NOKIAN CAPACITORS
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Harmonics and Reactive Power Compensation in Practice

1. General

Harmonics in utility and industrial networks have an increasing trend all over the world. This is clearly related to the increasing use of non-linear loads and devices in industry and in commercial buildings. These non-linear devices are often thyristor or diode rectifiers, which thus contribute to the deterioration of the power quality in the networks, can be found for example in the following applications:

- in variable speed drives (VSD)
    - for manufacturing and process industry
    - for inductive heating in metal industry
    - for lifts and air-condition pumps and fans in commercial buildings
- in uninteruptable power supplies (UPS) for computers and other essential loads in commercial and industrial buildings
- in computers and in other office equipment

In figure 1 there is a typical DC-drive with 6-pulse thyristor rectifier and in figure 2 a typical voltage source inverter drive with 6-pulse diode rectifier. Same rectifiers can be found also in uninterruptible power supplies (UPS).

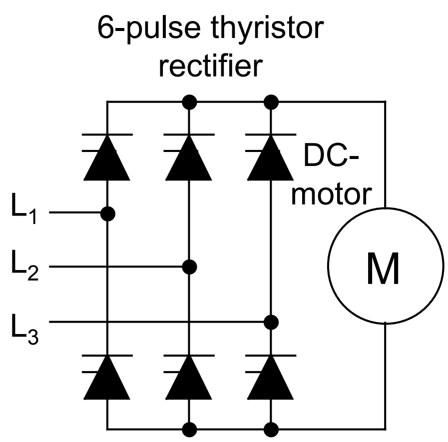


Figure 1. Typical DC-drive with 6-pulse thyristor rectifier.

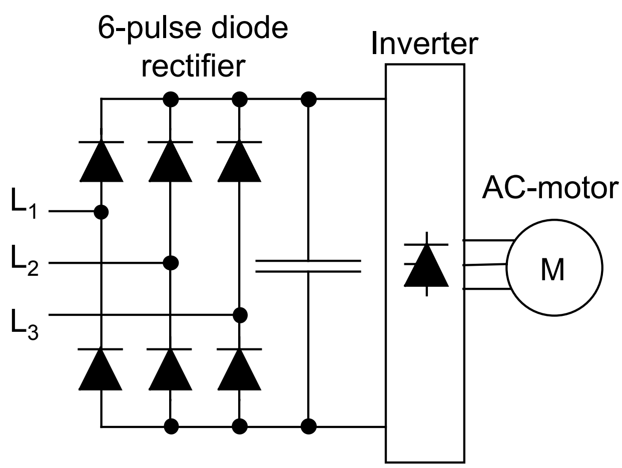


Figure 2. Typical voltage source inverter drive with 6-pulse diode rectifier.

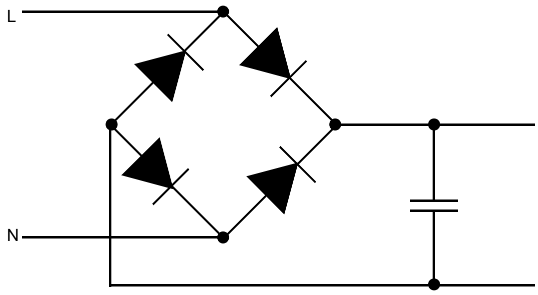


Figure 3. One phase rectifier used for Switch Mode Power Supplies.

In figure 3 there is one phase rectifier with capacitive smoothing used for Switch Mode Power Supplies. This kind of power supplies are widely used in computers, monitors and in many other electronic equipment.

Rectifiers produce harmonic currents having following harmonic orders or frequencies:

$$n = \frac{f_n}{f_f} = k \cdot p \pm 1$$

where:

f_n = frequency of the harmonic current
f_f = fundamental frequency of the system
n = order of the harmonic
k = 1,2,3,....
p = pulse number of the rectifier

If the rectifier is connected into an unlimited bus the amplitudes of the harmonic currents can be calculated as follows:

$$I_n = \frac{I_1}{n} \qquad (2)$$

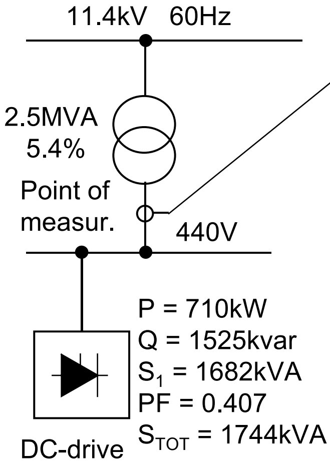
where:

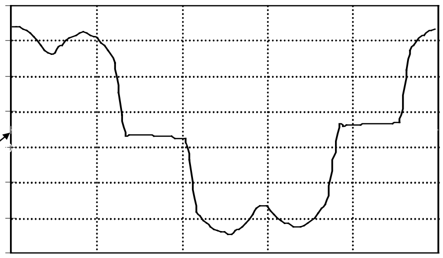
I_n = amplitude of the harmonic current order “n”
I_1 = fundamental current of the rectifier
n = order of the harmonic

However in real networks harmonic currents can have significantly higher amplitudes than calculated with formula (2) above. In next chapter there are some measured harmonic currents of different kind of rectifiers.

1.1 Harmonic currents in real networks

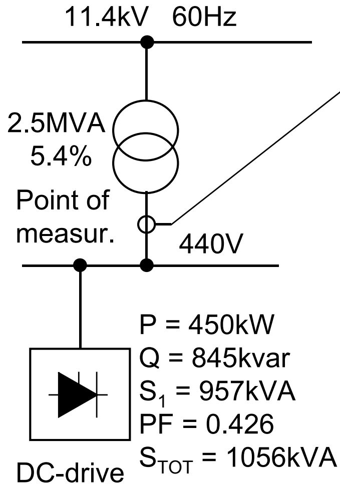
In figure 4 the are measured AC-side fundamental and harmonic currents of a DC-drive with its load information. As can be seen the 5th harmonic is in this case 28% corresponding to 632A of the fundamental whereas its theoretical value according to formula 2 is 20%.

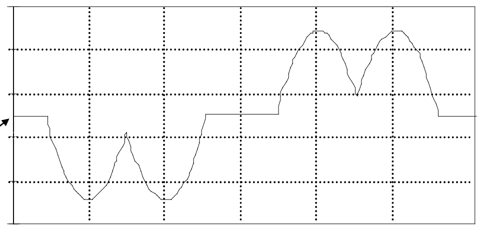




Order of harmonic	Supply current	
	A	%
1	2261	100
5	632	28
7	78	4
11	147	7
13	41	2

Figure 4. Fundamental and harmonic currents of a DC-drive with high load.





Order of harmonic	Supply current	
	A	%
1	1255	100
5	515	41
7	122	10
11	108	9
13	28	2

Figure 5. Fundamental and harmonic currents of a DC-drive with low load.

In figure 5 there is the same DC-drive than in figure 4 but now with lower load. Fundamental current is decreased from 2261A to 1255A. However the percentages of the harmonics are clearly increased. For example the 5th harmonic current is now 41% of the fundamental current corresponding to 515A. However it should be noted that absolute values of the harmonic currents are higher under high load situation.

