Elimination of Harmonic Disturbances in Softstarters

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Abstract

Power system infrastructure has been facing many challenges when it comes to harmonics distortion, and power electronic devices are no exception considering their wide usage in the system. In this thesis the focus is on the impact of these system harmonics on the electrical motors which are vastly used in industry for different applications. Motors usually come with a softstarter, and are connected to the grid. Softstarters are used to avoid mechanical stress and voltage drops in the network while starting up motors and being connected as a group with the motor to the grid means that they will also be affected by the system harmonics. Softstarter consists of various power electronics components, such as Switches in shape of thyristors, resistor and capacitor. An important part of a softstarter is the snubber circuits which is sensitive against high-frequency harmonics. The snubber circuit is mainly composed of a snubber resistor and a capacitor. In fact, presence of high-frequency harmonics in the system, would reduce the impedance of the snubber circuit's capacitor. Thus the overall impedance of the snubber circuit would drop and accordingly current passing the snubber resistor would increase. The snubber resistor would become too hot and most probably melt. As a result, this phenomena in many cases, causes faults in the facility or even it causes a failure in the system. Considering the consequences of failure, it is necessary to cope with the destructive harmonics in an effective way. In this thesis, we are purposing a new strategy and a novel solution to maintain a reliable performance of the softstarter's while facing high frequency harmonics of the system. As the source of the issue are the high frequency harmonics, the best solution would be to eliminate them when they show up. That can be done by a properly designed and adjusted high pass-filter. In this work we tried to consider a cost effective solution that can also eliminates the harmonics. We are proposing using an extra indicator that is fine tuned and is adjusted in a way that together with the rest of the components it shapes high-pass filter, which would block the high frequency harmonics as they appear. To be able to do that the existing circuit was deeply measured and analyzed and with the gathered information regarding the current behaviour of the system under high frequency harmonics, an inductor was adjusted and added to the circuit. Various tests to verify the performance are done and are presented in this report. From the result it can clearly be seen that the inductor together with the rest of the system could properly act as a high- pass filter and eliminate the destructive high frequency harmonics.

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0.1 Acknowledgements

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This thesis is dedicated to the memory of my father who passed away recently fighting with COVID-19.

Raheleh Mahdivand

Chapter 1

Introduction

1.1 Motivation

Power system community has been facing many challenges during its history so far and solutions to the faced problems have dramatically changed the system design. Newly adopted smart facilities in the system has both opportunities and difficulties, which turns the system's related issues into a hard quandary. Specifically, the issues which could impact the whole system are highlighted to tackle in the first place. One of the system's variables which would exacerbates whole system, once the variable get worse, is harmonics and the harmonic extortion issue. The mentioned smart means have bad impacts from the system harmonics point of view, thus these harmonics should be tackled in the first place by a proper declining harmonic circuits.

1.2 Harmonics

Generally, harmonic waves act like destructive noises in the power system and it could have the facilities operation failure. Power semiconductor devices which use switching function are one of the main sources of harmonics in the power system. At this regard, there are protection guidelines for classified and recommended harmonic levels in the power distribution systems e.g. IEEE 519 [1]. Consider above mentioned thoughts, harmonics are still common problems to the distribution system. Fundamentally, the harmonics could be divided into two primary section; current harmonics, and voltage harmonics. The current harmonics are applied by non-linear loads which cause disturbance in the sinusoidal current curve, such as rectifiers. Additionally, the voltage harmonics are caused by the current harmonics and due to source impedance. It should be mentioned that the problem would be more complex in presence of bigger loads, which could have harmonics with higher impact. At this regard, the dimensional level of the system, and the way that the devices are connected to the system are the other plausible reasons for the system harmonics.

1.3 Softstarters

Moreover, the electric devices' problem is not restricted only to the harmonic issues, which the device should cope with. More precisely, in electric motors, start-up inrush current is another challenging problem which different actions have been taken overtime. Softstarter devices are to control the inrush current in a tolerable way which the motors would run as fine as it has to be [2]. To achieve this, softstarters modify voltage which is the main variable of the system by slowly adding the input voltage. Further, the softstarters are able to control torque by modifying the voltage, indirectly. At this regard, with controlling the voltage input through the motor device, there are two controlled parameters; start up inrush current and torque which the values are 10 times and 3 times bigger than the normal values, respectively.

1.4 Electric motor drives

For some industries even the speed of the motor needs to be controlled while operation, while the motor is running. To do so, variable frequency drives (VFDs) are to control the speed of AC electrical motors [3-6]. The speed would be controlled through setting the frequency point of the motor voltage. Consider that, the VFD's function is analogous as softstarters, but it also could keep the motor at a desired speed. The VFD is however more complex compared to a softstarter in a way that it is bigger and overpriced. The VFDs, in some cases, are responsible for harmonic disturbances in systems that they have been used together with softstarters, simultaneously [7-8]. A common application is to use a softstarter in a parallel mode with the VFD, which in that case the softstarter is exposed to a lot of harmonic disturbances generated by the VFD which in turn could cause physical damages in its electronic circuit. In fact, particularly, there has been problems with overheating of filter components in the softstarter so far. Harmonic guidelines set the demands for maximum harmonics upstream from a VFD but there are often no demands on harmonics generated downstream from a VFD.

1.5 Objective problem

Hence the propitious snubber circuits function in the softstarters for the electric motor's start running, there is a harmonic problem with the snubber circuits in the high frequencies. Overally, the snubber circuits consist of a couple of series resistor and capacitor, which the main function of the components is to limit voltage peaks by reducing the voltage and current rate over a semiconductor device like a thyristor. The snubber circuits are also used to preclude incoming harmonics from the thyristors and protect the device. This is standard practice for softstarter which has been examined so far. The figure 1.1 shows a simple layout of thyristor and the protection circuit in a simple softstarter device. While the resistor gets warm enough in temperature from the current that travels through it, this could cause extortion damages as a result. The higher the harmonics could get into the snubber's circuits, the larger the currents pass through the snubber circuit is.

1.6 Thesis objectives

The proposed thesis objective is to investigate the harmonics generated from the VFDs and how it impacts the network and the connected devices. Precisely, the purpose of the study is to investigate the harmonic consequences on the function of the parallel softstarters with the VFDs. To obtain this matter, there are two primary steps to tackle, which could be divided as follows. First of all, the harmonic disturbance definition should be well determined for the VFD's outcome. This should also contain the impact of different aspect of the system like total impedance and connected devices. Second of all, as solutions, the plausible harmonic reduction methods should be found.

In detail, the power bus-bars could have been connected with more than one drives as softstarter, which makes the problem more delicate to handle. In turn, there should be a sensitive data extraction to have a better accuracy, thus authors

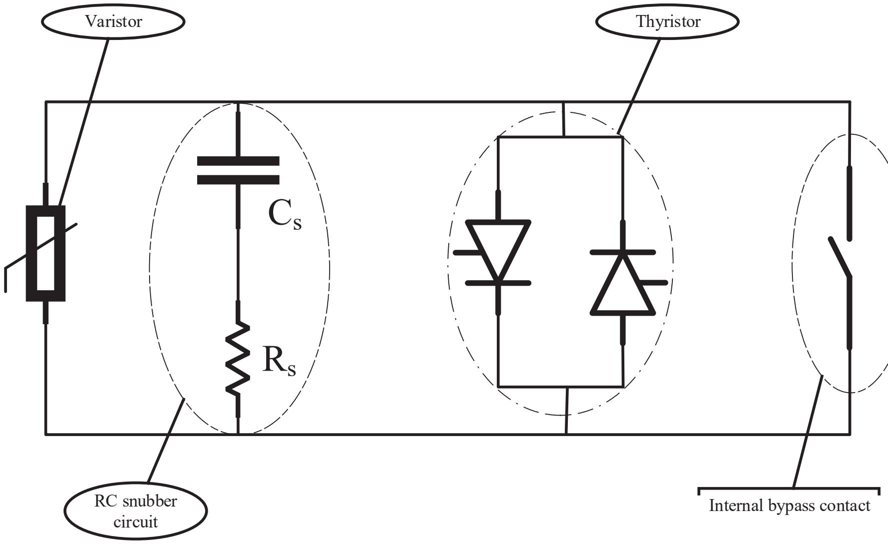

Figure 1.1: Layout of thyristor and protection circuit in softstarters

have used an oscilloscope device to obtain the voltage data with $2\mu s$ time steps. The snubber resistor's temperature change has been closely monitored during the test, as well. Then, the data, which had been extracted in the real test measurement, has been analyzed by the MATLAB software to find the present harmonics in the system.

Chapter 2

Harmonics and the Fourier analysis of the harmonic distortion

2.1 Harmonics

In a short summary, harmonic distortion definition is “the value of variation in a measured wave with its pure sinusoidal counterpart”. The distortions could be expressed as superimposed unwanted multiple frequencies on a fundamental frequency of a waveform or sometimes just random distortions. Consider the linear load functions, the calculated current is proportional to the input voltage because the linear load’s impedance is totally fixed, even during alternating sinusoidal waveforms. In the opposite side, non-linear loads are not fixed along the alternating waveform and the current drawn by non-linear loads is not proportional to the voltage which is applied to them.

Fundamental frequency could be expressed as the lowest plausible frequency of a periodic waveform. This so-called fundamental frequency is in fact the first harmonic of a waveform that has the base frequency of f and periodic time of T. The undesired higher harmonics are multiplications of the base frequency which has been added to the wave, unwillingly. These harmonics impose distortions on the fundamental sinusoidal waveform [9-11]. The summation of the mentioned waves is a non-sinusoidal complex waveform which is called Fourier series. Considering this, Fourier series are used to analyze system harmonics and study the system reaction at each harmonic individually. To analyze the harmonics of a sample signal, usually, the data of the signal would be well recorded in a period. These data represents series of amplitudes that are sampled using a specific time sample. The best way to perform most modern spectral and harmonic analysis on such a data package is to apply Discrete Fourier Transform (DFT) [9].

Distortions, on the other hand, are often prelude to a system by common electrical devices or industries; for instance, steel industry, diodes, transistors, silicon-controlled rectifier (SCR’s), variable speed drives and other solid-state switches that control the motor power by chopping and cutting the sinusoidal waveform. In fact, if in an electrical circuit, inductive reactance and capacitive reactance become equal in magnitude, it can provide a path for energy to travel between inductor and capacitor. This well-known phenomenon only happens in the resonant frequencies. In such conditions, the magnetic field of the inductor and the electrical field of the capacitor is converted to each other, until the travelling energy fades away [3].

2.2 Total harmonic distortion

Total Harmonic Distortion (THD) represents how well the output signal of a system replicates the input signal. This value is calculated as a deviation percentage of voltage or current waveforms from the source waveform. As a limitation, the IEEE 519 standard expresses that THD for a system should not exceed 5%. Decreasing the THD of the power system, the operation quality and life time duration of the facility could be well improved. The following equation (2.1) shows the THD formula for a sample voltage wave, which is the sum of the powers of all harmonic components to the power of the fundamental frequency.

$$THD = 100 \times \frac{\sqrt{v_2^2 + v_3^3 + ... + v_n^n}}{v_1} \tag{2.1}$$

In which v_1 is the fundamental line to neutral rms voltage and v_2, v_3, v_n are 2_{nd}, 3_{rd} and n_{th} harmonics [2,9].

2.3 Harmonics analysis by Fourier series

The well-known Fourier law, which has been presented by Joseph Fourier, a French mathematician, is to transform the non-sinusoidal repetitive waves to a bunch of frequency series of sinusoidal waves. At this way, summation of whole sinusoidal waves would be the same as the input non-sinusoidal wave. According to Fourier law, any continuous repetitive periodic wave could be separated through the Fourier function into a d.c. offset term, a fundamental sinusoidal component and series of sub-fundamental frequencies.

To analyze harmonics of a signal, usually, the data of the considered signal are recorded over a test period. This data represents series of amplitudes that are sampled using a specific time sample. The best way to perform most modern spectral and harmonic analysis on such a data package is to apply discrete Fourier transform (DFT) [9].

2.3.1 Fourier series and coefficients

The continuous sample repetitive wave in the Fourier domain, could be written as simple as the equation (2.2).

$$x(t) = a_0 + \sum_{n=1}^{\infty}(a_n cos(\frac{2\pi nt}{T}) + b_n sin(\frac{2\pi nt}{T})) \tag{2.2}$$

In which a_0 represents the average value of the function $x(t)$, and a_n and b_n represent the nth harmonic components of function $x(t)$.

Considering that T is the wave's time period, all the coefficients could be simply calculated as presented in the following formulations. Applying the integral to both sides of the (2.2) from $-T/2$ to $T/2$, is the first step of the coefficient calculations and the result is the equation (2.3):

$$\int_{-T/2}^{T/2} x(t)dt = \int_{-T/2}^{T/2} [a_0 + \sum_{n=1}^{\infty}(a_n cos(\frac{2\pi nt}{T}) + b_n sin(\frac{2\pi nt}{T}))]dt \tag{2.3}$$

Separating the right part bodies of the integration formula and changing the priority of the summation and integration functions, which are totally unrelated, the right side of the equation could simplified as follows:

$$\int_{-T/2}^{T/2} x(t)dt = a_0 \int_{-T/2}^{T/2} dt + \sum_{n=1}^{\infty}[a_n \int_{-T/2}^{T/2} cos(\frac{2\pi nt}{T})dt + b_n \int_{-T/2}^{T/2} sin(\frac{2\pi nt}{T})dt] \tag{2.4}$$

$$\sum_{n=1}^{\infty}[a_n \int_{-T/2}^{T/2} cos(\frac{2\pi nt}{T})dt] = 0 \tag{2.5}$$

$$\sum_{n=1}^{\infty} b_n \int_{-T/2}^{T/2} sin(\frac{2\pi nt}{T})dt = 0 \tag{2.6}$$

Considering that the sinusoidal functions' integral in a period is equal to zero, the second part shown in the (2.5) and third part shown in the (2.6) of the right side of the (2.4) are equal to zero. It should be noted that since the frequency is $2\pi nt$ and the lower/upper bound of the integral are $T/2$ and $-T/2$, the integral is on a period. The (2.4) shows the resulted equation:

$$\int_{-T/2}^{T/2} x(t)dt = Ta_0 + 0 \tag{2.7}$$

Then the a_0 could be easily determined as:

$$a_0 = \frac{1}{T} \int_{-T/2}^{T/2} x(t)dt \tag{2.8}$$

Multiplying both sides of the (2.2) to the $cos(2mt/T)$, in which m is any fixed positive integer, all the a_n coefficients can be obtained as follow:

$$\begin{gathered}\int_{-T/2}^{T/2} x(t)cos(\tfrac{2\pi mt}{T})dt = \\ \int_{-T/2}^{T/2}[a_0 + \sum_{n=1}^{\infty}(a_n cos(\tfrac{2\pi nt}{T}) + b_n sin(\tfrac{2\pi nt}{T}))]cos(\tfrac{2\pi mt}{T})dt \\ = a_0 \int_{-T/2}^{T/2} cos(\tfrac{2\pi mt}{T})dt + \sum_{n=1}^{\infty}(\int_{-T/2}^{T/2} a_n cos(\tfrac{2\pi nt}{T})cos(\tfrac{2\pi mt}{T})dt + \\ \int_{-T/2}^{T/2} b_n sin(\tfrac{2\pi nt}{T})cos(\tfrac{2\pi mt}{T})]\end{gathered} \tag{2.9}$$

While the m is not equal to n, the all terms in the right side of the (2.9), are zero, since the orthogonal functions:

$$a_n \int_{-T/2}^{T/2} cos(\frac{2\pi mt}{T})dt = 0 \tag{2.10}$$

$$\sum_{n=1}^{\infty} b_n \int_{-T/2}^{T/2} sin(\frac{2\pi nt}{T})cos(\frac{2\pi mt}{T}) = 0 \tag{2.11}$$

$$\sum_{n=1}^{\infty} a_n \int_{-T/2}^{T/2} cos(\frac{2\pi nt}{T})cos(\frac{2\pi mt}{T})dt = 0 \tag{2.12}$$

However, when the n and m indexes are equal, the result is not equal to zero.The result of this conditional situation is as follows:

$$\begin{gathered}\int_{-T/2}^{T/2} x(t)cos(\tfrac{2\pi mt}{T})dt = \\ a_n \int_{-T/2}^{T/2} cos(\tfrac{2\pi nt}{T})cos(\tfrac{2\pi mt}{T})dt + \tfrac{a_n}{2} \int_{-T/2}^{T/2} cos(\tfrac{4\pi nt}{T})dt + \tfrac{a_n}{2} \int_{-T/2}^{T/2} dt\end{gathered} \tag{2.13}$$

Further simplification will result as in the following formula. The (2.14) shows the a_n related to the input signal $x(t)$.

$$a_n = \frac{2}{T}\int_{-T/2}^{T/2} x(t)cos(\frac{2\pi nt}{T})dt : for\ n = 1\ to\ \infty \tag{2.14}$$

Similarly, by multiplying both sides of equation (2.2) by $sin(2\pi mt/T)$, in which m is any fixed positive integer, all the b_n coefficients can be obtained as equation (2.15), likewise the calculations for an [9].

