An Overview of Harmonic Analysis and Filter Selection for an Industrial Plant

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***Abstract*--This paper presents a harmonic analysis and the design and selection of harmonic filters for a hybrid cooling tower at a refinery plant. This study can be extended to any industrial plant with numerous variable speed drives (VSD). In this industrial complex, variable speed drives constitute the total load of power transformers. The harmonic analysis of the system shows that harmonic elimination with passive filters is possible only for certain current and power ranges. The studies also indicate that ferro-resonance occurs under light load conditions. This phenomenon creates over-voltages in the network and damages the equipment. The purpose of this paper is to highlight important points in the design or selection of voltage harmonic filters in industrial networks with large non-linear loads.**

***Index Terms*: Industrial plants Harmonic Analysis, Industrial plants harmonic filter design, Passive harmonic filter limitations, Harmonic elimination, Harmonic rejection, Passive Filters Resonance, Passive Filters Ferro-Resonance.**

NOMENCLATURE

VSD	Variable Speed Drive	*THD*	Total Harmonic Distortion
EMC	Electro-Magnetic Compatibility	Z_n	The total impedance of single tuned filter
EMI	Electro-Magnetic Interference	R_{SC}	Ratio Between Short Circuit Current and Load Current
AHF	Active Harmonic Filter		
PHF	Passive Harmonic Filter		
PLL	Phase Locked Loop		

I. INTRODUCTION

A VSD is an electronic device that controls key parameters like speed, torque and position of an AC motor by varying the frequency and voltage of the power supplied to the motor based on its load needs [1].

These days, VSDs have a significant load share due to electric machine requirements, power grid limitations, and energy-saving considerations. Consequently, VSDs have seen extensive use in industrial applications such as pumps, fans, cranes, conveyors, and more [1].

VSDs have many advantages; however, due to the full-bridge diode rectifier at their input and two-level voltage source inverters at their output, they can generate low and high frequency harmonics with significant amplitude, polluting the power systems. These harmonics flow through the power system, causing various issues such as supply voltage distortion, overloading of electrical equipment, reduction in system efficiency, increased equipment temperature and losses, capacitor bank failures and problems in protection relay performance [4].

Many methods have been employed to resolve VSD harmonics problems, such as using special power transformers, active or passive harmonic filters, and active front-end inverters [2].

Among this equipment, passive harmonic filters are commonly used in industries due to their simple structure, reliable operation, and lower installation and maintenance costs [3].

In the presence of system capacitance, certain transformer and reactor combinations can give rise to ferro-resonance phenomena, due to the nonlinearity and saturation of the reactance [4]. Resonance can occur over a wide range of Xc/Xm. Ref. [5] and [6] specify the range as: $0.1 < Xc/Xm < 40$.

Low-voltage plants commonly use high-capacitive cables in industrial areas. When industrial plants have non-linear loads like VSDs taking a major share of the transformer load, many passive filters are often used. These situations can cause ferro-resonance due to several factors: capacitance of cables, capacitance of passive harmonic filters, saturable inductance of passive harmonic filters, and the range of harmonic orders.

There are several solutions for preventing ferro-resonance and resonance phenomena. Some of these methods include [7]:

- Adding secondary resistive loads up to 4 percent of the transformer's nameplate rating.
- Increasing the circuit losses during ferro-resonance without significantly increasing them during normal operation.
- Adding damping resistors.

The methods mentioned above have some disadvantages, such as increasing total system losses and incurring additional costs.

For plants with many VSDs, the design phase should consider using the lowest possible number of passive filters to decrease the chance of resonance and ferroresonance.

Typically, passive filters are designed and tuned to filter one of the harmonic orders and are installed in parallel with the VSDs [8]. They work by creating an alternative low-resistance

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path for the flow of harmonic currents, effectively reducing the amount of harmonic distortion in the system [9].

By using high-order passive filters connected in parallel with loads, it is possible to filter two harmonic orders or high-frequency harmonic orders. Although it is possible to use a series of passive filters based on the filter's nominal current, the cost of the filter will increase. Typically, single-tuned first-order shunt passive filters are widely used, while other types of passive filters are rarely employed.