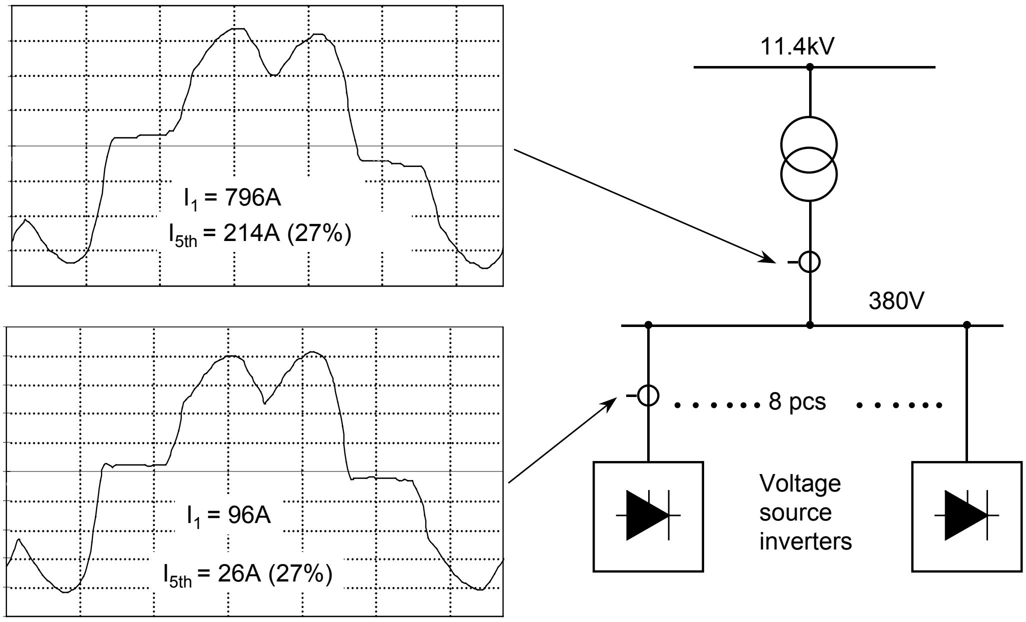


Figure 6. Measured currents of voltage source inverters.

In figure 6 there are 8 sets of voltage source inverters connected to 380V network. To demonstrate that harmonics of this type inverters add arithmetically measurement was first made at one of the inverters and then at the main feeder. As can be seen 5th harmonic at the main is 8 times higher corresponding to the number of the inverters.

In figure 7 there is the typical current drawn by one phase rectifier with capacitive smoothing. Harmonic content of this kind of current is very high.

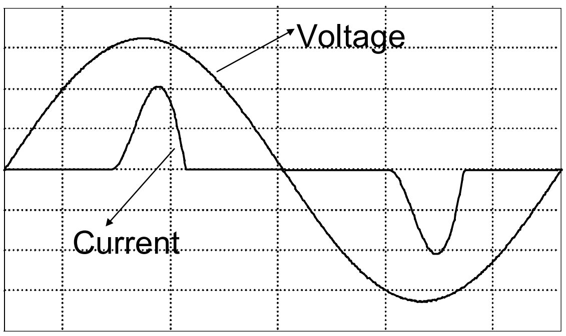


Figure 7. Current drawn by one phase rectifier with capacitive smoothing

Typical harmonic components are 3rd ~ 80%, 5th ~ 60%, 7th ~ 45% and 9th ~ 35%.

It should be noted that zero sequence harmonics accumulates in the neural wire. These zero sequence currents in neutral wire may reach values bigger than currents in each phase.

2. Effects of Harmonics

2.1 Transformers

Harmonic currents cause an increase in copper losses and stray flux losses. Harmonic voltages cause an increase in iron losses. The overall effect is a higher temperature rise, as compared to purely fundamental sinusoidal current and voltage operation. It shall be noted that these additional losses due to harmonics will rise in proportion to the square of the current and frequency, resulting in decreased fundamental loading capacity of the transformer. When selecting correct rated power for the transformer to supply non-linear loads, an adequate derating should be made to ensure that the temperature rise of the transformer will remain within permissible limits. Also it should be kept in mind that all additional losses due to the harmonics will be paid by the customers in terms of kilowatt hours consumed. Harmonics applied to the transformer can also lead to increased audible noise.

2.2 Power Cables

Non-sinusodial currents in conductors will cause more heating than that what would be expected for the RMS value of the waveform. This additional heating is caused by two phenomena known as skin effect and proximity effect, both of which depend on frequency as well as conductor size and spacing. These two effects result as an increased ac resistance, which in turn leads to increased $I^2 \times R_{AC}$ losses.

2.3 Motors and Generators

The main effect of the harmonic currents and voltages in rotating induction and synchronous machinery is increased heating caused by the iron and copper losses at harmonic frequencies. These additional losses lead to decreased machine efficiency and can also affect the torque developed. Pulsating torque output can affect product quality in cases where motor loads are sensitive to such variations. As examples from sensitive loads some synthetic fibre spinning and some metal working applications can be mentioned.

Also in case of rotating machinery, harmonics can increase audible noise emission as compared with sinusoidal magnetisation. Harmonic pairs like 5^{th} and 7^{th} can create mechanical oscillations at 6^{th} harmonic frequency in a generator or in a motor-load system. Mechanical oscillations are caused by oscillating torque’s due to the harmonic currents and the fundamental frequency magnetic field. If the mechanical resonance frequency coincides with the electrical stimulus frequency, high mechanical forces can be developed and there is a risk of mechanical damages in the machinery.

2.4 Electronic Equipment

Power electronic equipment is sensitive to harmonic distortion of the supply voltage. This equipment is often synchronising its operation to the voltage zero crossings or to other aspects of the voltage wave shape. Harmonic distortion of the voltage can lead to the shifting of the voltage zero crossing or change the point where one phase to phase voltage becomes higher than an other phase to phase voltage. Both of these are important points for different kind of power electronic circuit controls. Misinterpretation of these points by the control systems can lead to the malfunction of the control system. Disturbances of the telecommunication equipment are also possible due to the inductive or capacitive coupling between power and telecommunication lines.

Computers and some other kind of electronic equipment like programmable controllers require usually that the total harmonic voltage distortion (THD) of the supply is less than 5% and one individual harmonic component is less than 3% of the fundamental voltage. Higher distortion values may result in misoperation of the control equipment, which in turn can lead to production and process interruptions, which can have high economical consequences.

2.5 Switchgear and Relaying

Like in other type of equipment too harmonic currents cause also in switchgear additional losses leading to increased heating and reduced fundamental current carrying capability. An increased temperature of some insulating components results in shortening of their lifetime.

Older solid-state tripping devices on low voltage circuit breakers have responded to the peak currents. This type of tripping devices may cause nuisance tripping in feeders supplying non-linear loads. New tripping devices respond to the RMS values of the current.

The response of the protective relays to the distortion depends a lot on the measuring principle used and there is no any common rules which could be used to describe what is the impact of harmonics on large variety of the relays. However it can be said that normal harmonic distortion levels in networks do not cause problems in relay operation.

2.6 Power Factor Correction Capacitors

Capacitors differ from other type of equipment due to its capacitive nature, which can dramatically change the system impedance under system resonant condition. The reactance of a capacitor bank decreases with the higher frequencies, and therefore, bank acts as a sink for higher harmonic currents. This effect increases the heating and dielectric stress of the insulation material. Frequent switching of non-linear magnetic components like transformers can produce harmonic currents, which will add to the loading of the capacitors. It should be noted that the fuses usually do not provide overload protection for the capacitors. The result of the increased heating and voltage stress due to harmonics is a shortened lifetime.

The major concern arising from the use of capacitors in power systems is the possibility of the system resonance. This effect leads to harmonic voltages and currents that are considerably higher than they would be in the case without resonance.