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} x(t)sin(\frac{2\pi nt}{T})dt : for\ n = 1\ to\ \infty \tag{2.15}$$

2.4 Effects of Harmonic distortions

Harmonic distortions have several negative impacts on the power system and specially on the equipment connected to the system. One of the serious problems could be the distortion impact on the power factor, which causes overheating in the neutral conductors, motor cores and transformers, due to the distractive and unwanted current initiated from the harmonics. At this regard, there should be fundamental actions toward the matter, if not, there would be serious damages to the power system and would shorten the life time of the jointed facilities. High order harmonics can also cause interference with the communication system since communication system operates at high frequencies [3].

2.5 Minimizing the effect of harmonic distortions on a system

Generally, there is no way to preclude the entire harmonics in the system, which means the operators should confront the harmonics and its belongings. In fact, the harmonics are an inevitable part of the system and whenever the more system's topology get complex, the harmonic distortion is harder to solve. At this regard, there are several actions to minimize the harmonics in the system. It should be mentioned that in some cases and in some facilities which are a source of harmonics, it could have the harmonics totally prevented. The following steps are to minimize the harmonic distortion effects on the system:

- Designing electrical equipment and systems to prevent harmonics from causing equipment or system damage.
- Analyzing harmonic symptoms to determine their causes and devise solutions.
- Identifying and reducing or eliminating the medium that is transmitting harmonics.
- Using power conditioning equipment to mitigate harmonics and other power quality problems when they occur.

Chapter 3

Different methods of starting an electric motor connected to the power system

In the electric motor devices, the main problem is about the starting duration, for which there are issues to solve. The first issue is about the start current and the second one is about the start torque. Overally, there are several starting method for electric motors, which would be present in this section. Each method has its opportunities and difficulties that is necessary to know. Here are the well-known methods:

3.1 Direct on line

Although direct on line (DOL) starting method, which has been shown in figure 3.1, is not the most optimal method for starting a motor, but it is still the most used method in the industry due to its size and price. Starting a motor up with the DOL method, full voltage and very high current are applied to the motor. As a result, the motor will start with very high torque. This method has either on or off state. The main components of the DOL starting method is a contactor and a thermal or electronic overload relay [12-15].

3.2 Star-delta-start

The main components building a star (Y)-delta(Δ) starter are contactors, a timer and an overload relay. The star-delta function is to have the motor's winding star connected which helps the motor to experience less current and thus less torque. The motor's windings would turn as delta connected after a considered time and draw full current and full torque. While starting, the motor's windings are connected as star in which the impedance is 3 times bigger than the impedance of delta connection. Then, since the voltage level is constant, the current drawn by a Y-connected motor is $1/3$ Δ-connected motor [14,15]. The changeover from star to delta is usually happening automatically by using a timer which triggers a relay on the contactor circuit [13]. The Star-Delta method for motor starting is revealed in the figure 3.2.

3.3 Softstarters

To extend the industrial motor's longevity, all forms of electrical stresses should be filtered before it touches the motor's operation. Considering the mentioned fact, both start up inrush current and start torque should be well precluded. Using

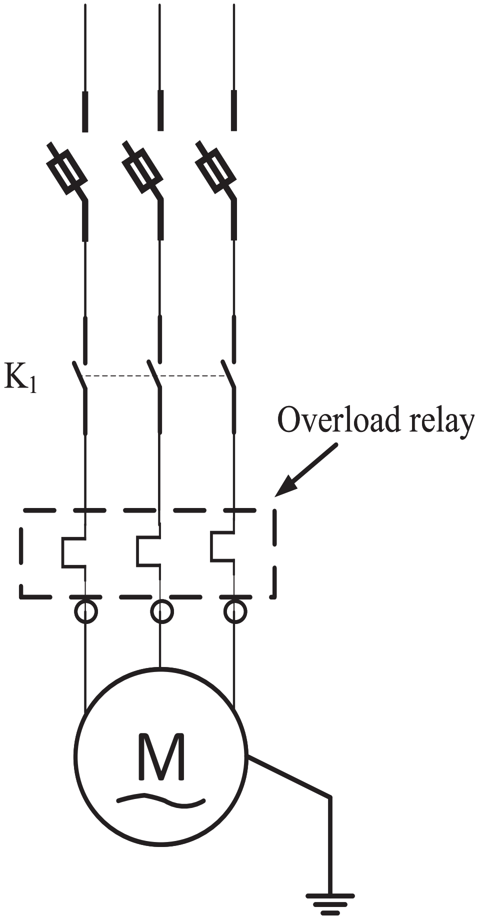

Figure 3.1: Direct on-Line method for motor starting

the well-known softstarters, the starting inrush current and starting torque can be minimized which otherwise can impose lots of stresses on the motor. The inrush current during the start of the motor can cause extra heating in the motor and high torque during the start of the motor introduces mechanical shocks to the system which could shortens the motor's lifetime.

Softstarters, generally, are constructed of three pairs of back to back thyristors, the basic motor with 3 back to back thyristors is shown in the figure 3.3. Each pair is responsible to control the voltage of a specific phase. Besides, the softstarters are responsible to ramp up the input voltage applied to the motor terminals gradually from the initial value to full voltage. This in turn would enable the motor to gently accelerate to desired speed. One of the advantages of using such starting method is that the torque can be adjusted after the exact need dependent of the motor load. The other advantage is preventing voltage drop in the network by controlling the starting current [15]. Soft-starter method for motor starting is shown in figure 3.4.

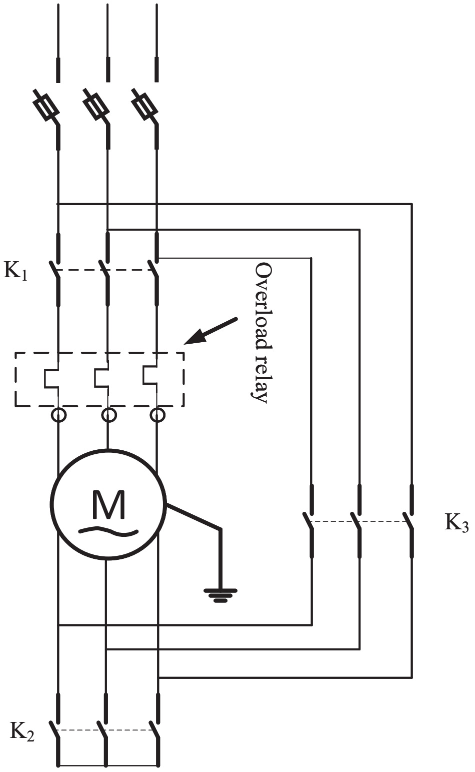

Figure 3.2: Star-Delta method for motor starting

3.3.1 Thyristors

The thyristor is a three-terminal, four-layer semiconductor device and these four layers build three p-n junctions. The three terminals of the thyristor are called anode, cathode and the gate. Anode is the positive terminal(p-layer), cathode is the negative terminal(n-layer) and gate is the control terminal (smaller p-layer). The thyristor acts as a switch and its impedance is preferably close to zero while conducting and infinite while blocking.

The most common way of turning a thyristor on is by triggering the gate while the thyristor is forward blocking state. Meaning that the thyristor is switched on by applying positive voltage between the anode and the cathode. The gate loses its control over thyristor once its turned on and current is flowing from anode to cathode [16]. The p-n schematic and electronic symbol of the thyristor is shown in figure 3.5

The thyristor cannot just be turned off by removing the firing pulse from the gate. In order to turn off the thyristor three different methods can be used [16,15].

- Natural commutation: By bringing the anode current below the holding current level. Holding current is a minimum anode-cathode current for a thyristor that thyristor needs to stay in on-state without a control pulse at the gate.
- Reverse bias turn-off: By applying negative anode to cathode voltage, it is

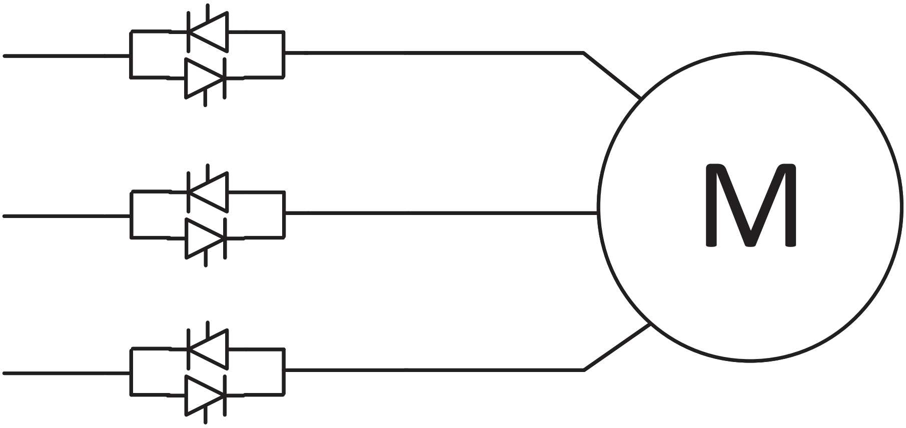

Figure 3.3: Basic motor with 3 back to back thyristors

possible to turn off the thyristor. The reverse biasing interrupts the anode to cathode current. This method is simple if the supply is alternating in which the thyristor is reverse biased over one half cycle. In the circuits with d.c. supply, capacitors are used in parallel with the thyristor to apply reverse voltage over the thyristor. This method is also known as forced commutation.

- Gate turn-off: In GTO (gate-turn-off) thyristors a small negative pulse on the gate can push the thyristor in off state. The applied negative voltage creates a low impedance path, and it causes some part of anode-cathode current to flow out of the gate. When the load current becomes less than the holding current, the thyristor turns off [14].

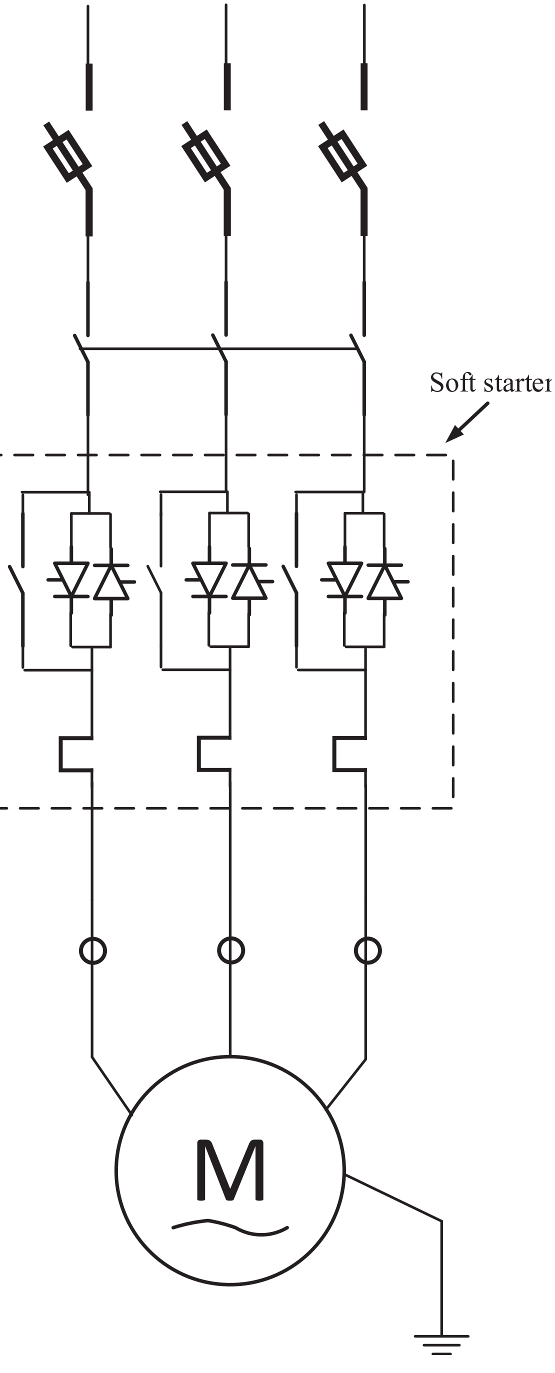

Figure 3.4: Soft-starter method for motor starting

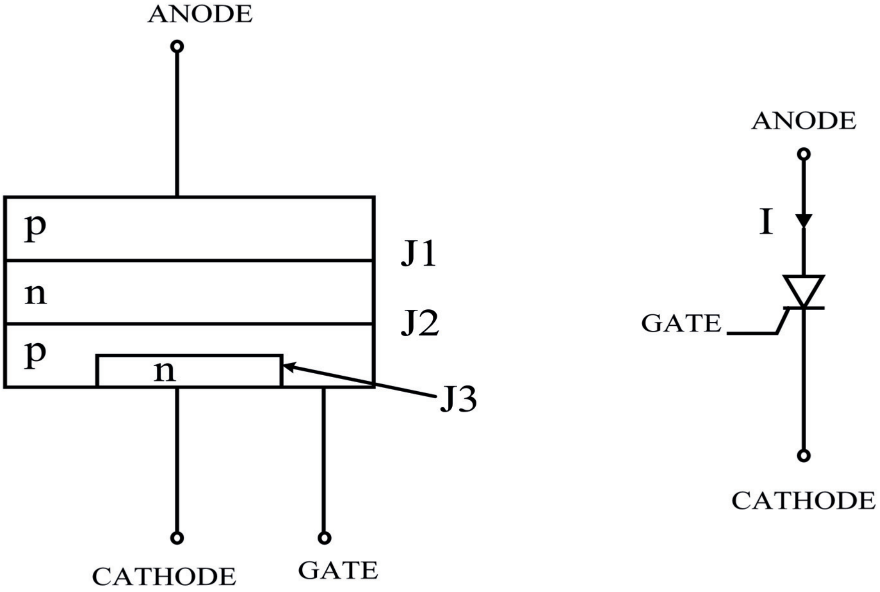

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Figure 3.5: The p-n schematic and electronic symbol of the thyristor

3.3.2 General about ABB softstarters:

The Softstarter devices from the ABB company are designed with several components consist of thyristors, PCB boards, bypass switches, heat sinks, fans and current transformers. The PCB boards are used to control the firing angel of the thyristors and thus control the level of injected voltage to the motor. The heat sinks and fans are the components used in softstarters for heat reduction. Current measurement in softstarters is performed using current transformers. The AC voltage that is injected to the motor is limited by changing the firing angle of the thyristors. At starting phase of the motor, the firing angel is large. Therefore, the thyristors are fired late and thus they pass only the last part of the sine way. Every half cycle, this firing angel decreases and at every half cycle more amount of voltage is passed through the thyristor until it reaches 100% of the voltage and this action is called ramp-up. Consequently, by voltage increment the current of the motor is increased proportionally. However, the torque is proportional to the quadrat of the voltage and a slight change in the voltage causes considerable change in the torque of the motor. Figure 3.6 illustrates how thyristors are fired in a softstarter [12].