To ensure high power quality in the electrical grid, manufacturers should meet electromagnetic compatibility (EMC) standards for the frequency ranges of 0 ~ 2kHz and 150kHz ~ 30MHz [10]. Consequently, inductors are conventionally located at either the DC or AC sides of the drive system to align with the EMC standards below 2 kHz [11], while electromagnetic interference (EMI) filters are implemented to comply with standards above 150 kHz [17].

Therefore, several standardization committees, including NASI, IEC SC 77 A, CISPR, and CIGRE, have recently engaged in defining emission limits for frequencies below 150 kHz [22].

In some cases, the inductance and capacitance characteristics of equipment such as cables, transformers, chokes, and filters, when combined with VSDs harmonics, can cause over-voltage problems due to resonance and ferro-resonance.

Based on the insulation voltage limits of low-voltage equipment, over-voltages due to ferroresonance can be very costly and can cause damage and failure of many devices.

The importance of this research area is that, in many refere nces, the focus for harmonic filter design and selection is prim arily on Total Harmonic Distortion (THD) and filter characteri stics. In other words, the impact of the filters on each other an d on other network components, which is addressed in this res earch, is often ignored. This oversight can lead to faults and a decrease in reliability.

This condition becomes more critical when many non-linear loads exist at the output of a single power transformer, a factor often not clearly addressed in references.

The primary focus of this paper is the analysis of the impact of various passive filter components on voltage waveform. Typically, this issue is not cited or considered. Additionally, a step-by-step comprehensive algorithm is presented for selecting harmonic filters.

The novelty of this paper lies in considering voltage nominal limits during the process of designing and selecting PHFs. This goal is in addition to the main objective of improving power quality using PHFs.

In reference [36], a passive filter solution was used for a practical solar power plant. This reference mentions that the chance of resonance occurring is high in plants, and in the event of harmonic resonance, even a small harmonic source can cause serious harmonic voltage/current distortion. This reference used the Inductive Power Filtering Method (IPFM) to resolve the harmonic resonance problem by adding a specific winding to the power transformer, with the passive filter connected to this winding. The disadvantage of this solution is the extra cost due to the special design of power transformers and the requirement for more expensive cables because of the high THD value in the plant.

In reference [37], the selection of passive harmonic filters is presented, and a block diagram for the steps of this process is shown. This reference considers resonance in the selection of passive harmonic filters, but it is simulated and practically tested for only one filter. The interaction of multiple filters is not considered in this reference.

In reference [38], active harmonic filters are suggested as a solution for avoiding passive filter resonance, and detailed information about active filters is provided. This solution is technically the best, but it is also the most expensive. In a practical design with economic concerns, more economical solutions should be analyzed first, and only if they are not sufficient should more expensive solutions be considered.

The paper is organized as follows: In part two, the total electrical system of an industrial plant is reviewed, reasons for harmonic pollution from VSDs are presented, and both AHFs and PHFs are briefly introduced. In part three, a library of VSD harmonic characteristics is created and a plant harmonic analysis is conducted. This section also includes a block diagram for harmonic analysis. Finally, based on the result of simulations under different conditions, appropriate filters are selected.

II. Introduction The Studied System

A. *Industrial Complex Total System Description*

This section discusses the electrical system of an industrial complex. The system consists of 24 fans powered by 200 kW motors. These motors are controlled by VSDs based on control system commands.

In this network, there are 24 VSDs supplied by four power transformers, each with a rating of 3.3 MW. Two transformers are considered spares, while the remaining two supply the VSDs continuously.

The selected VSDs are of the normal-duty type, featuring a four-quadrant sensorless vector control with a two-level inverter at their output and a two-quadrant three-phase full-bridge rectifier at their inputs.

The cable length between the transformers and VSDs, and between the VSDs and motors, are approximately 300 and 400 meters, respectively.

For VSDs input and output, symmetrical shielded cables with three phase conductors, a shield, conductive armor, and a separate PE conductor were selected based on plant site standards. These cables have significant capacitance values between phase conductors and between the phase conductors and shield conductors.

B. *Electrical System Single-Line Diagram*

According to control system commands, fan motors can operate in both directions at speeds ranging from 0 to their rated value. In other words, a VSD can supply a motor with any voltage and current below the nominal values.

The control system can shed some of the fans, resulting in the total load of the transformers being less than the no-load current of the 24 motors. In other words, transformer currents can range from 10% to 25%.