2.6.1 Harmonics and Parallel Resonance

Harmonic currents produced for example by variable speed drives can be amplified up to 10-15 times in parallel resonance circuit formed by the capacitance of the capacitor bank and the network inductance.

Amplified harmonic currents through the capacitors can lead to internal over heating of the capacitor unit. Please note that currents having higher frequency than fundamental frequency cause more losses than 50Hz current having same amplitude. An example of parallel resonance circuit with its equivalent circuit is shown in figure 8.

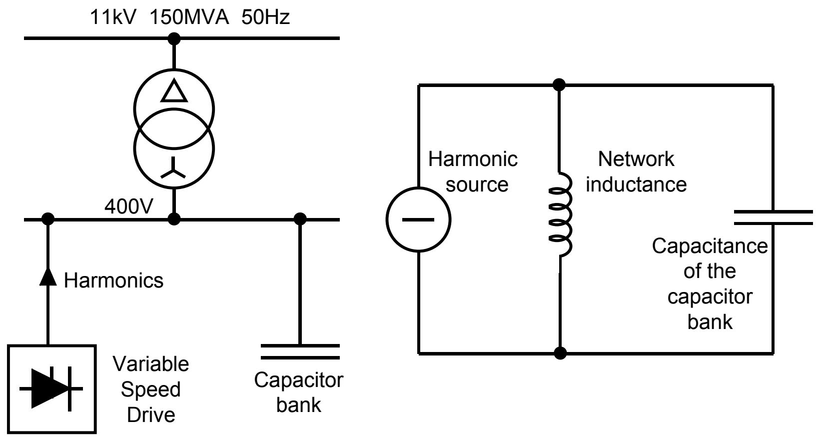


Figure 8. Parallel resonance circuit and its equivalent circuit.

2.6.2 Harmonics and Series Resonance

In case the voltage of the upstream network is distorted the series resonance circuit, formed by capacitance of the capacitor bank and the short circuit inductance of the supplying transformer, can draw high harmonic currents through the capacitors. Series resonance can lead to high voltage distortion levels at low voltage side of the transformer. For an example of series resonance circuit please refer to figure 9.

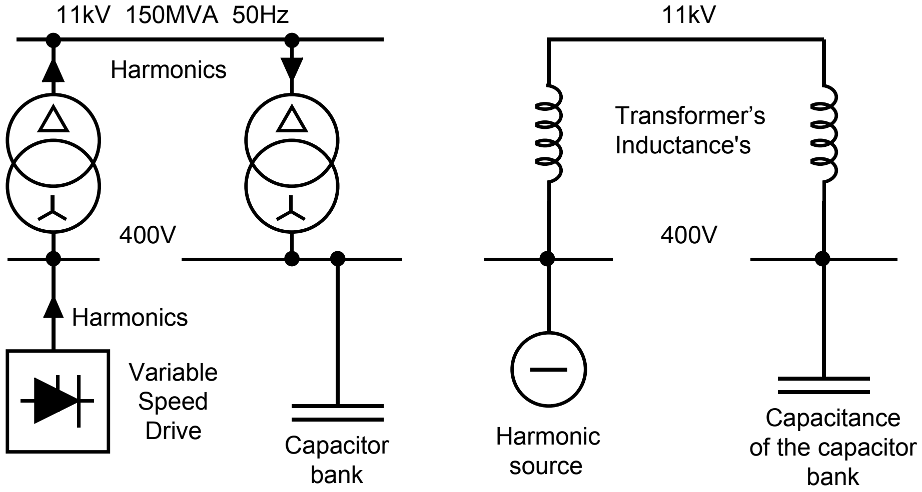


Figure 9. Series resonance circuit and its equivalent circuit.

2.6.3 Recommendations.

Whenever there is unlinear load (dc-drives, inverters, UPS, all kind of rectifier, etc.) connected to the bus at which capacitor bank is intended to be used care should be taken when designing reactive power compensation system.

To avoid parallel or series resonance at low voltage level filter or blocking type capacitor banks should be used.

In cases where there are harmonic limits imposed by the utility or generating authorities quite often filter capacitor bank turns out to be necessary to meet requirements like stated for example in IEEE standard 519-1992 or in Engineering Recommendation G5/3. For typical filter capacitor bank arrangements where there are 3 tuned branches for 5^{th}, 7^{th} and 11^{th} harmonic please refer to figure 10. The number of tuned branches depends on the harmonics to be absorbed and on required reactive power to be compensated. In some cases even one tuned branch might be enough to reach desired voltage distortion and target power factor.

To be able to design filter capacitor bank harmonic producing load should be identified and at existing plants harmonic measurement is desirable.

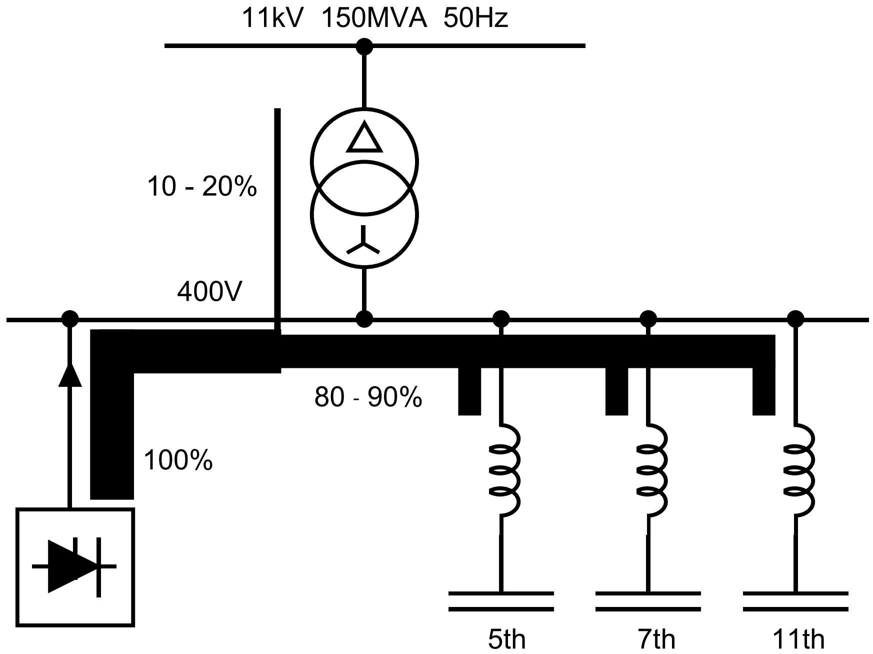


Figure 10. Reactive power compensation with filter capacitor banks.

According to IEEE 519-1992 individual voltage distortion is allowed to be 3% of the fundamental. If for example at some bus non-linear load has caused an individual voltage distortion which has been measured to be less than 3% without capacitors, it may lead to assumption that any kind of electrical equipment could be connected at the same bus without any concern. Please note however, that whenever capacitor bank without any reactors is connected at such bus, there will be a certain parallel and series resonance frequency. If this resonance frequency coincides with some harmonic frequency, significant amplification of harmonic currents and voltage distortion will take place.

In cases where there are no harmonic limits blocking type capacitors can be used. However it should be kept in mind that major part of the harmonics is then injected into the upstream network. For typical blocking type capacitor bank please refer to fig 11. The required number of steps depends on load power factor and target power factor. For the design of blocking capacitor bank voltage distortion limits are usually given. Typical values for low voltage could be for example: U3rd = 0,5% U5th = 5% and U7th = 5%.