The ABB company has three types of softstarters; PSR, PSE and PSTX. The functionality of these softstarters is almost the same but the rated operational current of the devices is different. The PSR and PSE are smaller with less components compared to the PSTX. The PSTX has 6 thyristors, 1 pair of back to back thyristor for every phase and the output voltage of the PSTX softstarters is controlled by firing pulses that are applied on each thyristor pair in each phase. The PSTX is used for current range from 30A to 1250 A. However, both the PSR and PSE types use 4 thyristors in 2 phases of the 3-phase model, which in turn these types are controlling the output voltage to the motor only at 2 phases. Besides, the third phase without thyristors is short circuited and just passes through the current and the voltage. The PSR is used for current range from 3A to 105A. The PSE is used for current range from 18A to 370A. Moreover, while the motor

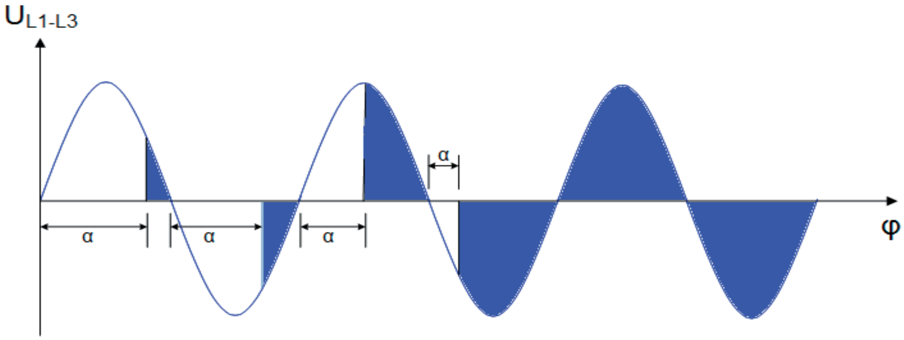


Figure 3.6: Thyristor firing of a two-phase controlled softstarter, α= firing angle and φ= phase angle

is going to stop, an opposite principal is used to reduce the current and torque of the motor. The voltage level applied to the motor is decreased gradually from full voltage to zero voltage for soft stopping of the motor. This action is called ramp-down. All the thyristors are active during ramp-up or ramp-down of the voltage. While during steady-state that the softstarter is supposed to pass 100% of the voltage, the thyristors are bypassed by closing the bypass switch.

3.3.3 Inside-delta connection softstarters

Reportedly, majority of the customers which have got overheated snubber circuit have suffered a big motor with low inductance in the system. The inside-delta procedure, which it has been graphically shown in the figure 3.7, makes it possible to use low rated softstarters for big motors. When the softstarter is inside-delta, it will be only practicing 58% $(1/\sqrt{3})$ of the in-line current. All functionality will be identical regardless of connecting in line or inside-delta. However, with the inside-delta connection, 6 cables are needed between the softstarter and the motor, and if this distance is long, an in-line connection might be a more cost efficient solution.

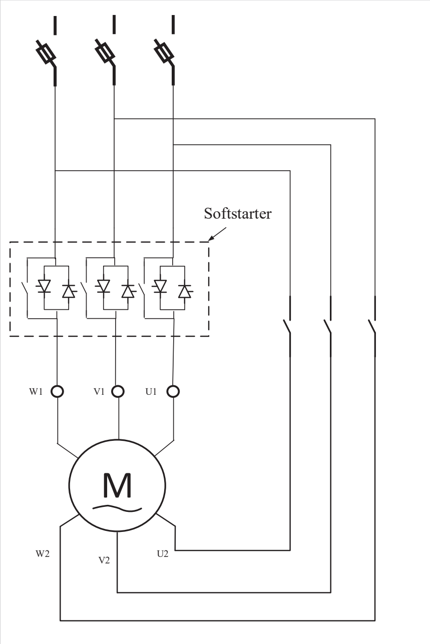


Figure 3.7: existing inside-delta connection

3.3.4 Snubber circuit soft starters

Snubber circuits are used in power electronic devices to decline the electrical stresses which are imposed to the facilities during start-up/shut-down regarding the fact that thyristors used in softstarters are vulnerable outside of the safe-operating conditions.

This thesis focuses on the snubber circuits that the ABB company uses on its PSE and PSTX products to protect the thyristor against over-voltage in the course of thyristor shut-down. The thyristor of the snubber circuit is shown in the figure 3.8. The rate of voltage change (dv/dt) between anode and cathode of the thyristors must remain within its safe limits while the thyristor is starting-up, but still, it should be large enough to be able to block the thyristor. Besides, if the dv/dt becomes too large, thyristors will still conduct without receiving the firing signal from the gate. At the shut-down process of semiconductor devices, a reverse voltage is applied to the thyristors which in turn this causes the P-N junction in a semiconductor device to operate as a capacitor. Due to this transient voltage, there should be a RC snubber circuit connected in parallel with the thyristor to restrain

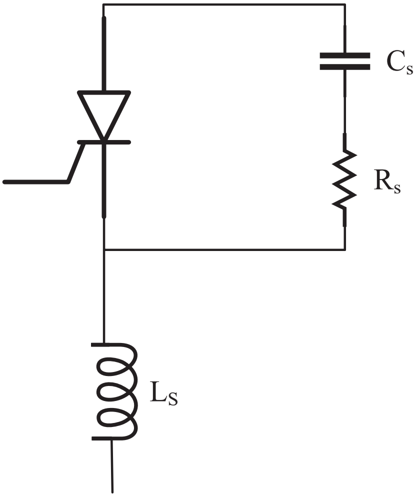


Figure 3.8: Thyristor snubber circuit

the transient voltage over the thyristor and keep it within reasonable operation area. Further, the snubber could affect the shut-down loss of the thyristors and consequently the softstarter. If the di/dt does not keep the bounds during the thyristor's start-up, the area at cathode gate junction may forme as a hot spot which may damage the thyristor. Having the di/dt under control can be archived by connecting an inductor in series with the thyristor [17,18].

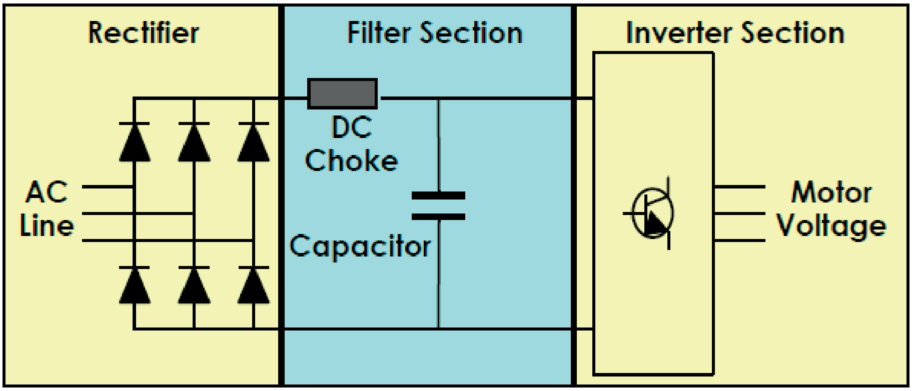


Figure 3.9: The main circuit of VFD model

3.4 Variable frequency drive

Variable frequency drive (VFD), which has been demonstrate graphically in the figure 3.9, is employed to control the AC induction motor speed by converting the fixed voltage and input frequency to variable voltage and output frequency as a power source. The input frequency that is applied to a motor could be calculated (3.4.1), considering the speed and number of the motor poles, as follows.

$$N = \frac{120f}{P} \tag{3.4.1}$$

Where:
N=speed (rpm)
f=frequency (Hz)
P=number of motors poles

The VFD is consist of 4 different parts; Rectifier (for AC to DC conversion), choke and DC bus (for DC voltage filtering), inverter (for DC to AC conversion) and a control unit (often PWM). The root mean square (RMS) output value of the inverter produces the AC voltage signal with a desired frequency.

3.5 Harmonics from VFDs

As mentioned, all VFDs have an AC to DC rectifier part with a big dc capacitor to flatten the voltage ripples. The dc bus capacitor draws charging current only when it is discharged into the motor load. The charging current circulates into the capacitor while the input rectifier is forward biased. This happens while the input voltage is higher than the dc voltage across the dc bus capacitor. The pulsed current drawn by the dc bus capacitor is rich in harmonics because it is discontinuous. The voltage harmonics generated by VFDs are due to the flat-topping effect caused by a weak ac source charging the dc bus capacitor without any intervening impedance. The distorted voltage waveform gives rise to voltage harmonics, which is of more importance than current harmonics. The reason is simple. Voltage is shared by all loads and it affects all loads connected in an electrical system. Current distortions have local effects which belong to the circuit that are feeding the non-linear load. Non-sinusoidal current flows that came from the ac power source cause extra stress on the equipment that results in low overall performance.

Chapter 4

Results and discussion

One of the most important issues of simulating the electrical motors is to find an equivalent circuit model which represents the motor's application in a sensible way. That is because the real model of the motor is much more complex, here, in these set of simulations the inductances are neglected, which these calculations show that the losses are mostly due to common mode phenomena. Besides, it has been known that the first and foremost component of the circuit is the capacitor, which shows the motor properties and its cabling long. Generally, $300nF$ CM capacitance is typical for a $400kW$ motor with $100m$ cabling, the smaller the motor power and shorter motor cable is, the lower losses due CM circuit would be.

Moreover, it is also crucial to discover a sensible value for dissipation factor of the capacitor and to design a proper equivalent circuit of the snubber circuit. The dissipation factor, which the information is coming from the manufacture "Kemet", for a $100nF$ capacitor is almost 20Ω around 1kHz. Additionally, the dissipation factor for a $20kHz$ frequency is around 100Ω according to calculations. At this point, there are two data packages to cope with, package one is with high harmonics and package two is with low harmonics. During the high harmonics in the system the snubber circuit's resistor gets too hot, thus in turn causes wrong doing in the system. At normal condition, while the harmonics are lower than $2kHz$, the max temperature of the resistor doesn't pass the $70°C$.

Technically, the motor's inductance effect on the total impedance is variable dependent on the frequency, which goes up at higher network frequencies. Smaller electric motors have larger inductance thus better protective effect on the snubber circuit [16]. Furthermore, electric motors bigger than $400kW$ have more vulnerable snubber circuit since those large motors have a smaller induction value. For instance, the motor inductance of the ABB test motor with $37kW$ power is around $0.5mH$ and, in comparison, the inductance of a big motor, as big as a $400kW$ motor, is around $0.01mH$. As a solution for the large motors, an extra inductor object in series to the motor inductance could be the best way to curtail the high harmonics. While adding the extra inductance is a great way to compensate the induction value of the motor, but the resonance of the snubber circuit must be taken into account.

Reportedly, the majority of customers who have got overheated snubber circuit have had big motors with low inductances in the system. The inside-delta process is used for the big motors to compensates for the low impedance problem. The inside delta connection makes it plausible to locate the softstarter inside the delta circuit and allows for a simple replacement of existing star delta starters. While the softstarter is inside delta it will just be experiencing 58% ($1/\sqrt{3}$) of the In-line current. Hence it is feasible to downsize the devices in order to attain a more economical response. All functionality will be identical regardless if connecting in line or inside delta. However, with the inside delta connection, 6 cables are required between the softstarter and the motor, and if this distance is long, an in line connection might be a more cost efficient solution.

Generally, there are two different ways for current to pas through the softstarter shown in figure 4.1. Common mode and differential mode. In the differential mode the harmonic current is not high since harmonics don't sum up.Thus the differential mode does not affect the temperature significantly, but in common mode the harmonic current would cause the heating since the harmonics sum up in the common mode. The snubber resistors heating up occurs at high order harmonics since during the high frequency the impedance of the capacitor is very low, close to zero, that reduces the whole impedance. Moreover, this let the whole current to flow through the resistor and heat the resistor up.

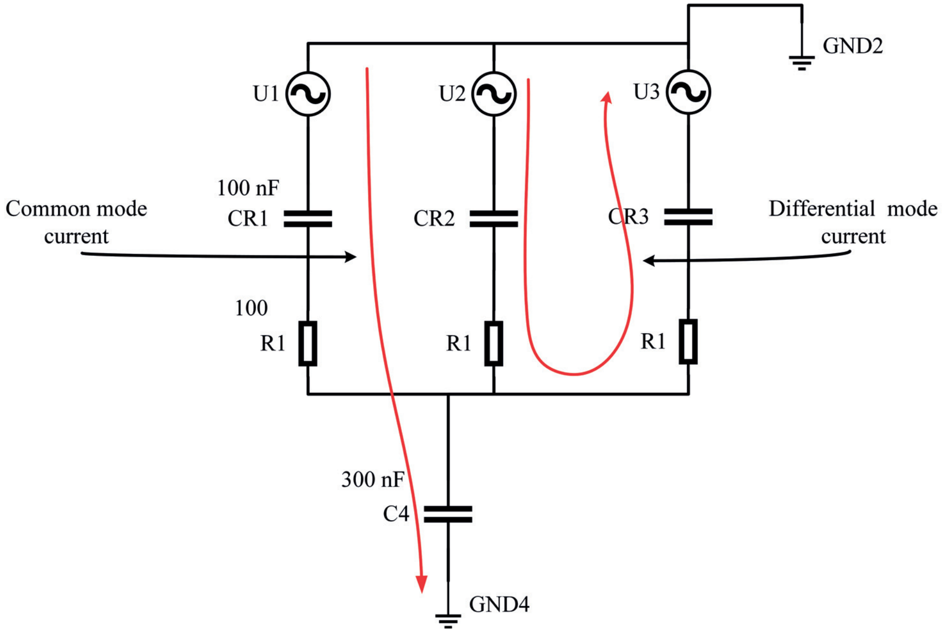


Figure 4.1: Different ways of current passing through the softstarter: common mode and differential mode

To inquiry the overheating problem of the snubber resistor in electric motors, one of the plausible reasons could be connecting to electric drives. As reported, in majority of cases that overheating has happened when one or multiple drives were connected to the same bus-bar [17]. To investigate the harmonics of the VFDs, several measurements with several drive types have been done at the ABB's drive lab FIDRI Helsingfors. To assure the thesis measurements, other industries' measurement like paper mill, marine and chemical plants are also analyzed.