Appendix 1 illustrates the VSDs and the arrangement of the plant's electrical system. This appendix includes the PCC incoming panel arrangements and transformers for two packages of VSDs, and it provides an overview of the entire electrical system of the plant.

III. Variable Speed Drives and Harmonic Solutions

A. Variable Speed Drives Harmonic Current Injection

VSDs are highly effective devices for the complete control and protection of electrical machines. Typically, VSDs consist of three stages [23]:

1- Input rectifier
2- DC link capacitor bank and choke
3- Output inverter

Low voltage VSDs have a three-phase full-bridge diode rectifier at their inputs and two-level voltage source inverters at their outputs. The classic full-bridge diode rectifier is a source of current harmonics for the power grid.

The VSD structure is shown in Fig.
1.

In practice, THD value for industrial VSDs with DC chokes is around 30% to 45%. However, if harmonic reduction criteria are not considered in the selection of the DC choke and capacitor bank, THD value can exceed 70%.

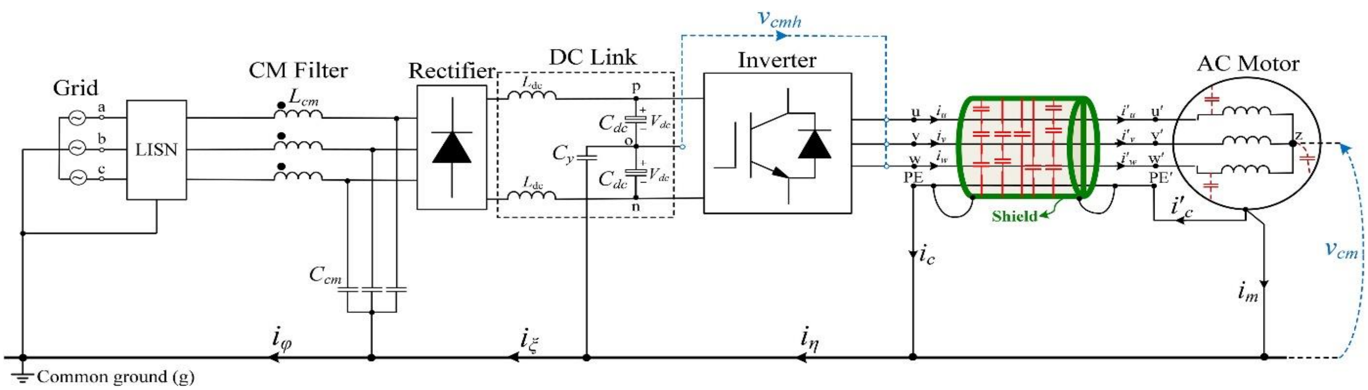

Fig. 1. Conventional type VSD structure [23]

B. Passive Harmonic Filters

It's possible to eliminate or reduce harmonic components using shunt or series filters. Shunt filters create low impedance against harmonic orders, while series filters create high impedance against harmonic orders to block harmonic currents [24].

The most common method to reduce harmonics is through the use of shunt filters, which are frequently utilized in various industries.

In many cases, it is possible to meet standards related to harmonics, such as IEEE519-2014, by using passive shunt filters. However, for some plants, this may not be feasible.

The total circuit of passive filters is illustrated in Fig. 2. Typically, shunt passive filters are installed to ground the harmonic content produced by VSDs [25].

When these filters are installed near VSDs, the resonance frequency of the filter is typically set around the 5^{th} and 7^{th} harmonic orders [26].

In Fig. 2, common passive filter configurations are illustrated:

(a) single-tuned filter,
(b) first-order high-pass filter,
(c) second-order high-pass filter, and
(d) third-order high-pass filter [27]

Among the above items, the single-tuned filter is the most well-known and widely used in industries. In this paper, the single-tuned filter is used for harmonic mitigation.

Sigle-tuned filters consist of a capacitor and an inductor, which provide a low impedance path against a specific harmonic order with a certain frequency.