Typical detuning frequencies are 204hz corresponding to 6% reactor and 189hz corresponding to 7% reactor respectively. The use of 7% reactors allows normally more non-linear load to be connected than the use of 6% reactors. The linearity of the iron core of the reactor should be designed so that saturation is not possible with inrush current and at rated voltage distortion.

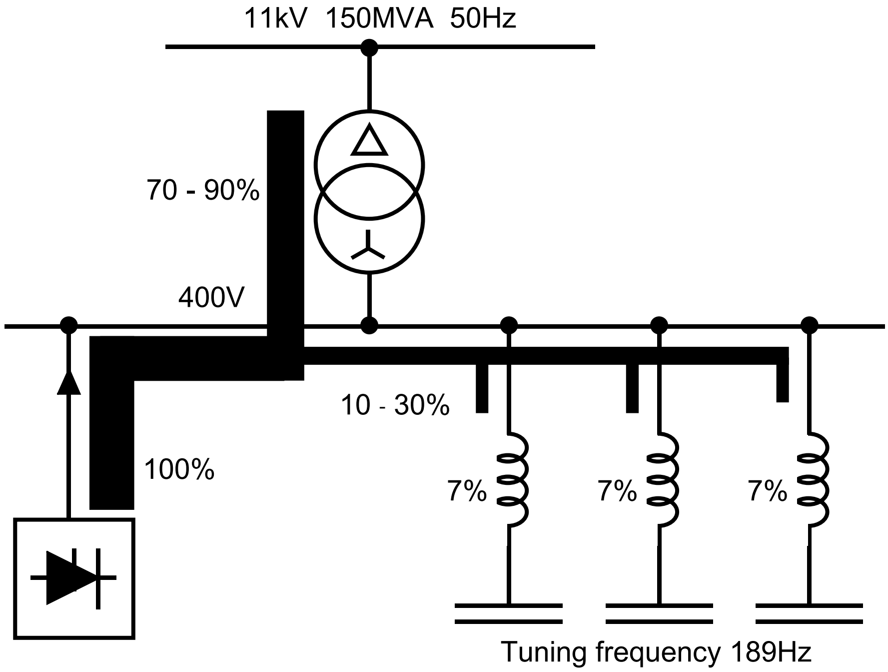


Figure 11. Reactive power compensation with blocking capacitor banks.

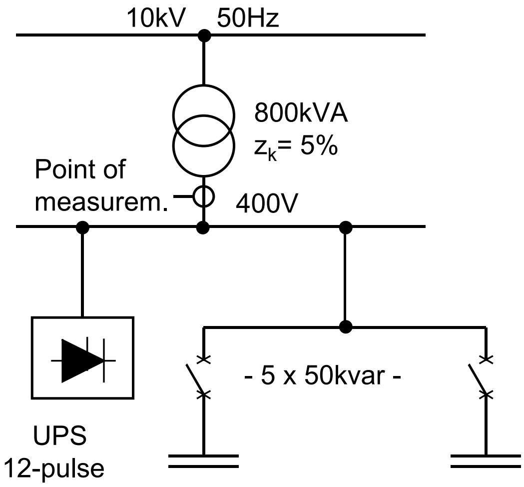
When designing reactive power compensation system, for example for a new commercial building, the use the capacitor units having higher rated voltage than system voltage (for example 525V units in 400V system) is quite often justified if it is not known what kind of load will come with the tenants. The use of higher rated units enables reactors to be added later on if it turns out that load will produce harmonics.

Whenever there is a doubt that ambient temperature of the capacitor units may exceed upper limit of their temperature category it is advisable to use cooling fans in capacitor cubicles. Please note also that in cases where blocking or filter reactors are used forced cooling should always be used since the reactors are causing a lot more losses than capacitor units.

3. Documented Power System Harmonic Resonance Cases and Problem Solutions

3.1 Case 1

In a rather big office building many capacitor units were reported to be thermally damaged. Failed units were found in automatically controlled capacitor banks connected on transformers supplying UPS equipment for computers. Harmonic measurements were made to find out reason for damages. In figure 12 there are measured fundamental and harmonic currents of the supplying transformer as well as measured total harmonic distortion (T.H.D.) of the voltage. As can be seen there is heavy resonance at 11th harmonic when two 50kvar steps are on causing the 11th harmonic current of 30A (produced by the UPS) to be amplified to 283A corresponding to an amplification factor of approximately 10. Please note also that T.H.D. of the voltage has increased to 19.6%.

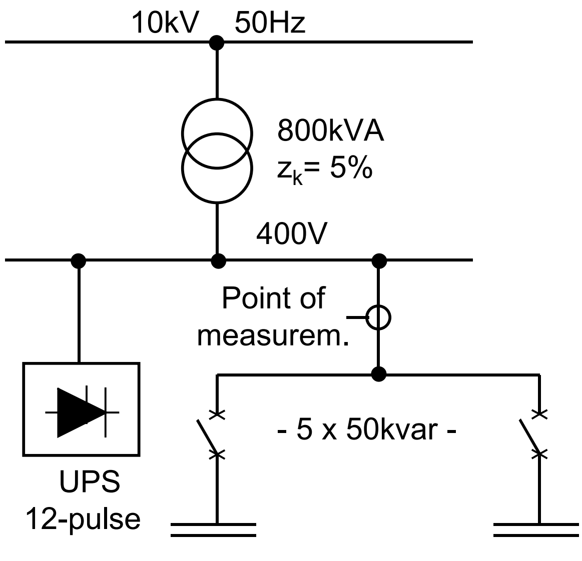


Order of harmonic	Supply current		
	0 kvar A	50kvar A	100kvar A
1	600	538	512
5	10	8	11
7	4	5	9
11	30	62	283
13	6	9	44
17	2	8	2

THD(V)	3.8%	5.9%	19.6%

Figure 12. Measured supply current in case 1. Capacitors without reactors.

In fig 13 there are measurement results of the capacitor bank current. The RMS current of the capacitor bank was 364A with two steps on corresponding to 2.5 times rated current thus the reason for damages was revealed. According to IEC 60831-1 (Standard for Low Voltage Capacitors) the permissible current for capacitors is 1.3 times rated current.

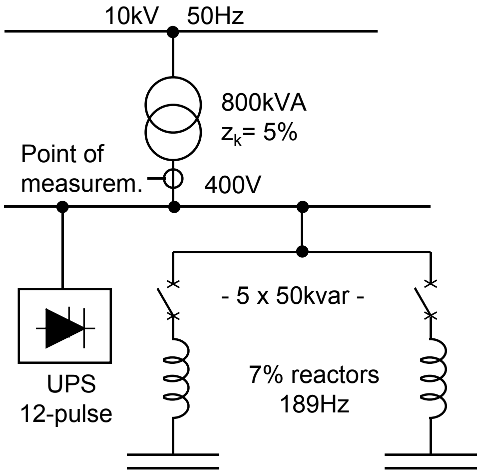


Order of harm.	Current of the capacitor bank	
	50kvar on A	100kvar on A
1	70	142
5	4	11
7	2	4
11	36	327
13	16	69
17	9	3

I_{RMS}/A	83	364

Figure 13. Measured capacitor bank current without reactors for case 1.

Since the harmonic measurements confirmed that there has been a resonance in the power system the reactive power compensation system was redesigned and the decision was made to use blocking capacitor banks with 7% reactors. In fig 14 there are measurement results of the supply current and the THD of the voltage when the new capacitor bank with 7% reactors was commissioned.