The measurements have been done at both differential mode and common mode and the results are compared to well distinguish the differences. In order to have more realistic analysis, in some of the measurement cases only a single drive is connected to the transformer and in other cases multiple drives have been considered. Unlike the differential mode which harmonic flows in opposite direction, in the common mode harmonics are to sum up since they flow at the same direction in a pair of lines. This results in high harmonics in common mode.

Since the harmonics and losses over snubber resistor are negligible in differential mode, only the common mode has been examined. The analysis demonstrates that in the common mode more harmonics are imposed in the system since the power loss over the snubber resistor is more than the differential mode.

The following designed circuit in figure 4.2 represents the snubber circuit of a

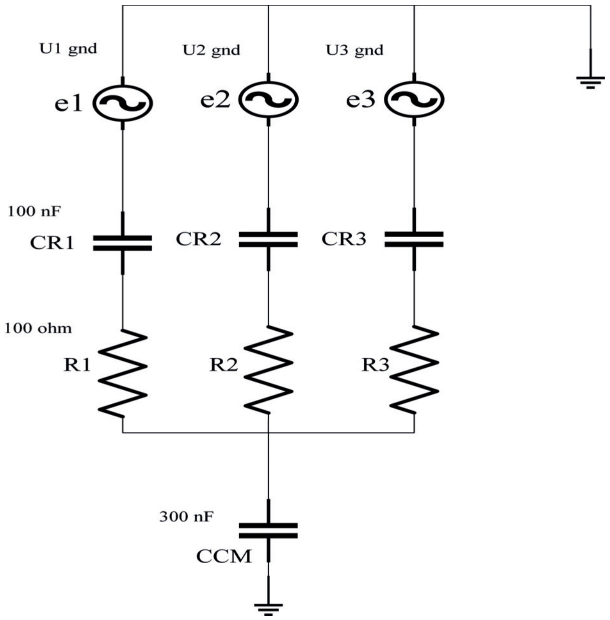


Figure 4.2: A sample snubber circuit of a 3-phase softstarter connected to a 3-phase motor

three phase softstarter that is connected to a 3-phase motor. The motor used at this model is a $400kW$ facility, which is modeled by a $300nF$ capacitor unit. Obviously, the actual circuit is much more complex, here, the model has been simplified and the motor's inductances are neglected. The mentioned $300nF$ common mode capacitance is typical for $400kW$ motor with $100m$ cabling, smaller power motor and shorter motor cable means lower losses due to common mode circuit. Moreover, the measurement analysis shows that most of the losses are due to common mode phenomena [18].

As it is clear in the following figures demonstrated in every case, the magnitude of the high frequency harmonics are reduce when the inductor is employed on the design. The effect is more clear in the case no. 3 with 300 nF capacitance than the other cases. As the magnitude of the high frequency harmonics reduce the dissipated power over the snubber resistor is also decreased thus the snubber resistors current decreases and the resistor doesn't heat up like before. This solution is verified by ELGAR at the ABB Lab in Västerås. The voltage level of the sample data is scaled down to to apply it to the snubber circuit at the Lab environment. There was a drastic change in the heat level of the snubber resistor when a 10mH inductor was added in series to the snubber circuit.

4.1 Harmonic analysis using MATLAB

MATLAB software is one of the best tools used to analyze the measured data to find the harmonics and power losses over the snubber resistor. To have a better understanding, a 3-phase simulation model has been designed, which has been shown in the figure4.3, with the MATLAB simulation package. The measured data is available as an excel file consists of the voltages of every time spot during an entire period. The time intervals are considered 2 μs in the simulation. The sinusoidal power source details used in simulation are 690V, 50Hz. The simulation analysis is also done either with a $400kW$ motor and $37kW$ motor, respectively. The snubber circuit in both PSE and $PSTX$ softstarters have been tested. There are totally nine set of recorded data; five set of data for the $400kW$ motor and four set of data for the $37kW$ motors, respectively.

The excel file can be used as an input file to a controlled voltage source in MATLAB Simulink. By calculating the FFT (fast furrier transform) of the data, the harmonics for a source effected by a drive at the same network can be identified [17]. At the first set of data, no monitoring of temperature were applied at the FIDRI lab in connection with the voltage measurement since the network harmonic was high and it could heat up and damage the snubber circuit. Since the lab in Västerås cannot model the problems with $690V$, the data from FIDRI have been re-scaled to be able to simulate at the Västerås's lab. With degrading the voltage from $690V$ to $300V$ and applying it to a snubber circuit, the effect of harmonics over the snubber resistor could be then well analyzed.

For the data that have high harmonic frequencies around $20KHz$, the capacitor in the circuit is almost short circuited. Thus the entire parallel voltage is applied to the resistor and that's why the current increases dramatically. As a result, the resistor gets too hot and here is when the circuit gets the problem. At this regard and to overcome this problem, an inductor could help to bypass these noisy harmonics. It should be noted that the inductor becomes open circuit for the high frequency harmonics. as a result, the current would decreased at the present branch. As it mentioned before, the system's resonance, which is around $5KHz$ and it doesn't effect the functionality, must be considered. The PSE for a two phase facility is a capacitor with $68nF$ and the $PSTX$ for a three phase facility is a capacitor with $100nF$. Further, the dissipation factor for a $100nF$ capacitor is around 20Ω at $1KHz$.

4.1.1 Results for FFT from MATLAB

To assure that the results are reliable enough, 5 data sets considered at the study from Finland data sets. Since the value of capacitor is different for different motors, here, we considered three different scenarios of capacitor to cover the wide verity of motors; $100nF$, $200nF$, and $300nF$. Furthermore, different cabling scenarios have been considered too; Shorter cabling means the smaller capacitor and it results in less harmonics, less current over snubber circuit.

In cases with harmonics higher than $10kHZ$, when $10mH$ inductor is used in the circuit, the current over the snubber resistor decreases significantly. Therewith, for harmonics less than $10KHz$, using an inductor is not quite effective. While the THD of a system is not high enough, then the snubber resistor doesn't get hot either and no action is required. For the data set no. 6 and 7 of the lab drives, harmonics are low thus there is no sign of heating. At this regard, the THD for each phase in previous data sets is around 10%. The temperature around the snubber resistor did not go beyond $70°C$.

To find the best possible equivalent model, There is a quite challenging decision on the right value of resistor to make the best equivalent circuit in the MATLAB simulation. The measurements in the lab showed that the elements should be chosen to make around $100mA$ over the snubber resistor.

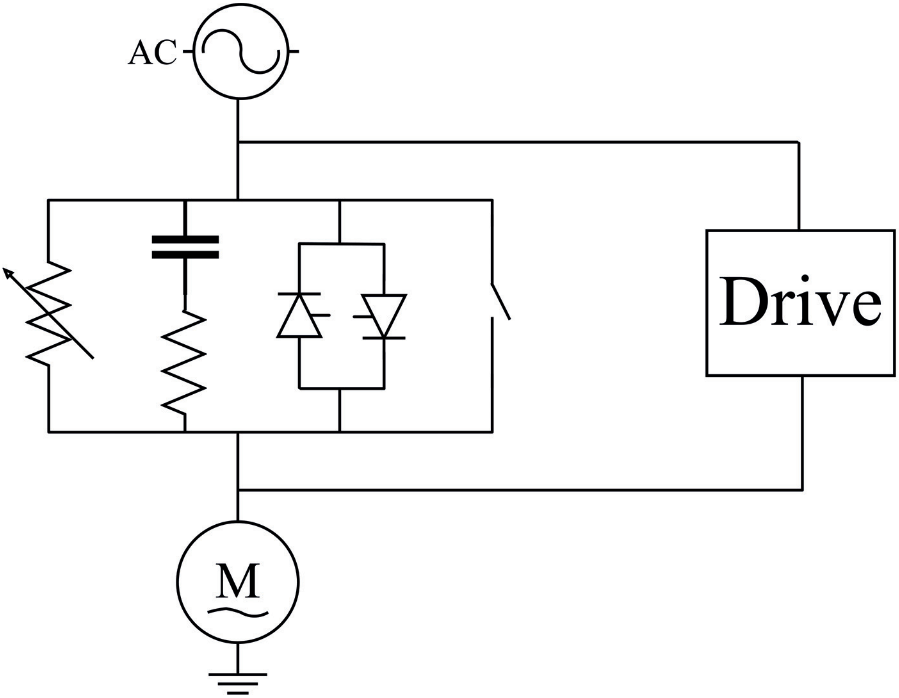


Figure 4.3: A detailed graphical model of the snubber resistor

4.1.2 Case study

Generally, the real circuit of the softstarter which is connected to the motor is way to complex and that's why we considered a relax counterpart to simulate (the indunctances have been neglected). The calculations show that most of losses do happen in the common mode. The common mode calculation is performed on a pair of line in which the signals and noises have same direction flow. The differential mode calculation is performed on a pair of line in which the signals and noises have opposite direction flow.

As a solution, a $10mH$ inductor could decrease the power loss for the snubber resistor which has higher common mode capacitor more than the one with lower common mode capacitor. When the cabling between the motor and the softstarter is long, using an inductor can really help minimizing the snubber resistors power loss and thus heat up. The PSTX snubber circuit resistors are designed for $7W$ ($264mA$) continuous operation. For harmonics around $20kHz$ with $100nF$ as common mode capacitor, using a $10mH$ inductor in series with the snubber resistor is not able to bring the current down below $264mA$. To cope with the former problem, using higher value for the inductor could be the best solution, which can decrease the current even more.

The simulink model is used for analysis and identification of the harmonics, and the results are compared to the harmonics of the original circuit. Here, A $10mH$ inductor is used to support the snubber circuit against the harmful high frequency harmonics. The main parameter in the circuit is the current passing through the resistor as it is the significant parameter to reveal how warm the resistor would get. Thus we choose the current as the reference with a accuracy of 3 digits. This case is based on the data that is collected at the FIDRI lab in Finland site which forms a 3-phase motor that is paralleled with a drive unit, in two different occasions.

4.2 Circuit

Verification of the Simulink model:

The simulation model consists of all snubber circuits components and a capacitor which represents the cabling and motor capacitances. 100Ω resistor as a snubber resistor, 100nF capacitor with a 2Ω resistor as a dissipation factor, is considered as snubber circuit's capacitor. $300nF$ is used as an equivalent component for 100m cabling and motor capacitance. The circuit is even simulated with $200nF$ and 100nF to figure out how short cabling can affect the circuit and power dissipation at snubber resistor. $100\mu H$ is equivalent for a $400kW$ motors inductance. This value is calculated by using motor datasheets for ABB motors.

For each case the table shows the total THD, the peak voltage, the harmonic frequency, the voltage value at that frequency, the snubber resistors current and the snubber resistors dissipated power.

4.3 Case 1

The case no. 1 is based on the data collected at the FIDRI lab in Finland of a 3-phase $400kW/50Hz$ motor with earthed star point that is in parallel with a single IGBT based drive unit. The inductance of the motor is approximately $100\mu H$. the considered inductance is small due to the proportional power scale of the motor connected to the system and high harmonic content (over 20%) of the case reflects this fact.

Owing to the fact that the motor is not able to minimize the high order harmonics entering the circuit, these high harmonics are circulating in the circuit and damaging the snubber resistor. It should be mentioned that the exact values cannot be shared as it is counted as sensitive information of the ABB properties.

4.3.1 Input signal

The 3-phase input data in the common mode practice have been shown in the following figures (4.4,4.5, and4.6). These figures demonstrate voltage in a way that each phase had been grounded and the measurement criteria is between the phase and ground. The sampling step of collecting data is 2μS.

4.3.2 Results of study

The study is done considering three different scenarios where each scenario has a different capacitor size (100, 200 and 300 nF) to simulate the equivalent capacitance of the motor as well as the cabling system. Each scenario has been simulated with and without the extra inductor and the results in both way are reported. As it is shown in the following tables (4.1, 4.2, and 4.3), adding the inductance could reduce the dissipated power significantly through reducing the current that flows through the snubber resistor in the high harmonic contents. In other words, in high frequencies the inductor acts as a filter and compensates for the low impedance of the capacitor.

This solution has been verified by ELGAR at the ABB Lab in Västerås. The voltage level of the sample data has been scaled down to be applicable to apply to the snubber circuit in the Lab model. There was a dramatic change in the heat level of the snubber resistor when a $10mH$ inductor was added in series to the snubber circuit. The snubber resistor didn't heat up when a $10mH$ inductor was placed in series with the snubber circuit. During the test the heat of the snubber resistor was constantly monitored with a heat camera. In all simulation cases, the $10mH$ series inductance could draw down the snubber resistor current to below $264mA$, except for phase 2 with 100nF as a cabling capacitor. At this case, a slightly higher amount of the series inductance can solve this problem and draw the current to below $264mA$.

As it is shown in the following table, adding the inductance could reduce the dissipated power significantly through reducing the current that flows through the resistor in the high harmonic contents. In other words, in high frequencies, the inductor acts as a filter and compensates for the low impedance of the capacitor. As shown in the table the dissipation is improved between 7,96 − 37,41 times for different scenarios.