The total impedance of single-tuned filters is given by:

$$Z_n = R_n + j\,(\omega_n L - 1/\,\omega_n C) \quad (1)$$

At resonance frequency:

$$\omega_n L = 1/\,\omega_n C \quad (2)$$

The reactance and capacitance of a single-tuned filter at the tuned frequency are:

$$X_0 = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}} \quad (3)$$

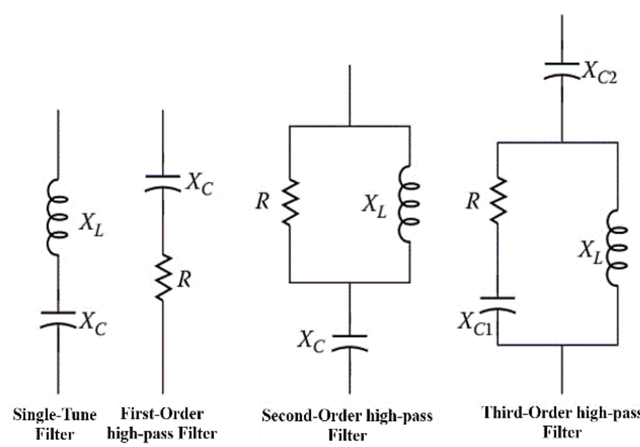

Fig. 2. Commonly used types of passive filters

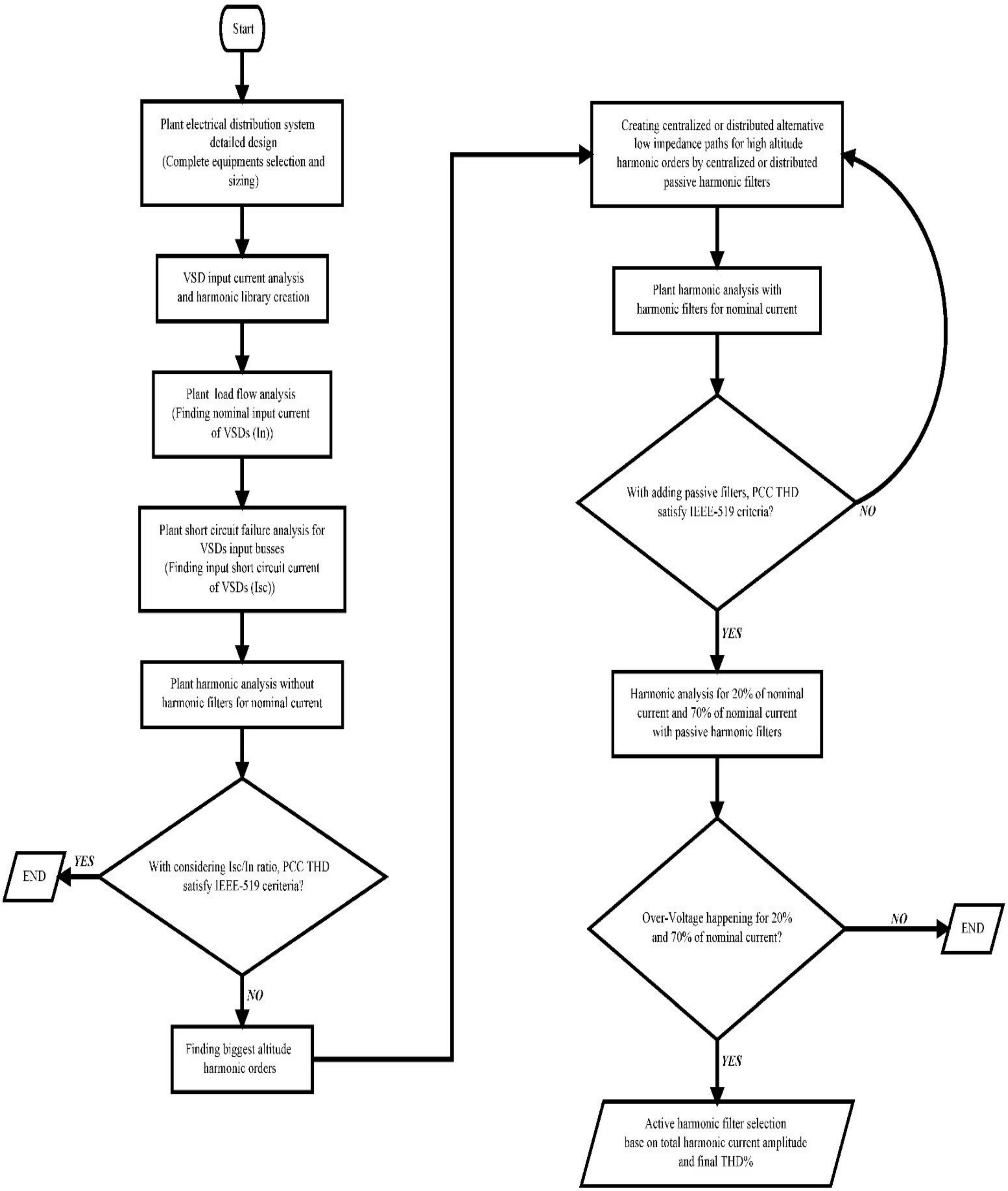

Fig. 3. Block diagram for passive filter selection in industrial plants

Active Harmonic Filters

By injecting harmonic distortion into the system that is equal to the distortion caused by the nonlinear load, but of opposite polarity, the waveform can be corrected to a sinusoid [4].

This procedure is achievable with inverters and active devices. Due to active switching devices and control complexities, these devices are more expensive than passive filters.

Active filters can set the cutting frequency around harmonics and inter-harmonics frequencies in dynamic or steady-state conditions, a capability that passive filters lack.

Additionally, the probability of over-voltage problems can be reduced by replacing passive harmonic filters with active harmonic filters.

Selection of active harmonic filters is much easier compared to passive filters, which require detailed design based on the plant's situation and arrangement.

Active harmonic filters select and operate like a black box that compensates for harmonic currents.

There is a limitation on the number of active harmonic filters that can be connected in parallel with each other. Typically, some manufacturers allow a maximum of 12 or 16 active harmonic filters (AHF) to be connected in parallel. This limitation on the number of parallel connected AHFs is due to the behavior of Phase Locked Loops (PLLs), as many PLLs cannot lock properly with each other.

