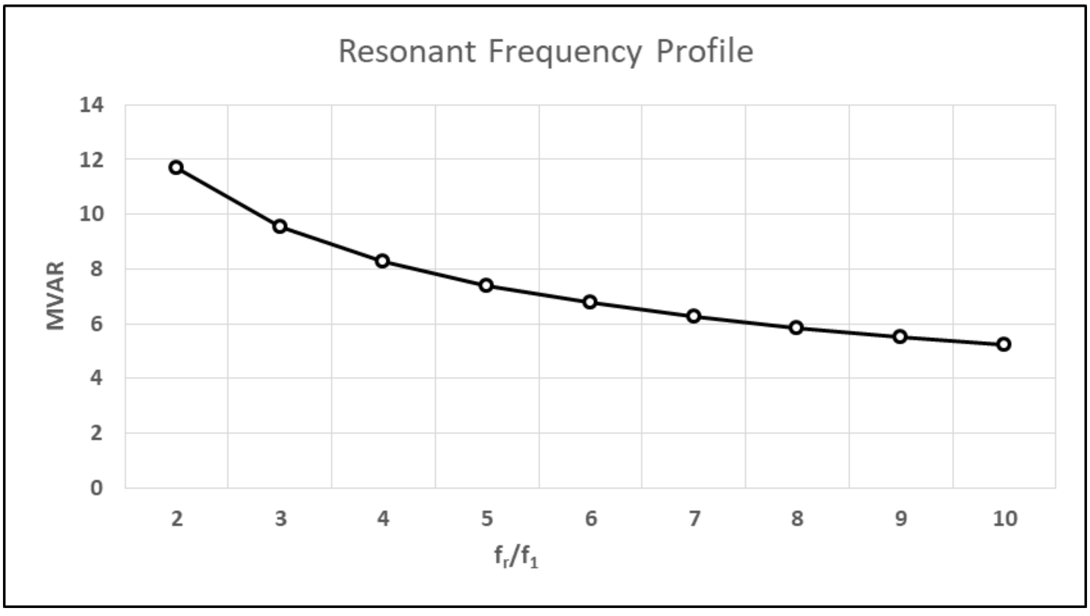

Figure 6: Resonant frequency locus for varying MVAR load

5 Conclusions:

The measurement and analysis carried out clearly establishes that very lightly loaded MV networks are susceptible to harmonic resonance, which could have a runaway effect under certain operating conditions, causing severe damage to the end user equipment. A particularly severe and most likely scenario is the fifth harmonic resonance, discussed in this paper.

Transformer’s fast automatic voltage regulation can help to some extent but the resonant conditions can persist even after the minimum tap position is reached during operations. Cost-effective mitigation solution for this phenomenon is to change the system frequency response characteristics under all potential operating conditions. This can be achieved by proper network design, system element specifications and timely operational interventions.

Possibility of such a phenomenon should be factored in at design stage, through a network model analysis and arrive at an optimum load profile for each phase of development to avoid conditions that can result in harmonic resonance. For existing networks, smart load management, protection system support and online monitoring should be effectively used.

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