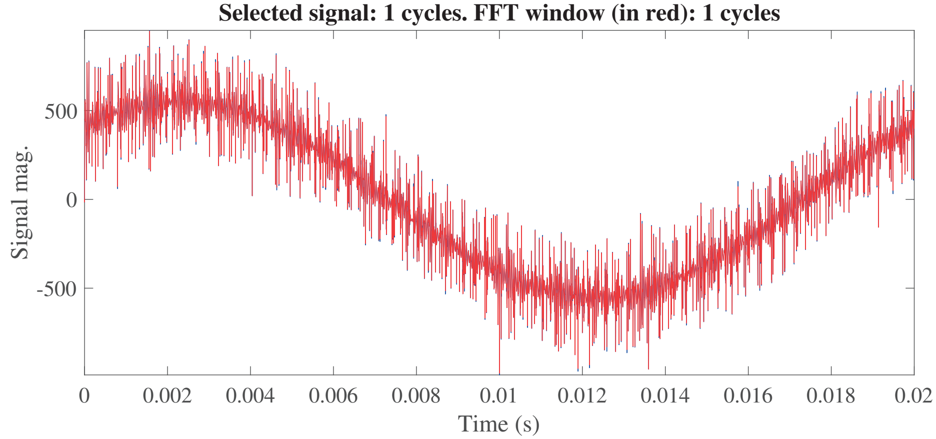


Figure 4.4: The input signal phase no.1

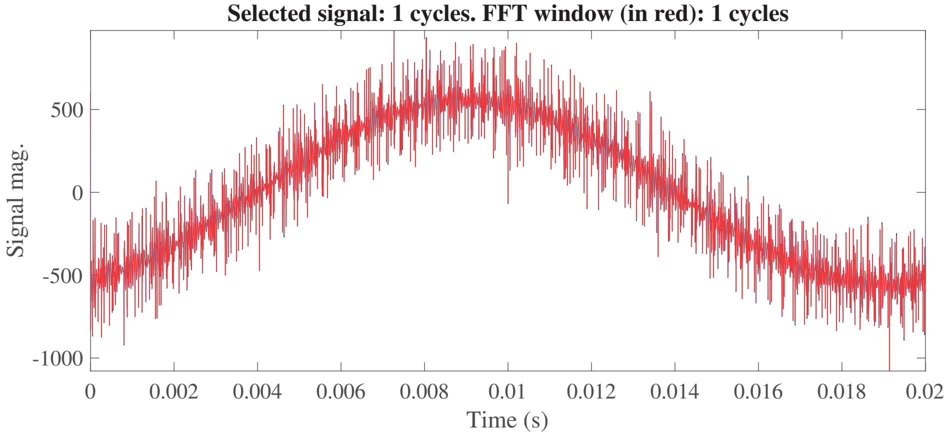


Figure 4.5: The input signal phase no.2

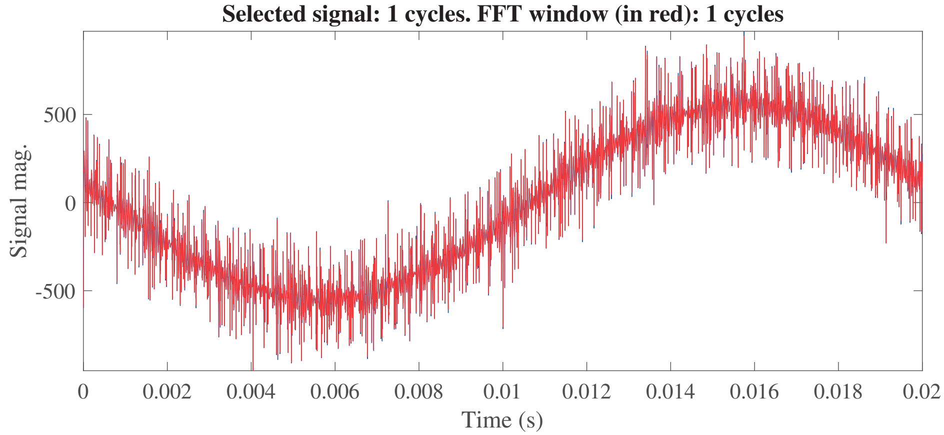


Figure 4.6: The input signal phase no.3

Case.1 phase.1	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	10,34	553,06	21050	6,62	0,221	4,88
Without inductor	21,43	553,01	21050	22,32	0,731	53,48
CM Capacitor=200nF						
With inductor 10mH	9,45	552,97	21050	5,95	0,186	3,46
Without inductor	29,05	552,90	21050	34,27	0,995	91,26
CM Capacitor=300nF						
With inductor 10mH	9,17	552,90	21050	5,75	0,176	3,10
Without inductor	33,23	552,90	21050	40,81	1,079	116,38

Table 4.1: Results of study in case no.1-phase 1 with three different capacitor values and with/without inductor

Case.1 phase.2	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	17,23	554,08	21050	7,58	0,279	7,78
Without inductor	22,55	554,05	21050	23,75	0,787	62,02
CM Capacitor=200nF						
With inductor 10mH	16,71	554,36	21050	6,98	0,252	6,34
Without inductor	30,13	554,34	21050	35,75	1,008	101,56
CM Capacitor=300nF						
With inductor 10mH	16,54	554,60	21050	6,69	0,244	5,96
Without inductor	34,29	554,58	21050	42,29	1,130	127,62

Table 4.2: Results of study in case no.1-phase 2 with three different capacitor values and with/without inductor

Case.1 phase.3	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	13,02	553,96	21050	6,53	0,242	5,86
Without inductor	22,29	553,95	21050	23,33	0,778	60,04
CM Capacitor=200nF						
With inductor 10mH	12,33	553,78	21050	5,86	0,210	4,43
Without inductor	29,87	553,75	21050	35,28	1,002	100,38
CM Capacitor=300nF						
With inductor 10mH	12,12	553,82	21050	5,66	0,202	4,08
Without inductor	34,09	553,89	21050	41,83	1,126	126,68

Table 4.3: Results of study in case no.1-phase 3 with three different capacitor values and with/without inductor

These output figures (4.7, 4.8, 4.9, 4.10, 4.11, 4.12, 4.13, 4.14, and 4.15), are to prove the main claim about the results. The magnitudes are reduced when the inductor is employed on the design.

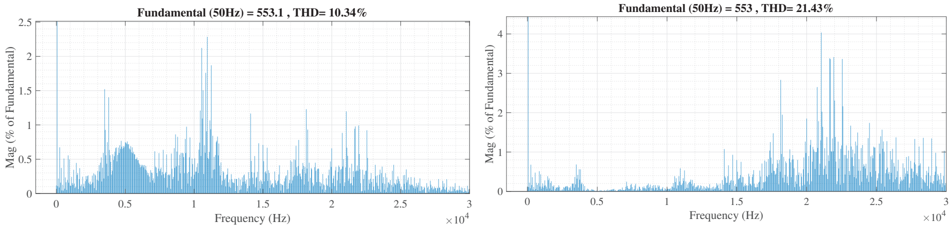


Figure 4.7: The case no.1 phase 1 with $100nF$ with/without extra inductor

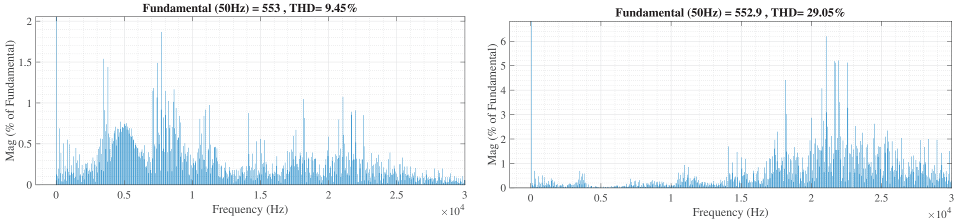


Figure 4.8: The case no.1 phase 1 with $200nF$ with/without extra inductor

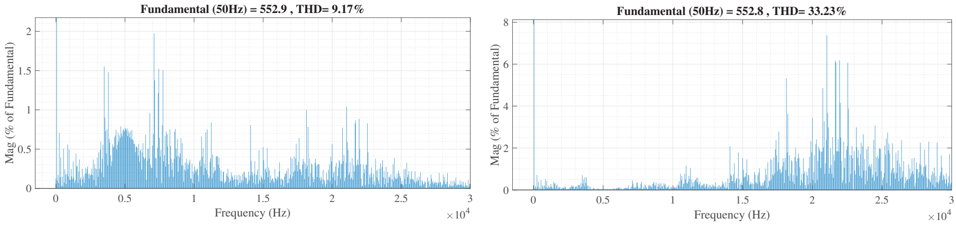


Figure 4.9: The case no.1 phase 1 with $300nF$ with/without extra inductor

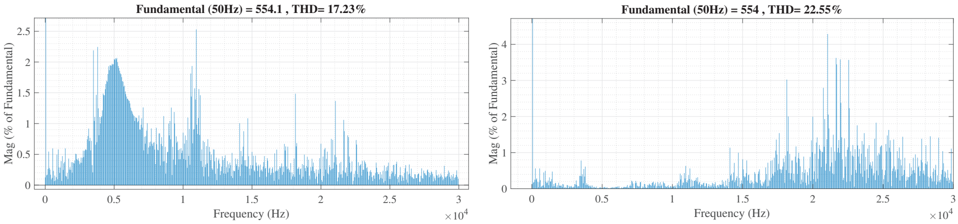


Figure 4.10: The case no.1 phase 2 with $100nF$ with/without extra inductor

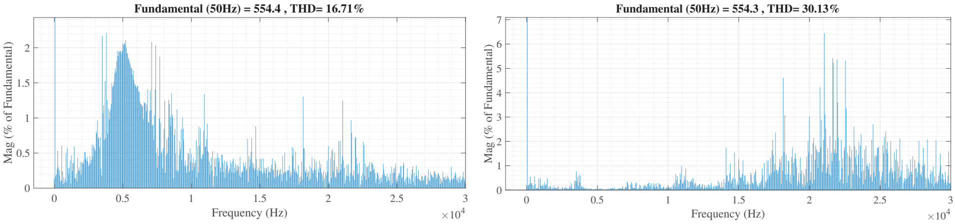


Figure 4.11: The case no.1 phase 2 with $200nF$ with/without extra inductor

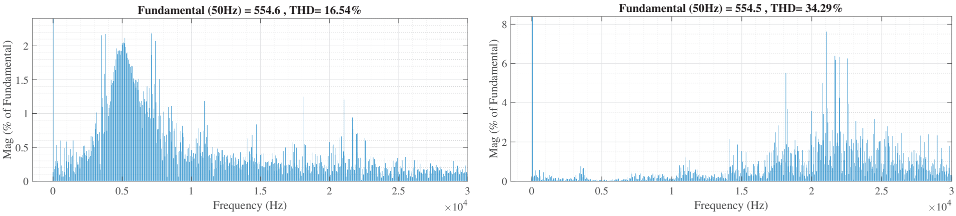


Figure 4.12: The case no.1 phase 2 with $300nF$ with/without extra inductor

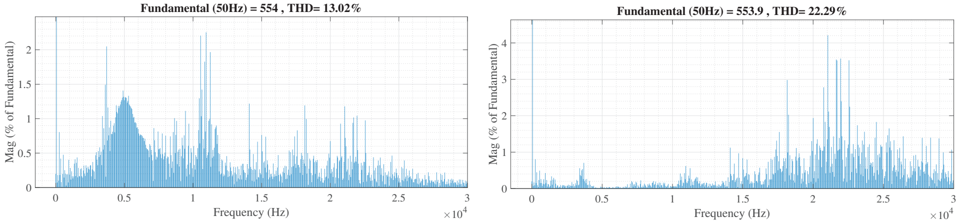


Figure 4.13: The case no.1 phase 3 with $100nF$ with/without extra inductor

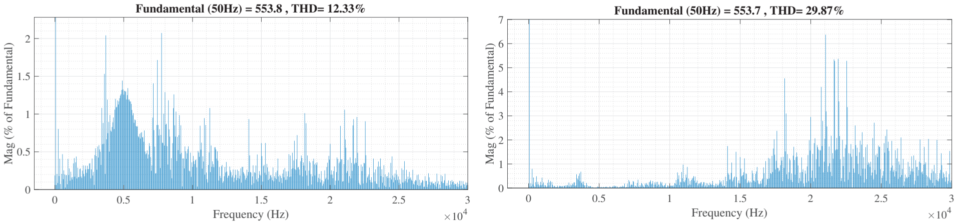


Figure 4.14: The case no.1 phase 3 with $200nF$ with/without extra inductor

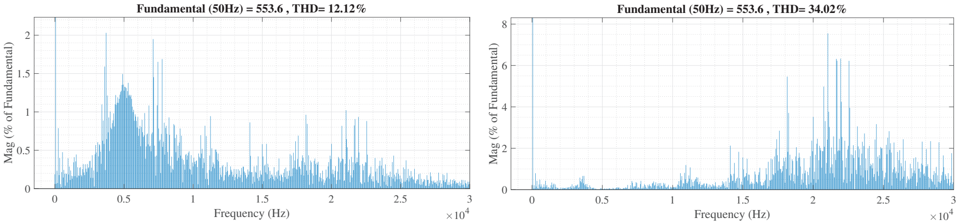


Figure 4.15: The case no.1 phase 3 with $300nF$ with/without extra inductor

4.4 Case 2

The case no.2 is based on the data collected at the FIDRI lab in Finland of a 3-phase $400kW/50Hz$ motor with earthed star point that is paralleled with a single diode based drive unit. The inductance of the motor is approximately $100\mu H$. The considered inductance is small due to the proportional power scale of the motor to the system that is connected to and high harmonic content (over 20%) of the case reflects this fact.

Due to this fact the motor is not able to minimize the high order harmonics entering the circuit. Thus these high harmonics circulate in the circuit and effects the snubber resistor. The exact values cannot be shared as it is counted as sensitive information of the ABB properties.

4.4.1 Input signal

The 3-phase input data in the common mode practice have been shown in the following figures (4.16,4.17, and 4.18). These figures demonstrate voltage in a way that each phase had been grounded and the measurement criteria is between the phase and ground. The sampling is done every 2μS.