IV. Simulation Results

In this section, the electrical system will be simulated using ETAP software.

Table I shows the values of the main parameters.

TABLE I
Network and Transformers Data

Transformer Data	
Primary Voltage [V]	33 kV
Secondary Voltage [V]	400 V
Frequency [Hz]	50
Network Sk [MVA]	1150
Transformer Sn [kVA]	3150
Supply Cable Type	Shielded XLPE Copper with Armor and PE Conductor
Cable Quantity	36
Cable Impedance [uOhm/m]	115
Supply System Data	
Cable length [m]	50
L_{dc} [uH]	10.7
C_{dc} [mF]	90
U_{dc} [V]	518
P_{dc} [kW]	2100

The simulation results without harmonic filters are presented in Table II. These results show the THD for each VSD in the previously described industrial plant.

TABLE II
Harmonic Analysis for Each VSD

VSD Network Data			
Cos ø1	0.989	$THD_{Current}$	43.1 %
Tot. Power Factor	0.908	$THD_{Voltage}$	1.1 %

Harmonic Orders Data

Harmonic Order	f [Hz]	Current [A]	I_n/I_1	Voltage [V]	U_n/U_1
1	50	257.9	100 %	399.8	100 %
5	250	93.2	36.1 %	2.6	0.6 %
7	350	49.7	19.3 %	1.9	0.5 %
11	550	21.5	8.3 %	1.3	0.3 %
13	650	14.8	5.7 %	1.1	0.3 %
17	850	12.4	4.8 %	1.2	0.3 %
19	950	9.1	3.5 %	1.0	0.2 %
23	1150	8.4	3.2 %	1.1	0.3 %
25	1250	6.5	2.5 %	0.9	0.2 %
29	1450	6.1	2.4 %	1.0	0.2 %
31	1550	5.0	1.9 %	0.9	0.2 %
35	1750	4.6	1.8 %	0.9	0.2 %
37	1850	3.9	1.5 %	0.8	0.2 %
41	2050	3.5	1.4 %	0.8	0.2 %
43	2150	3.1	1.2 %	0.7	0.2 %
47	2350	2.7	1.1 %	0.7	0.2 %
49	2450	2.4	0.9 %	0.7	0.2 %

The final results of high-altitude harmonic orders for each VSD, based on Table II, are shown in Fig. 4.