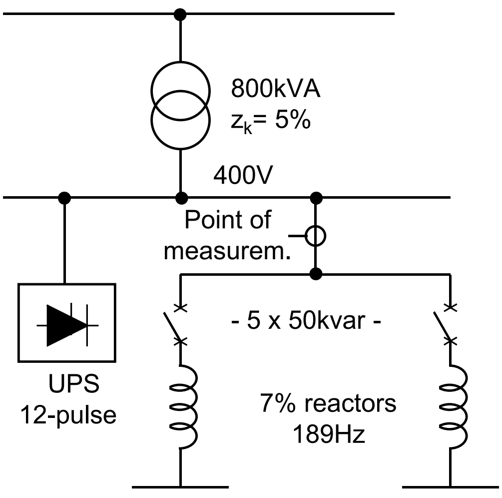


Order of harmonic	Supply current		
	0kvar A	50kvar A	100kvar A
1	773	735	691
5	13	17	20
7	7	6	5
11	45	42	40
13	16	15	14
THD(V)	6.4%	6.0%	5.7%

Figure 14. Measured supply current in case 1 with new blocking capacitor bank.

Please note that with this new capacitor bank resonance can be avoided with any number of steps connected on thus there is no any amplification of the harmonic currents. To verify the new design commissioning of the new bank was made under maximum non-linear load condition and the harmonic currents were found to behave like expected.

In fig 15 there are measured currents of the new blocking capacitor bank. As can be seen from the currents remain within expected values with any numbers of steps connected on.



Order of harmonic	Current of the capacitor bank		
	50kvar A	100kvar A	150kvar A
1	75	151	227
5	5	10	13
7	1	1	1
11	3	6	8
13	1	2	3
RMS / A	75.2	51.5	227.6

Figure 15. Measured capacitor bank current with reactors for case 1.

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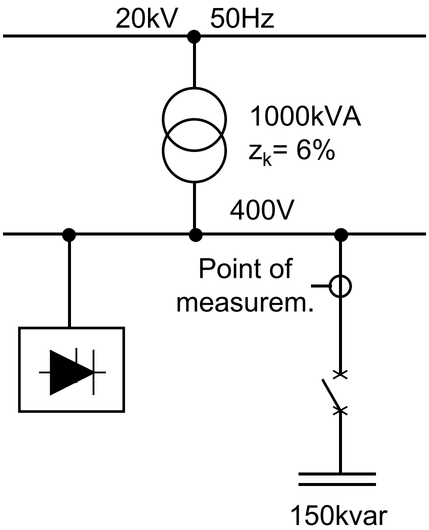
3.2 Case 2

The one line diagram in fig 16 is an extract from the whole supply system of a plastic moulding company. The fixed 150kvar capacitor bank had suffered several failures but kept in service changing time to time failing units. To find out reason for continuous failures a harmonic measurement was carried out with the results as shown in fig 9. The RMS current of the capacitor bank was measured to be 371A main harmonic component being the 11th harmonic. Measured RMS current corresponds to the 1.71 times rated current, which certainly explains why capacitors kept failing. Since the voltage T.H.D., even without capacitors, turned out to be as high as 8.1%, the company is now considering to use filter capacitor banks for reactive power compensation to be able to maintain good power quality for all equipment.



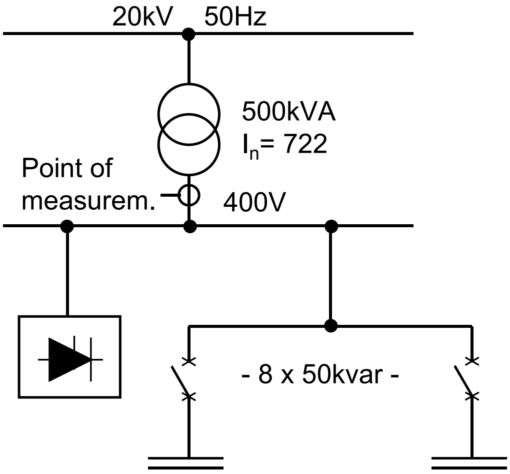
Order of harmonic	Capacitor current I_C / A	Voltage distortion	
		With capacitor %	Without capacitor %
1	209	-	-
5	100	9.7%	7.7%
7	45	2.7%	1.3%
11	283	11.3%	2.3%
RMS	371	15.1%	8.1%

Figure 16. Measured current of the capacitor bank in case 2.

3.3 Case 3

The owner of the company purchased the capacitor bank sown in one line diagram in figure 17. His decision was based on the electricity bill only according to which he was paying penalty for poor power factor. Altogether 400kvar were needed to improve power factor up to the penalty limit.
The measurement during the commissioning of the capacitor bank revealed that 500kVA transformer supplying the factory was slightly overloaded and 5th harmonic current was 62A being 9% of the fundamental. When capacitor bank was connected on fundamental current decreased to 492A because reactive power was compensated but 5th harmonic current was amplified to 456A being now 93% of the fundamental and the THD of the voltage increased to 16.2% being totally unacceptable for the supply of the load.

Capacitor bank was switched off and its replacement with blocking type capacitor bank was put on the way.



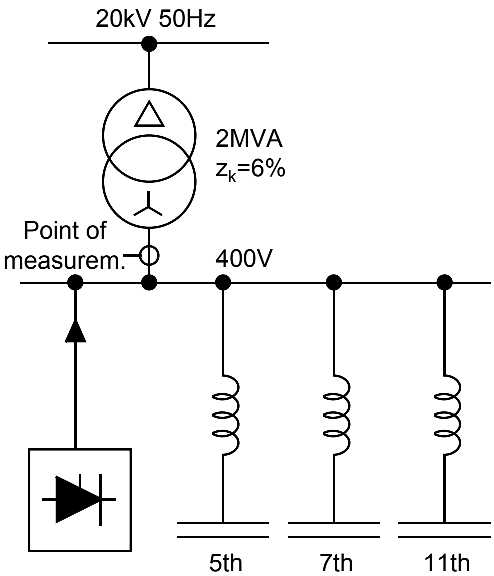
Order of harmonic	Supply current			
	Without capacitors		With 400kvar	
	A	%	A	%
1	772	100	492	100
5	62	9	456	93
RMS current	774	100.4	671	136
THD voltage		5.6		16.2

Figure 17. Measured supply current for case 3.

3.4 Case 4

In this case measurements were made to determine what kind of reactive power compensation system would be needed to improve power factor up to penalty limit. As can be seen from the measurement results the voltage was heavily distorted and the voltage THD was measured to be 12%.

It was evident that capacitor bank without reactors could not be used. Due to the high voltage distortion the decision was made to use filter capacitor banks for reactive power compensation.



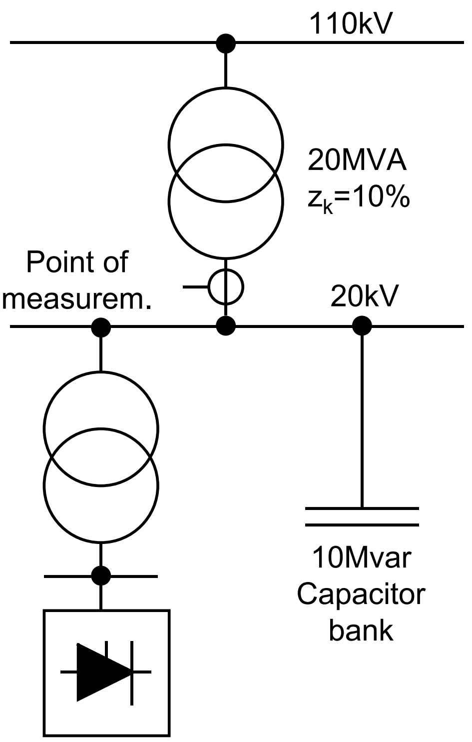
Order of harm.	Supply current			
	Filters off A	5th on A	5th,7th on A	All on A
1	1387	1065	956	860
5	402	51	51	52
7	44	57	1	2
11	245	193	77	10
THD(V)	12.0%	5.4%	3.0%	2.0%

Figure 18. Measured supply current and voltage THD for case 4.