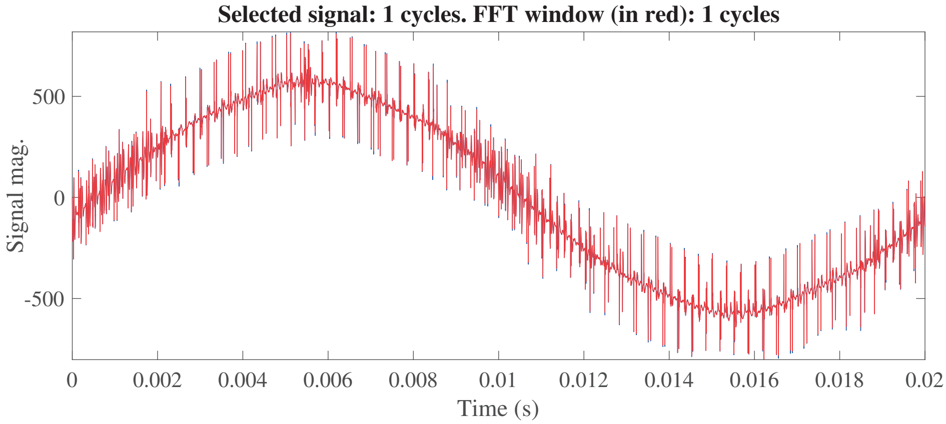


Figure 4.16: The input signal phase no.1

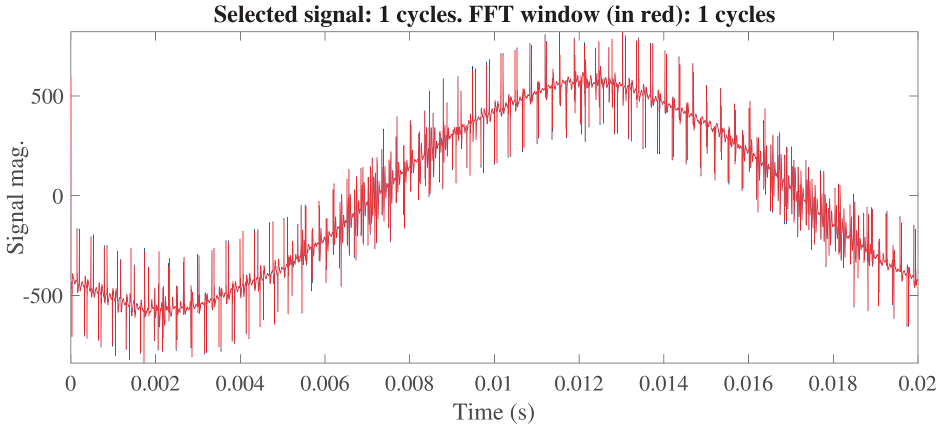


Figure 4.17: The input signal phase no.2

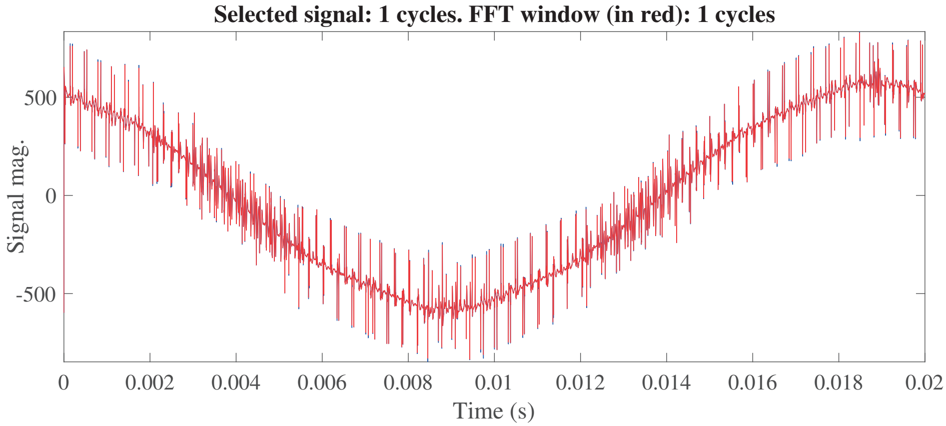


Figure 4.18: The input signal phase no.3

4.4.2 Results of the study

The study is done considering three different scenarios, in which every scenario implements a different capacitor size (100, 200 and 300 nF) to simulate the equivalent capacitance of the motor as well as the cabling system. In each scenario, the authors have considered both with/without inductor to present in detail results. As it is shown in the following tables (4.4, 4.5, and 4.6), adding the inductance could reduce the dissipated power significantly through reducing the current level through the snubber resistor at the high harmonic contents. In other words, in high frequencies the inductor acts as a filter and compensates for the low impedance of the capacitor.

Frequency figures (4.19, 4.20, 4.21, 4.22, 4.23, 4.24, 4.25, 4.26, and 4.27) of the section are shown here.

In all simulation cases, the series $10mH$ inductance could turn down the snubber resistor current to below $264mA$. As it is shown in the tables (4.4,4.5, and 4.6), adding the inductance could reduce the dissipated power significantly by reducing the current flow level of the resistor in the high harmonic contents. In other words, in high frequencies the inductor acts as a filter and compensates for the low impedance of the capacitor. As shown in the table the dissipation is improved between 5,63 – 49,90 times for different scenarios.

Case.2 phase.1	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	5,28	558,06	20950	1,84	0,102	1,04
Without inductor	15,28	558,01	20950	8,06	0,446	19,88
CM Capacitor=200nF						
With inductor 10mH	5,02	557,91	20950	1,69	0,091	0,82
Without inductor	15,91	557,81	20950	10,75	0,531	28,18
CM Capacitor=300nF						
With inductor 10mH	4,63	557,81	20950	1,32	0,081	0,66
Without inductor	17,27	557,71	20950	12,27	0,57	32,94

Table 4.4: Results of study in case no.2-phase 1 with three different capacitor values and with/without inductor

Case.2 phase.2	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	13,86	559,46	20950	1,51	0,191	3,60
Without inductor	13,59	559,39	20950	8,28	0,481	23,12
CM Capacitor=200nF						
With inductor 10mH	13,68	559,71	20950	1,21	0,182	3,32
Without inductor	16,15	559,01	20950	11,72	0,561	31,38
CM Capacitor=300nF						
With inductor 10mH	13,54	560,01	20950	1,39	0,178	3,16
Without inductor	17,47	559,91	20950	11,88	0,601	36,06

Table 4.5: Results of study in case no.2-phase 2 with three different capacitor values and with/without inductor

Case.2 phase.3	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	15,12	559,25	20950	0,71	0,203	4,14
Without inductor	13,17	559,01	20950	7,23	0,481	23,32
CM Capacitor=200nF						
With inductor 10mH	15,01	559,01	20950	0,78	0,196	3,86
Without inductor	15,74	559,01	20950	12,07	0,561	31,52
CM Capacitor=300nF						
With inductor 10mH	14,92	558,98	20950	0,98	0,193	3,72
Without inductor	17,08	558,89	20950	12,73	0,602	36,3

Table 4.6: Results of study in case no.2-phase 3 with three different capacitor values and with/without inductor

The following figures (4.19,4.20,4.21,4.22,4.23,4.24,4.25,4.26, ad 4.27) are to compare the frequency responses for all possible cases in both conditions (with and without extra inductor). The mentioned thought about the adding extra inductor's function in the high frequencies is clear.

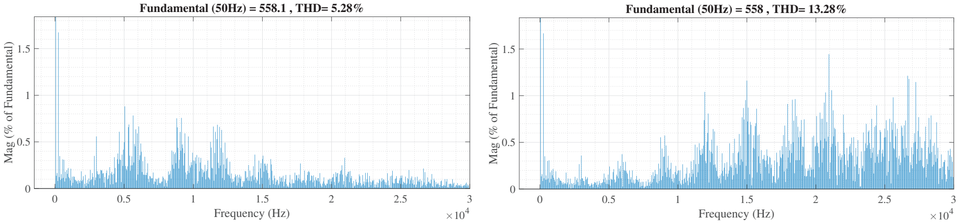


Figure 4.19: The case no.2 phase 1 with $100nF$ with/without extra inductor

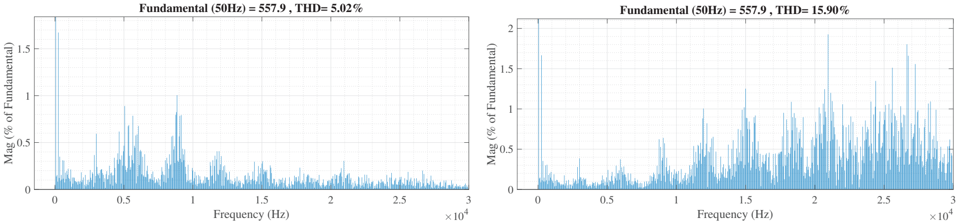


Figure 4.20: The case no.2 phase 1 with $200nF$ with/without extra inductor

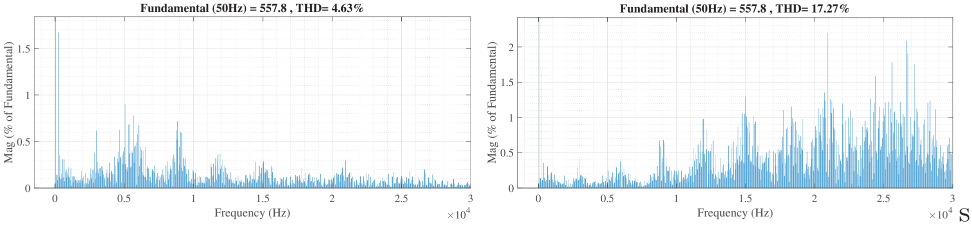


Figure 4.21: The case no.2 phase 1 with $300nF$ with/without extra inductor

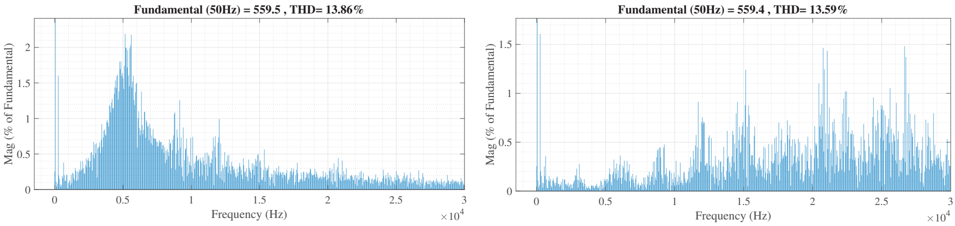


Figure 4.22: The case no.2 phase 2 with $100nF$ with/without extra inductor

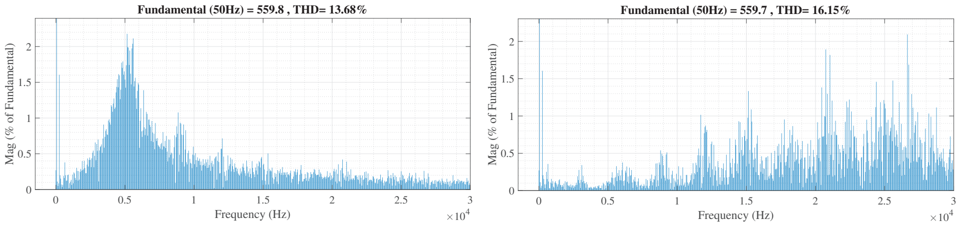


Figure 4.23: The case no.2 phase 2 with $200nF$ with/without extra inductor

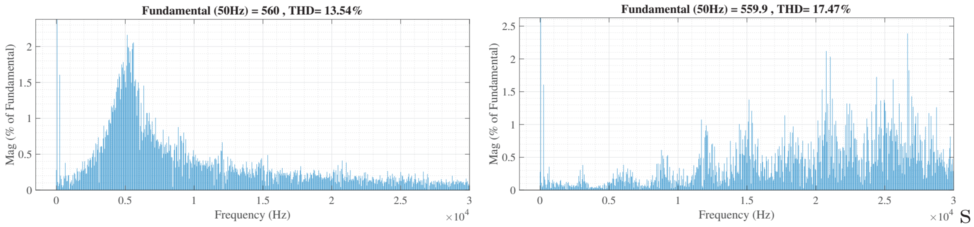


Figure 4.24: The case no.2 phase 3 with $300nF$ with/without extra inductor

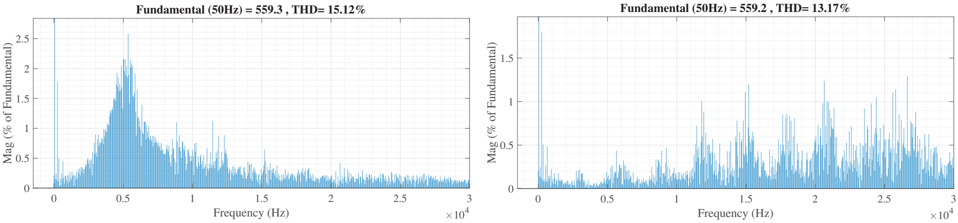


Figure 4.25: The case no.2 phase 3 with $100nF$ with/without extra inductor

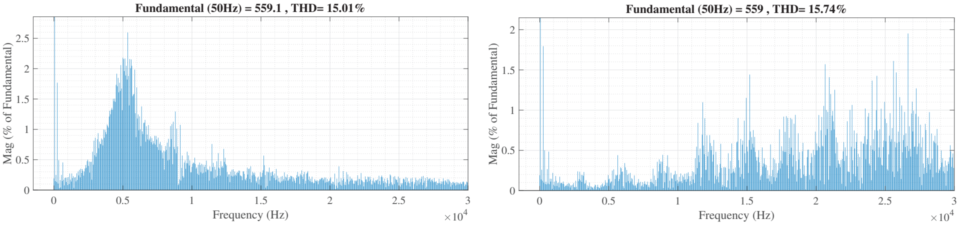


Figure 4.26: The case no.2 phase 3 with $200nF$ with/without extra inductor

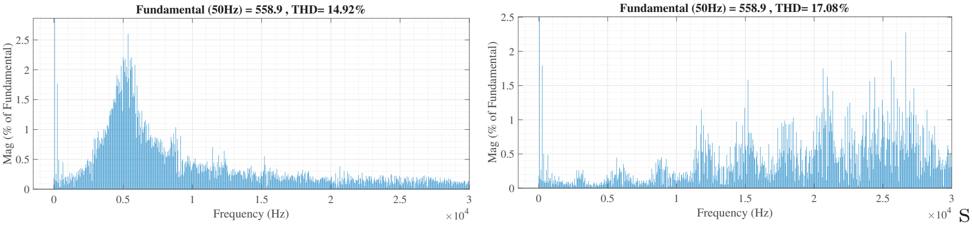


Figure 4.27: The case no.2 phase 3 with $300nF$ with/without extra inductor

4.5 Case 3

The case no. 3 is based on the collected data at Paper Mill from a 3-phase $400kW/50Hz$ motor with earthed star point that is in parallel with a multiple IGBT based drive unit. The inductance of the motor is approximately $100\mu H$. the considered inductance is small due to the proportional power scale of the motor connected to the system and high harmonic content (over 20%) of the case reflects this fact.

Due to the fact that the motor is not able to minimize the high order harmonics entering the circuit, these high harmonics circulate in the circuit and affect the snubber resistor. It should be mentioned that the exact values cannot be shared as it is counted as sensitive information of the ABB properties.

4.5.1 Input signal

The three phase input data in the common mode practice has been shown in the following figures (4.28,4.29, and 4.30). These figures demonstrate voltage in a way that each phase had been grounded and the measurement criteria is between the phase and the ground. The sampling is done each 2μS.

4.5.2 Results of the study

Again, the three scenarios including different capacitor size (100, 200 and 300 nF) has been chosen here to simulate the equivalent capacitance of the motor as well as the cabling system. Each scenario would present with/without inductor to present in detail result. As it is shown in the following figures (4.31,4.32,4.33,4.34,4.35,4.36,4.37,4.38, and 4.39), additional inductance could reduce the dissipated power through declining the current that flows through the snubber resistor at the high harmonic parts. In high frequency times the inductor acts as a high-pass filter and compensate the low impedance of the capacitor.

Like the other cases, the figures (4.31, 4.32, 4.33, 4.34, 4.35, 4.36, 4.37, 4.38, and 4.39), of this section are proving the main claim of the authors.

In all simulation cases, the $10mH$ series inductance could draw down the snubber resistor current to below $264mA$. For case no. 3 the harmonics are more distributed around $15kHZ$ and unlike case no. 1 and case 2 which had harmonics distributed around $20kHZ$ in which adding a $10mH$ inductor plays a big role and eliminates harmonics more. For a cabling capacitor as big as $100nF$ and $200nF$ adding a $10mH$ is not very effective and cannot draw the current below $264mA$. For these cases a bigger inductor should be employed. Besides, for a cabling capacitor as big as $300nF$ adding a $15mH$ inductor instead of a $10mH$ must be regarded in order to turn down the current below $264mA$.

As it is shown in the following tables (4.7,4.8, and 4.9), adding the extra inductance could reduce the dissipated power significantly by reducing the current flow level of the resistor in the high harmonic contents. In other words, in high frequencies the inductor acts as a filter and it compensates the low impedance issue of the capacitor. As shown in the mentioned tables, the dissipation is improved between 2,00 – 10,37 times for different scenarios by using a $10mH$ inductor and 27,86 times better by using a $15mH$ inductor. For cabling capacitor size equal to $100nF$ and $200nF$ adding a $15mH$ inductor didn't draw the snubber resistor current below $264mA$, and that's why the results are not added here. Total THD for all the scenarios in case no.3 is under 20. The frequency with high harmonic between $10kHZ$ and $30kHZ$ is at $14100HZ$.