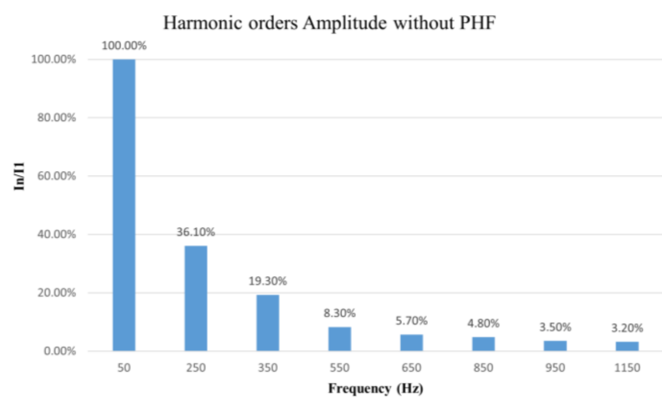

Fig. 4. Final results for the harmonic library of each VSD

According to the data in Table II and Fig. 4, the total harmonic current is approximately 40% for each VSD.

In Fig. 3, the block diagram for harmonic filter selection is presented. The rest of the analysis will be based on this diagram. The first two steps were previously completed in the content.

In the third step, load flow analysis is conducted. The plant is symmetrical, and all transformers and VSDs are similar. The only differing component is the power cable length.

For each VSD, load flow data is provided in Table III. Due to the differences in cable lengths, electrical parameters slightly differ for each VSD. However, these differences are negligible because they are too small.

TABLE III
VSDs Load Flow Data

Input Apparent Power	186.5 kVA
Input Voltage	400 V
Input Current	264.3 A
Input Power factor	0.98
Output Apparent Power	209.2 kVA
Output Voltage	400 V
Output Current	301.9 A
Output Power Factor	0.8738

The load flow analysis results for power transformers are shown in Table IV.

TABLE IV
Power Transformer Load Flow Data

Input Apparent Power	2296 kVA
Input Voltage	33 kV
Input Current	40.2 A
Input Power factor	0.967
Output Apparent Power	2245 kVA
Output Voltage	400 V
Output Current	3156 A
Output Power Factor	0.9793

In the fourth step, the input bus short circuit analysis for VSDs is conducted. The simulation results show that the input VSD short circuit current, according to IEC-60909, is 24.692 kA.

The simulation results for the power transformer show that the output bus short circuit current, according to IEC-60909, is 67.8 kA.

The IEEE-519 standard defines a ratio between short circuit current and load current. This standard is referred to this ratio as R_{SC}.

Simulations from steps 3 and 4 showed that the R_{SC} for the transformer output is equal to 21.48, and the R_{SC} for the VSDs input is equal to 93.42.

According to Table V, the total current harmonic distortion for the transformer is 8.0%, and the total current harmonic distortion for the VSDs input is 12.0%.

TABLE V
Harmonic Orders Limitations Based on IEEE-519

Maximum Harmonic Current Distortion in Percent of I_L						
R_{SC}	**h<11**	**11<h<17**	**17<h<23**	**23<h<35**	**35<h**	**THD_I**
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

V. Final Filter Selection

Based on Table II and Fig. 4, some of the harmonic orders have significant magnitude.

For this specific plant, harmonic analysis shows that the following harmonics have the main impact on THD:

- 5^{th} order at 250 Hz with 36.1% amplitude,
- 7^{th} order at 350 Hz with 19.3% amplitude,
- 11^{th} order at 550 Hz with 8.3% amplitude,
- 13^{th} order at 650 Hz with 5.7% amplitude, and
- 17^{th} order at 850 Hz with 4.8% amplitude.

According to the above data, a single-tuned filter should be used for the 5^{th}, 7^{th}, and 11^{th} order harmonics.

After this step and passive filter tunning, plant harmonic analysis will be repeated. If the IEEE-519 standard is not satisfied, a high-pass filter for high-frequency harmonics will be considered.

After tuning the filters for the 5th, 7th, and 11th orders, the total current harmonic distortion for the transformer output decreased from 14.9% to 4.6%. The output transformer waveform is presented in Fig. 6.