In fig 18 there are measurement results which were obtained during the commissioning of the filter capacitor banks. When all filters were connected on the voltage THD decreased from 12% to 2% only which is considered to be very good value for a low voltage supply system. Please note also a significant decrease of the fundamental supply current by approximately 520A due to compensated reactive power. Also harmonic currents have been absorbed effectively and supply current met the specified harmonic limits.

3.5 Case 5

In fig 19 there is an extract from a big paper mill supply system with a 10Mvar 20kV capacitor bank which was suffering from time to time nuisance tripping by the over current relay. Harmonic measurement showed abnormal high voltage distortion of 10.8% at 20kV bus and the 5th harmonic current in the supply was 135A.



Order of harmonic	Supply current			
	Without Capacitor		With Capacitor	
	A	%	A	%
1	435	100	355	100
5	6	1.4	135	38
THD(V)		1.5%		10.8%

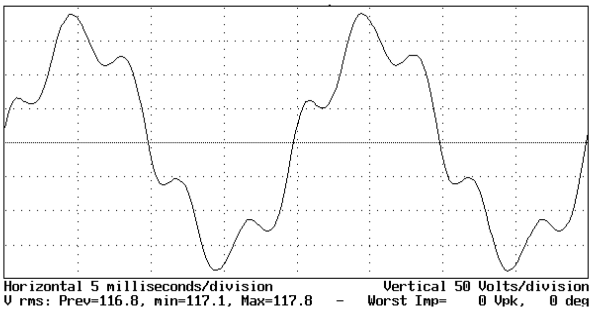
Figure 19. Measured supply current and voltage THD for case 5.

When capacitor bank was switched off the voltage distortion decreased to 1.2% and 5th harmonic current in the supply was 6A only. In this medium voltage resonance case amplification factor reached a high value of approximately 22. This capacitor bank was redesigned taking into account harmonic currents produced by the DC-drives of the paper machine. After computer simulations with several possible network configurations, the 5th harmonic filter turned out to be the best solution.

Modification of the capacitor bank was made by increasing its rated voltage by adding one more capacitor unit in series with existing units and installing air core filter reactors.

3.6 Case 6

The medium voltage networks of the utilities are considered to have a reasonably low voltage distortion. However in cases utilities are using substation capacitor banks without blocking reactors there is always the possibility of resonance if substation is supplying industrial plants having harmonic producing load.



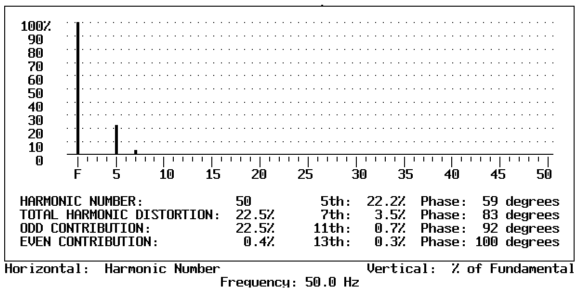


Figure 20. Voltage Curve Form at a Utility 11kV Substation and its Harmonic content

In fig 20 there is measured voltage curve form at 11kV bus of a substation where installed capacitor banks did not incorporate blocking reactors. As can be seen voltage is heavily distorted due to the resonance and 5^{th} harmonic voltage component was measured to be 22.2% of the fundamental. If this voltage is supplying a MV / LV transformer where there are capacitors on low voltage the series resonance circuit formed by capacitance of the capacitor bank and the short circuit inductance of the supplying transformer can draw high harmonic currents through the capacitors.

3.7 Case 7

In fig 21 there are measured voltage THD values over a period of 20 hours at a 11.4kV utility bus supplying several small and medium size industries. It was evident that utility capacitor banks caused the harmonics produced by the non-linear loads at the factories to be amplified. The harmonic measurements were initiated due to the information that at one plant installed LV side filter capacitor banks were suffering time to time nuisance tripping. Harmonic analysis revealed that the distortion was mainly consisting of 5^{th} harmonic with a maximum value of 8.1% during the measurement period exceeding clearly the 3% limit stated by the utility.

Calculations were made using measured distortion values and they resulted in RMS currents in LV side filters, which clearly exceeded setting of the thermal over current relay of the 5th filter. If action is not taken to remove the resonance in the 11.4kV system filters at LV should be modified to be blocking capacitor banks with 6% or 7% reactors which will result in higher harmonic currents to the utility system contributing to the further deterioration of the 11.4kV power quality.

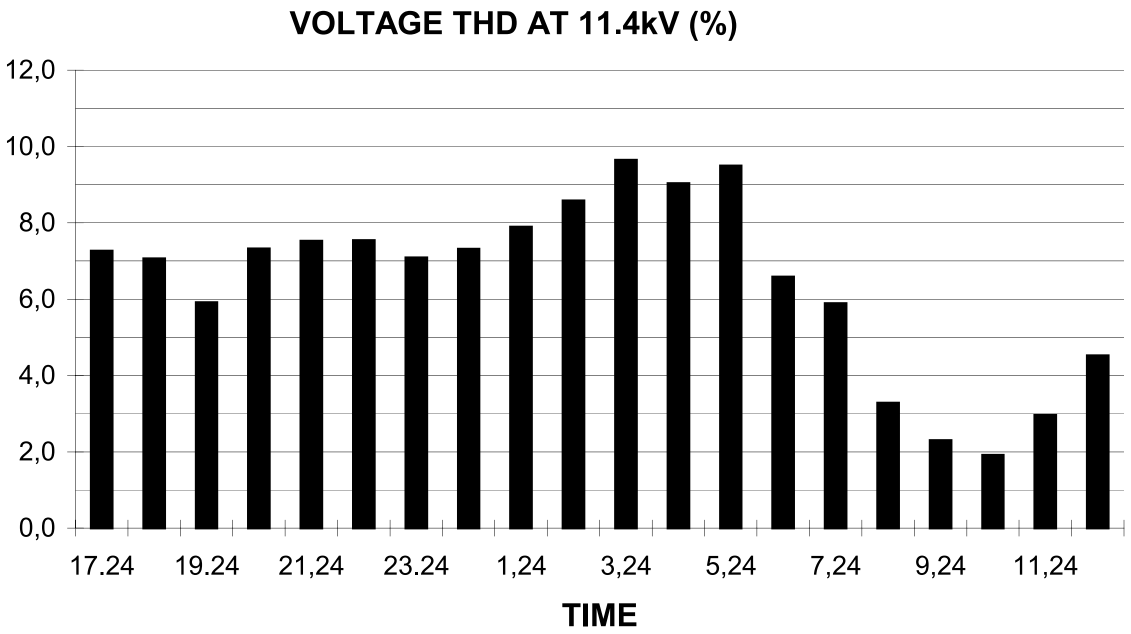


Figure 21. Measured Voltage THD of a Utility 11.4kV System for Case 7

3.8 Case 8

In fig 22 there is the one line diagram of a utility substation supplying 7 factories. On transformers TR1 -TR6 the load consists partly of non-linear loads but on transformer TR7 there is normal AC load only. Reactive power compensation was made using automatically controlled capacitor banks without any reactors. The manufacturer of the capacitor banks was informed that several capacitor units and fuse bases were thermally damaged on some transformers. A harmonic measurement was carried out and voltage distortion values on some transformers are shown in fig 15. Please note that TR7 is also suffering poor power quality due to the 5% distortion on 20kV utility bus.