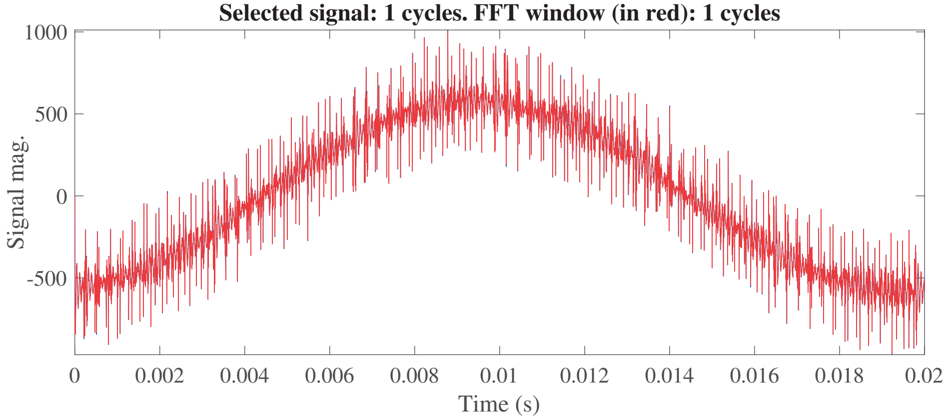


Figure 4.28: The input signal phase no.1

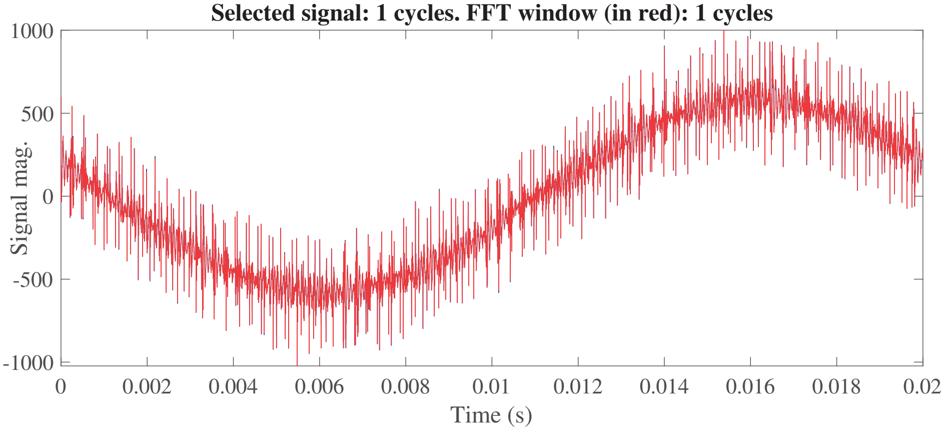


Figure 4.29: The input signal phase no.2

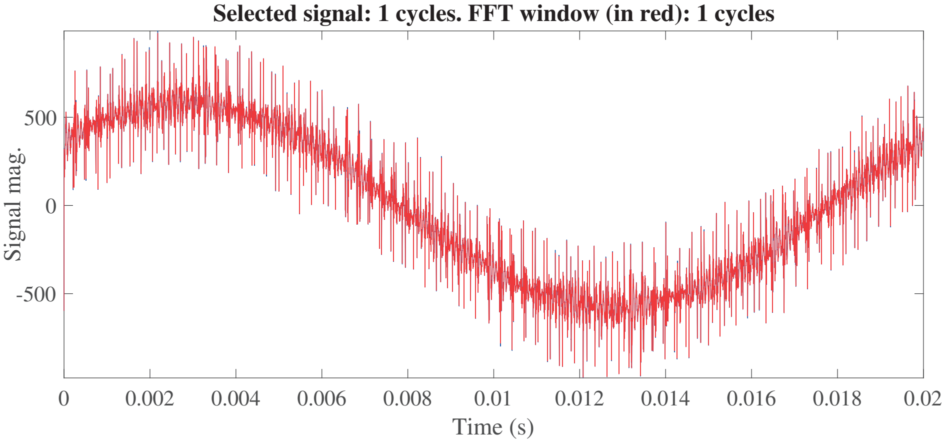


Figure 4.30: The input signal phase no.3

Case.3 phase.1	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	22,64	582	14100	29,49	0,52	27,14
Without inductor	21,48	579	14100	31,47	0,750	56,30
CM Capacitor=200nF						
With inductor 10mH	16,30	579	14100	27,21	0,343	11,82
Without inductor	28,21	579	14100	55,84	0,919	84,62
CM Capacitor=300nF						
With inductor 15mH	12,71	579	14100	15,39	0,202	4,08
With inductor 10mH	15,81	580	14100	25,52	0,321	10,34
Without inductor	32,29	579	14100	68,08	1,022	104,36

Table 4.7: Results of study in case no.3 phase no.1 with three different capacitor values and with/without inductor

Case.3 phase.2	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	22,03	581	14100	29,61	0,518	26,84
Without inductor	21,41	581	14100	31,85	0,743	55,30
CM Capacitor=200nF						
With inductor 10mH	15,58	581	14100	27,18	0,339	11,52
Without inductor	28,26	581	14100	56,73	0,918	84,42
CM Capacitor=300nF						
With inductor 15mH	11,48	582	14100	15,27	0,193	3,76
With inductor 10mH	15,14	580	14100	24,60	0,317	10,08
Without inductor	32,39	581	14100	69,04	1,023	104,58

Table 4.8: Results of study in case no.3 phase no.2 with three different capacitor values and with/without inductor

Case.3 phase.3	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	25,08	580	14100	29,11	0,539	29,08
Without inductor	21,49	580	14100	35,94	0,763	58,26
CM Capacitor=200nF						
With inductor 10mH	20,10	580	14100	25,38	0,374	13,98
Without inductor	28,33	580	14100	56,27	0,935	87,56
CM Capacitor=300nF						
With inductor 15mH	18,91	580	14100	13.56	0,248	6,15
With inductor 10mH	20,07	581	14100	23,21	0,356	12,68
Without inductor	32,45	580	14100	68,59	10,390	107,96

Table 4.9: Results of study in case no.3 phase no.3 with three different capacitor values and with/without inductor

As the magnitude of the high frequency harmonics reduce the dissipated power over the snubber resistor is also decreased thus the snubber resistors current decreases and the resistor doesn't heat up like before. This solution is verified by ELGAR at the ABB Lab in Västerås. The voltage level of the sample data is scaled down to to apply it to the snubber circuit at the Lab environment. There was a drastic change in the heat level of the snubber resistor when a $10mH$ inductor was added in series to the snubber circuit.

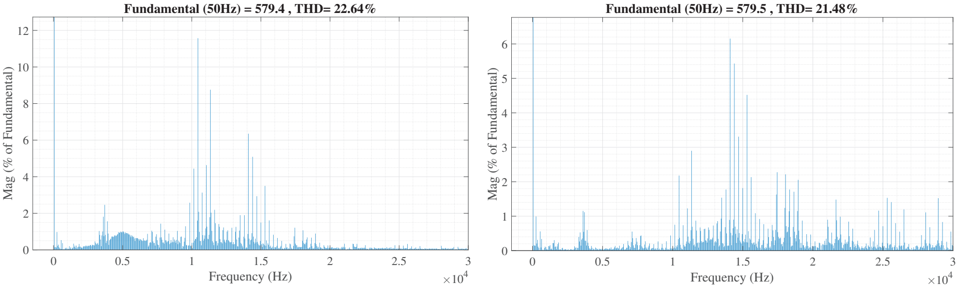


Figure 4.31: The case no.3 phase 1 with $100nF$ with/without extra inductor

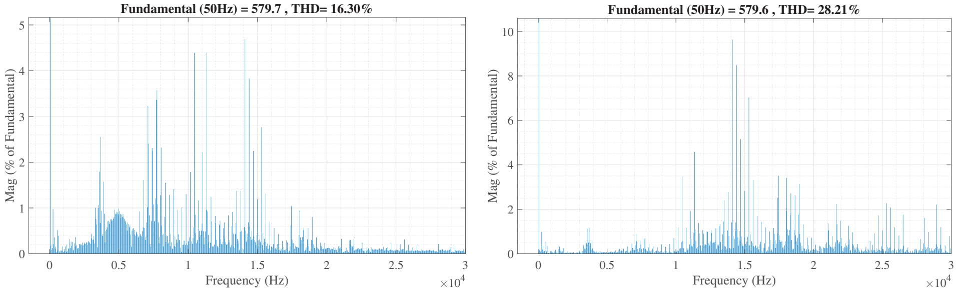


Figure 4.32: The case no.3 phase 1 with $200nF$ with/without extra inductor

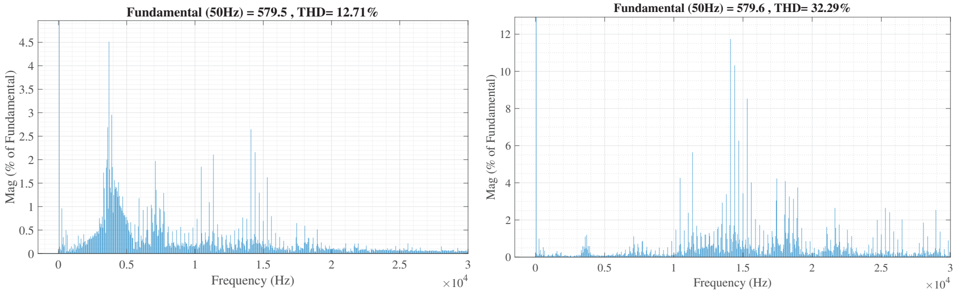


Figure 4.33: The case no.3 phase 1 with $300nF$ with/without extra inductor

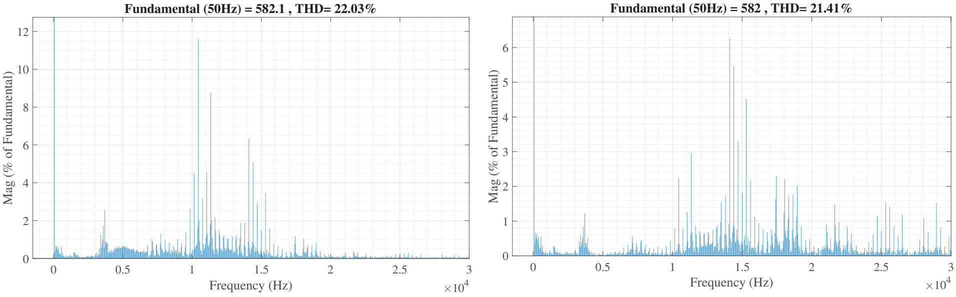


Figure 4.34: The case no.3 phase 2 with $100nF$ with/without extra inductor

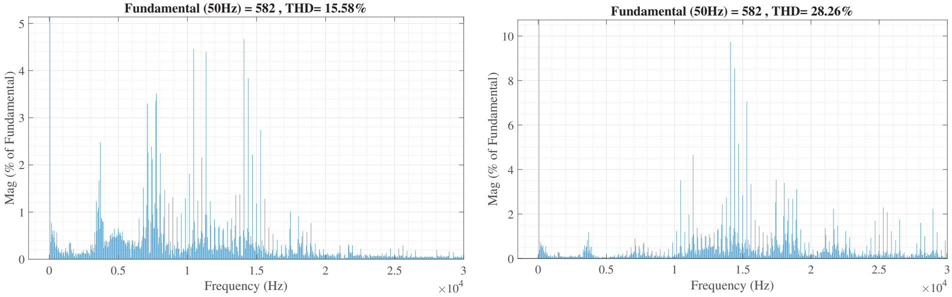


Figure 4.35: The case no.3 phase 2 with $200nF$ with/without extra inductor

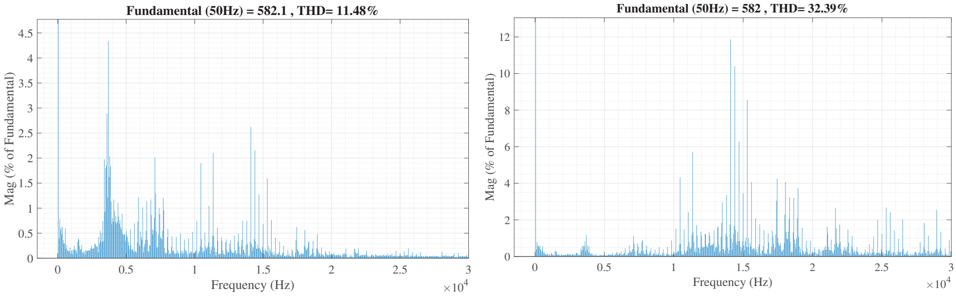


Figure 4.36: The case no.3 phase 2 with $300nF$ with/without extra inductor

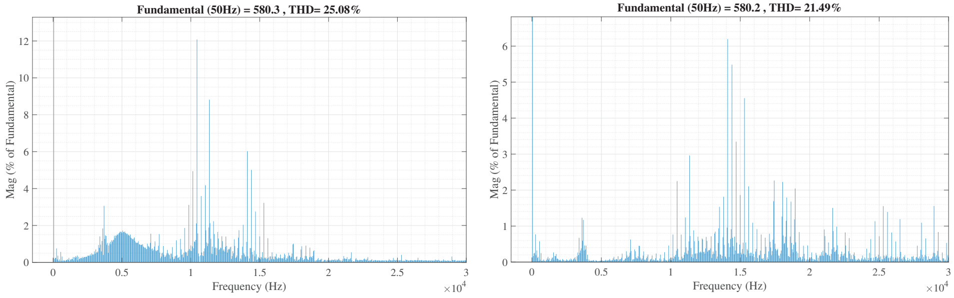


Figure 4.37: The case no.3 phase 3 with $100nF$ with/without extra inductor

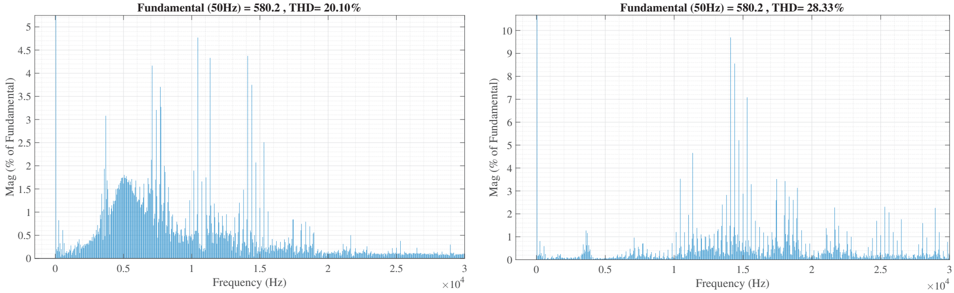


Figure 4.38: The case no.3 phase 3 with $200nF$ with/without extra inductor

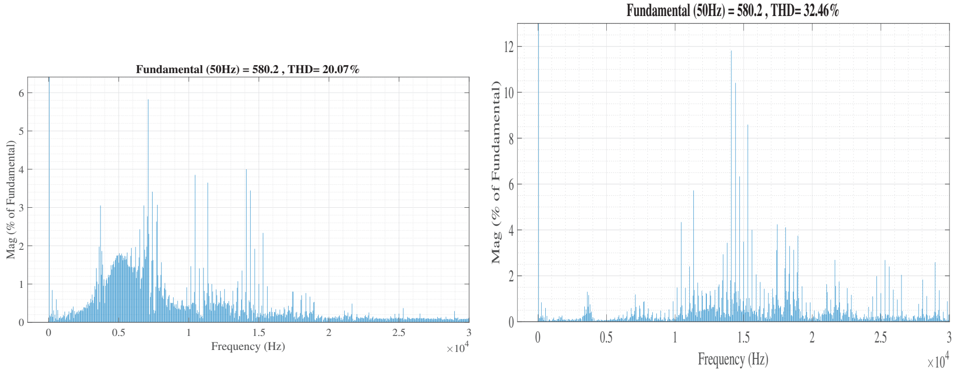


Figure 4.39: The case no.3 phase 3 with $300nF$ with/without extra inductor

4.6 Case 4

The case no. 4 is based on the collected data at chemical plant from a 3-phase $400kW/50Hz$ motor with earthed star point that is in parallel with a several single IGBT based drive unit. The inductance of the motor is approximately $100\mu H$. the considered inductance is small due to the proportional power scale of the motor to the system that is connected to and high harmonic content (over 20%) of the case reflects this fact.