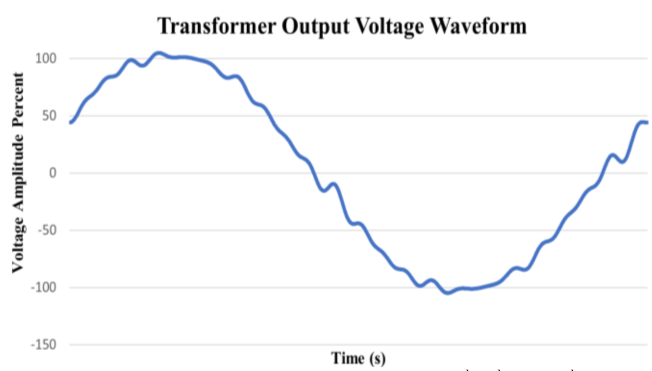

Fig. 6. Transformer output Voltage Waveform with 5^{th}, 7^{th} and 11^{th} Orders Harmonic Filters for 100%I_n

Table VI shows the harmonic filters data after selecting 5^{th}, 7^{th}, and 11^{th}-order harmonic filters.

TABLE VI
PHFs Characteristics After Tunning

	5^{th} Order Harmonic Filter	7^{th} Order Harmonic Filter	11^{th} Order Harmonic Filter
kVAR	144.8	85.4	72.45
uF	2881	1699	1441
X_L	0.0442	0.0382	0.0183
Q Factor	45	30	30
Current [A]	1010	540	245
Load [MVA]	2.245	2.245	2.245
Existing PF	0.979	0.984	0.985
Desired PF	0.99	0.99	0.99

At this step, centralized PHFs are considered. In other words, for every 12 VSDs connected in parallel, only one filter for the 5^{th} harmonic order, one filter for the 7^{th} harmonic order, and one filter for the 11^{th} harmonic order is used.

In a distributed PHF topology, for each VSD one filter for the 5^{th} harmonic order, one filter for the 7^{th} harmonic order, and one filter for the 11^{th} harmonic order are considered. In total, for 12 VSDs, 36 PHFs will be needed. In this situation, each VSD can operate independently.

Fig. 6 shows that the final harmonics with passive filters for each VSD are satisfactory, and the voltage waveform is close to a pure sine wave.

In the next step, the transformer output waveform is shown for 30% of the induction motor's nominal current. Fig. 7 indicates that at approximately 30% current, a 17% over-voltage occurs. In a distributed PHF topology, where the number of used PHFs increases sharply, the over-voltage situation worsens.

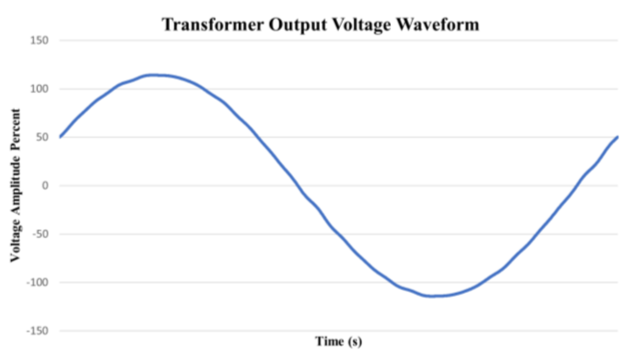

Fig. 7. Transformer output voltage waveform with 5^{th}, 7^{th} and 11^{th} Orders Harmonic Filters for 100%I_n

This permanent over-voltage at low currents makes it impossible to use passive filters.

Finally, an active harmonic filter with a capacity of 110 ampere is selected for each VSD.

VI. Conclusion

This paper presents methods for creating harmonic libraries for variable speed drives, conducting harmonic analysis in industrial plants, and sizing harmonic filter.

After presenting a diagram for passive and active harmonic filters selection and following the steps of the diagram for a practical plant, it has been shown that over-voltage makes using passive filters impossible.

After testing different cases and scenarios, it was found that in two situations, the chance of over-voltage will increase:

1. A large number of passive filters, chokes, and the inductance and capacitance of cables
2. Low current operation of devices

According to IEEE-519 related limitations, for some industrial plants, passive single-tuned harmonic filters can be a reliable, low-cost, easy-to-use, and resilient choice. However, other aspects such as resonance, ferro-resonance, and temporary and transient over-voltages must be checked, especially for all different load conditions.

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APPENDIX

Appendix 1, the single-line diagram of the plant.