While redesigning the reactive power compensation systems for the factories, the decision was made that harmonic currents shall be absorbed on the transformers they are produced thus harmonic filters should be used. The reactive power, number of branches and tuning frequencies of the filter capacitor banks were designed according to load on each transformer. Of course there was no need to replace existing capacitor bank on transformer TR7 because there was linear load only.

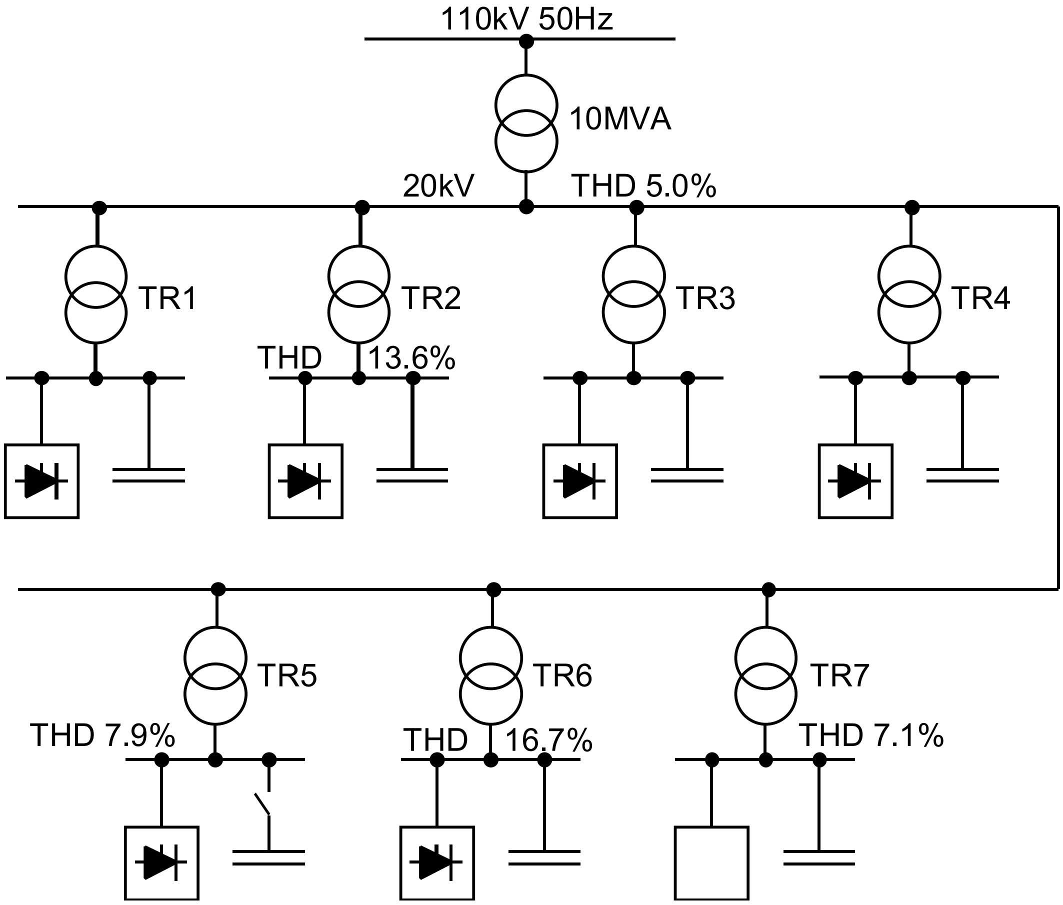


Figure 22. One line diagram for case 8 with measured voltage THD values. Capacitor banks without reactors

In figure 23 there is the one line diagram after existing capacitor banks on transformers TR1 -TR6 were replaced by the filter capacitor banks. As can be seen the measured distortion values remains within very low values since harmonics are effectively absorbed there were they are produced.

Please note also that the power quality on transformer TR7 is now well within the limits since filters on LV side of the transformers TR1 -TR6 have reduced harmonic emission to the 20kV network decreasing voltage distortion from 5% to 0.8%.

This case clearly demonstrates the important role of the utility in maintaining sufficient power quality for all customers.

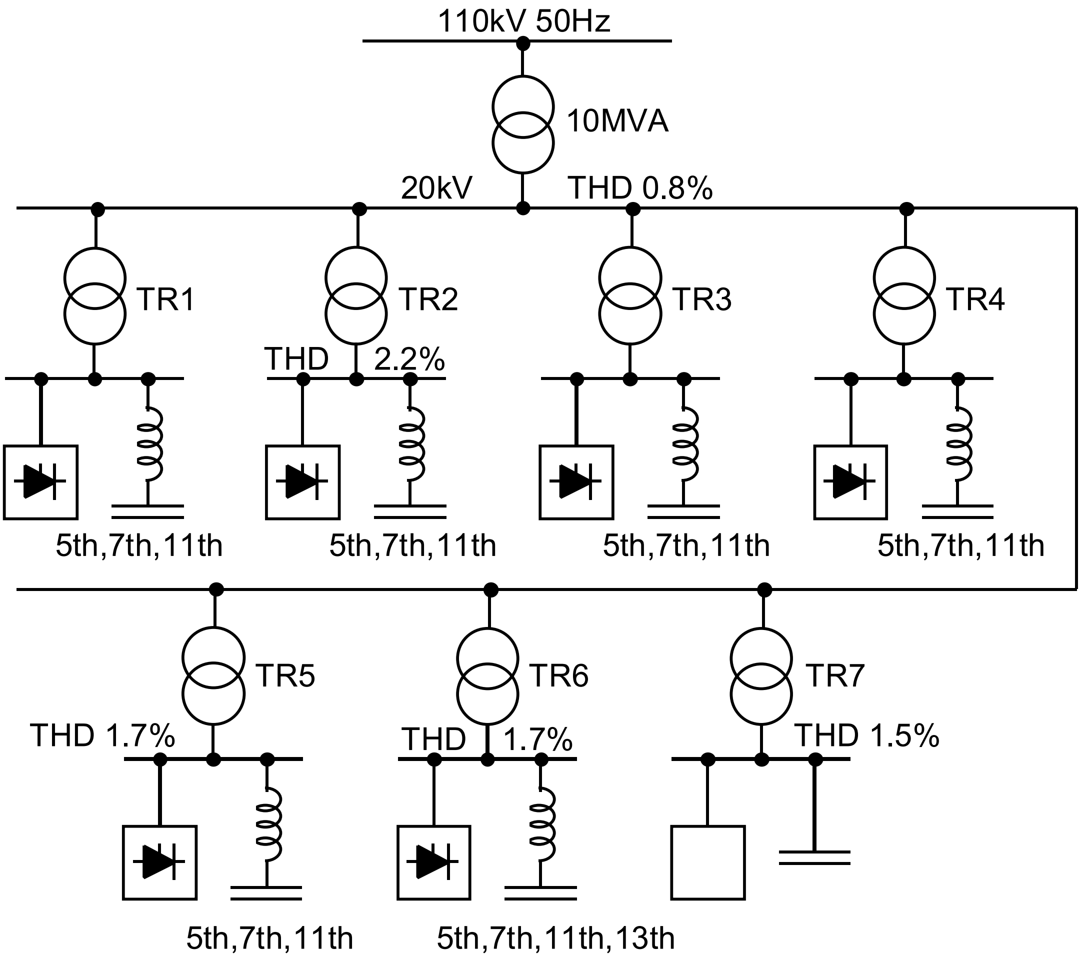
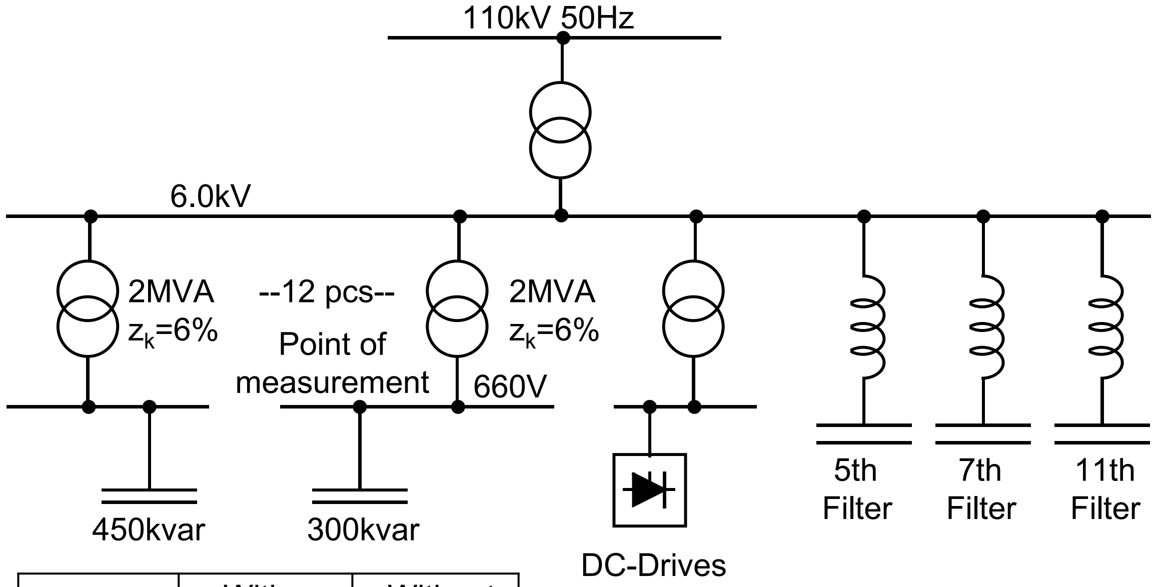


Figure 23. One line diagram for case 8 with measured voltage THD values with filter capacitor banks.

3.9 Case 9

This case deals with a series resonance circuit formed by a process transformer and a 300kvar 660V capacitor bank. In figure 24 there is an extract from a big paper mill supply system with 6kV harmonic filters tuned for 5^{th}, 7^{th} and 11^{th} harmonic. A voltage distortion measurement was made at LV side of one of the 12 process transformers having a fixed 300kvar capacitor bank. According to measurement results voltage distortion was 1.94% only when 6kV filters were on but increased to 7.15% when filters were switched off. The increase of the voltage distortion clearly verifies the series resonance and also the fact that harmonics can proliferate through MV network to the LV side of other transformers. In this kind of series resonance circuit the voltage distortion is caused in the short circuit impedance of the transformer by the harmonic currents flowing from MV network through to the transformer in to the capacitor bank.



	With Filters	Without Filters
THD(V) at 660V	1.94%	7.15%

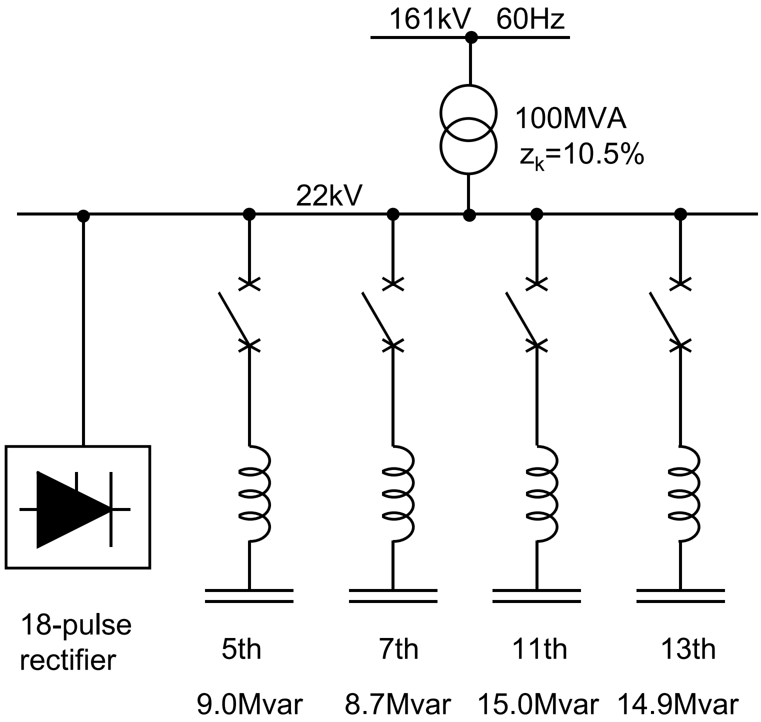
Figure 24. Measurement results for case 9 with and without 6kV filters.

3.10 Case 10

In case 10 Nokian Capacitor was asked to design and deliver harmonic filters for big chemical plant involving 18-pulse rectifier. According to customers specification 47.6Mvar at 22kV were needed to reach power factor limit imposed by the utility. The maximum total voltage distortion THD(V) at 22kV bus was to be reduced to 3%. To reach required voltage distortion four branch filter consisting of 5^{th}, 7^{th}, 11^{th} and 13^{th} filters was designed.

The total required reactive power of 47.6Mvar were divided between four branches assigning higher Mvar outputs to filters tuned for 11^{th} and 13^{th} harmonics. This arrangement resulted in lower impedance of these branches, which in turn means better absorption of higher order harmonics like 17^{th}, 19^{th} etc. In figure 25 there is the one line diagram of the system with measured voltage distortion at 22kV bus with and without filters.

As can be seen the total harmonic voltage distortion is reduced from 10.9% without filters to 1.9% when filters are connected on thus the required 3% distortion limit was clearly met.



Order of harm.	Filters off %	All filters on %
5	0.4	0.3
11	1.0	0.3
13	0.6	0.3
17	4.9	0.5
19	5.8	0.6
29	1.8	0.3
31	1.3	0.2
35	3.9	0.5
37	4.8	0.6
47	2.6	0.1
49	1.7	0.1
THD(V)	10.9	1.9

Figure 25. One line diagram for case 10 with measured voltage THD values without and with filter capacitor banks.

4. Conclusions

In most cases harmonic problems show up at the industrial plants or at the commercial customers before distortion level on the utility network reach critical values. Resonance conditions created by the use of the capacitors without reactors at the customer’s facilities will lead to high distortion on the low voltage bus where the capacitors are connected on. Problems like motor overheating, transformer heating and malfunction of the electronic equipment within the customer’s facilities are likely to occur. Therefore it is imperative for the customers to understand possible harmonic problems and take care that harmonic distortion remains within reasonable limits.

With previous documented cases it has become clear that whenever designing reactive power compensation systems harmonics should be kept in mind. Also it has been shown that there are solutions for the problems arising from harmonics. With proper design resonance situations can be avoided and possible emission limits imposed by the utility can be met.

Computer calculations allow a quick look at different network conditions and their output can be used as design data. However measurements at sites provide valuable information and their results can be used as input values for computer simulations or they can verify calculation results.