Due to the mentioned fact, the motor is not able to minimize the high order harmonics entering the circuit, and in turn these high harmonics circulate in the circuit and affect the snubber resistor. It should be mentioned that the exact values cannot be shared as it is counted considered as sensitive information of the ABB properties.

4.6.1 Input signal

The 3-phase input data in the common mode practice has been shown in the following figures (4.40, 4.41, and 4.42). These figures demonstrate the voltage in a way that each phase had been grounded and the measurement criteria is between the phase and the ground. The sampling is done each 2μS.

4.6.2 Results of the study

The study is done considering three different scenarios, in which each scenario has a different capacitor size (100, 200 and 300 nF) to simulate the equal model of the motor as well as the cabling system. Each scenario is simulated with and without the inductor. As it is shown in the following figures (4.43, 4.44, 4.45, 4.46, 4.47, 4.48, 4.49, 4.50, and 4.51), adding the inductance could reduce the dissipated power significantly by reducing the current flow rate through the snubber resistor at the high harmonic contents. In other words, in high frequencies the inductor acts as a filter and compensate the low impedance of the capacitor.

What we can see from figure is that the magnitude of high frequency harmonics are reduced significantly through applying the inductor to the system. The effect is more significant for the case with $300nF$ capacitance than the case with $100nF$. For case no. 4 the high harmonics are concentrated between $20kHZ$ and $30kHZ$. Thus the $10mH$ inductor has the powerful effect on reducing of the high frequency harmonics. High frequency harmonics above $20kHZ$ cause the most power dissipation in the snubber resistor hence applying of an inductor has a big effect on reducing these harmonics and as a result the power dissipation on the snubber resistor.

In all simulation cases, the series $10mH$ inductance could draw down the snubber resistor current to below $264mA$. For case 4, most of the harmonics are more distributed between $20kHZ$ and $30kHZ$, unlike case no.1 and case 2 which had harmonics distributed around $20kHZ$, adding an inductor as big as $10mH$ plays a huge role and eliminates harmful harmonics. Furthermore, applying a $10mH$ inductor draws the snubber resistor current below $264mA$ for all the cabling capacitance (capacitance values are: $100nF$, $200nF$ and $300nF$). At this regard, the following tables (4.10, 4.11, and 4.12) show that adding the inductance could reduce the dissipated power significantly through reducing the current flow rate through the resistor in the high harmonic contents. In other words, in high frequencies the inductor acts as a filter and compensate the low impedance of the capacitor.

From the mentioned tables, the dissipation is improved between 4,07 – 43,42 times for different values by using a $10mH$ inductor. Moreover, the total THD for all the scenarios in case 4 is under 20. The frequency with high harmonic between $10kHZ$ and $30kHZ$ is at $22350HZ$.

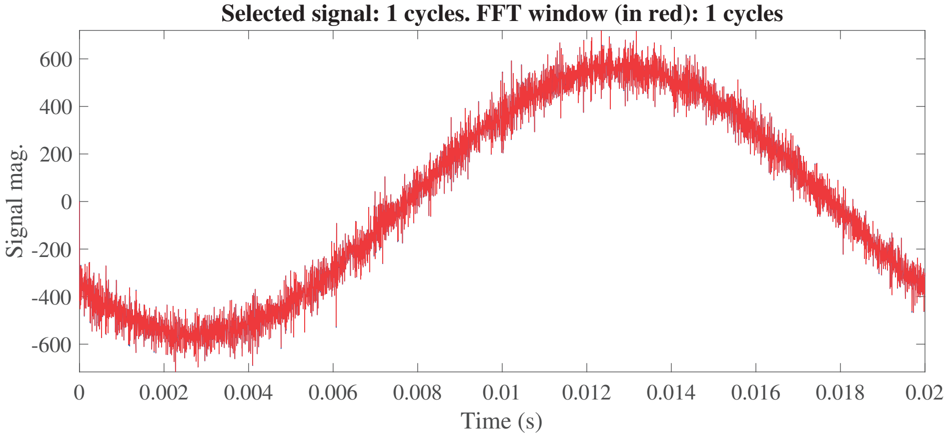


Figure 4.40: The input signal phase no.1

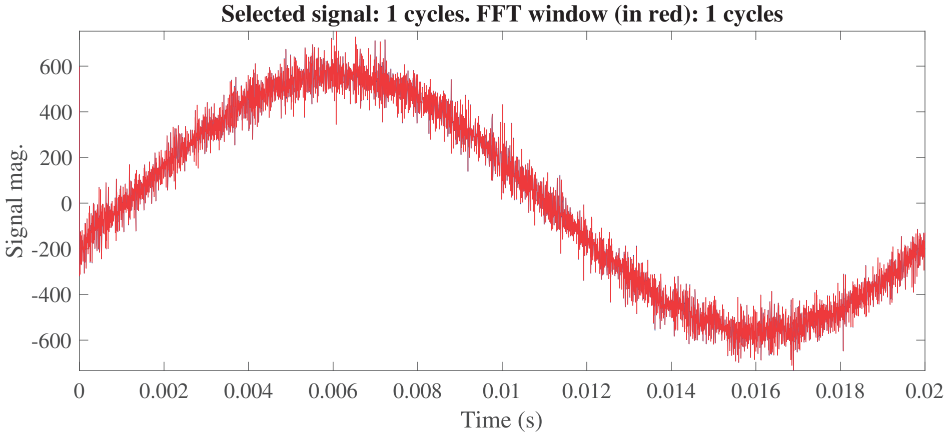


Figure 4.41: The input signal phase no.2

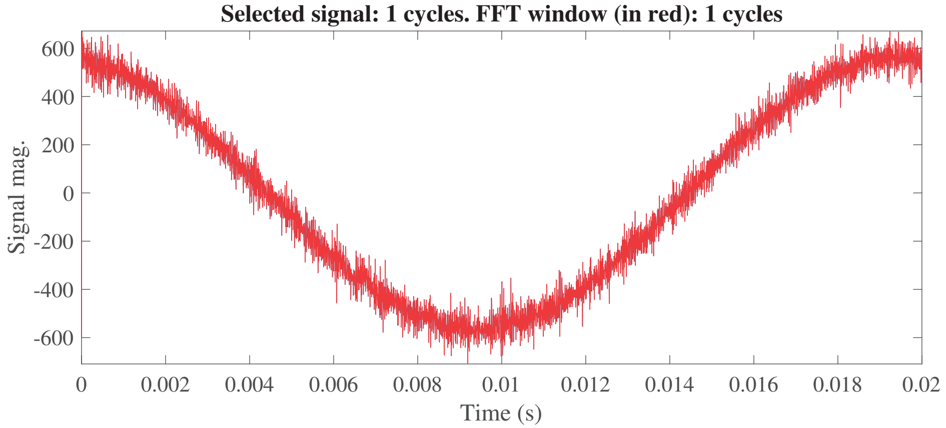


Figure 4.42: The input signal phase no.3

Case.4 phase.1	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	5,49	560	22350	1,12	0,085	0,73
Without inductor	11,05	560	22350	5,16	0,404	16,36
CM Capacitor=200nF						
With inductor 10mH	5,32	560	22350	0,98	0,077	0,59
Without inductor	13,04	560	22350	7,73	0,461	21,58
CM Capacitor=300nF						
With inductor 10mH	5,26	560	22350	0,97	0,074	0,56
Without inductor	14,03	560	22350	9,11	0,493	24,32

Table 4.10: Results of study in case no.4 phase no.1 with three different capacitor values and with/without inductor

Case.4 phase.2	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	10,80	560	22350	0,98	0,143	2,04
Without inductor	9,90	560	22350	4,86	0,375	14,10
CM Capacitor=200nF						
With inductor 10mH	10,72	560	22350	1,01	0,138	1,92
Without inductor	12,05	560	22350	7,39	0,430	19,30
CM Capacitor=300nF						
With inductor 10mH	10,69	560	22350	0,99	0,137	1,88
Without inductor	13,12	560	22350	8,76	0,470	22,16

Table 4.11: Results of study in case no.4 phase no.2 with three different capacitor values and with/without inductor

Case.4 phase.3	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	15,01	560	22350	1,01	0,193	3,74
Without inductor	9,70	560	22350	5,23	0,390	15,23
CM Capacitor=200nF						
With inductor 10mH	14,94	560	22350	1,02	0,189	3,58
Without inductor	12,20	560	22350	7,83	0,465	21,60
CM Capacitor=300nF						
With inductor 10mH	14,09	560	22350	0,96	0,180	3,54 heightWithout inductor
13,39	560	22350	9,23	0,490	24,98	

Table 4.12: Results of study in case no.4 phase no.3 with three different capacitor values and with/without inductor

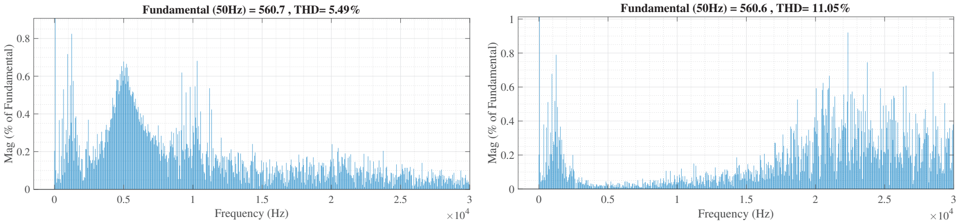


Figure 4.43: The case no.4 phase 1 with $100nF$ with/without extra inductor

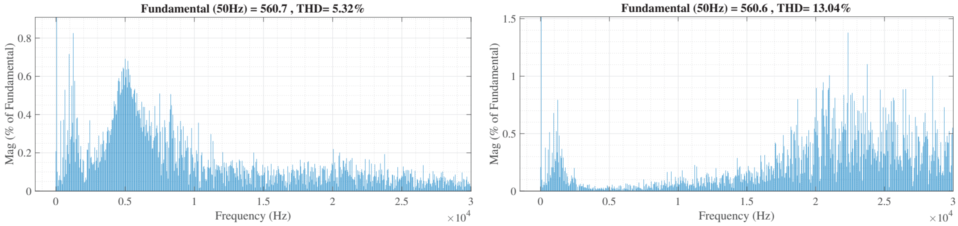


Figure 4.44: The case no.4 phase 1 with $200nF$ with/without extra inductor

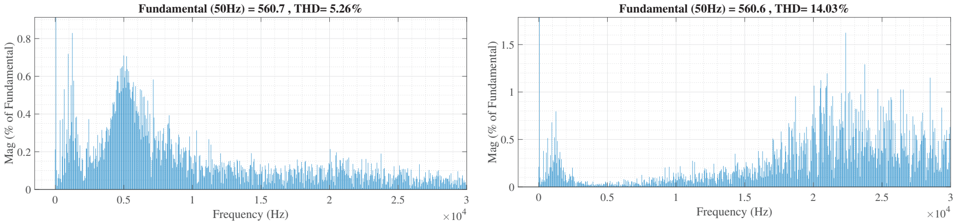
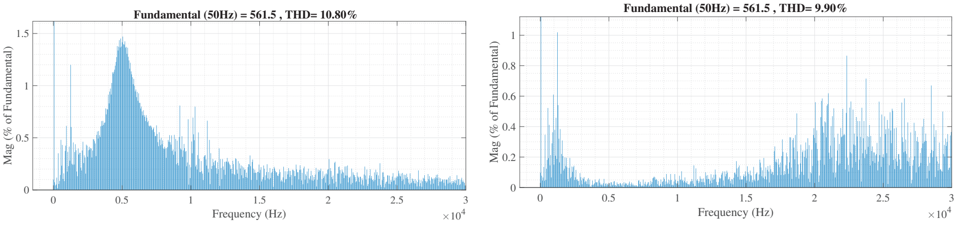
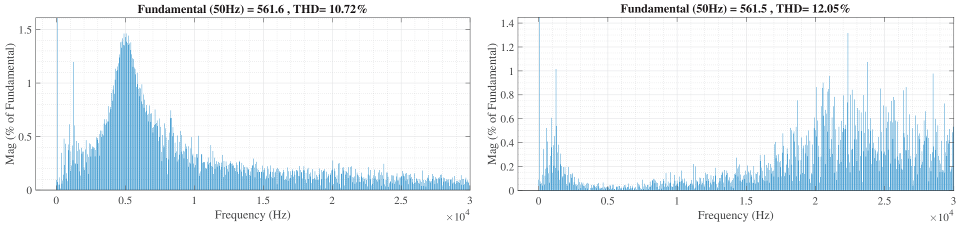


Figure 4.45: The case no.4 phase 1 with $300nF$ with/without extra inductor


Fundamental (50Hz) = 561.5 , THD= 10.80%

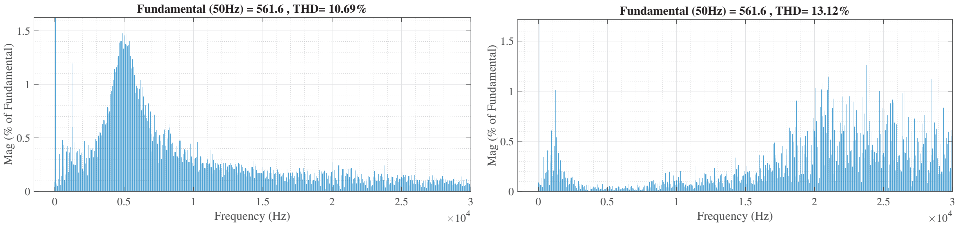
Fundamental (50Hz) = 561.5 , THD= 9.90%

Figure 4.46: The case no.4 phase 2 with $100nF$ with/without extra inductor


Fundamental (50Hz) = 561.6 , THD= 10.72%

Fundamental (50Hz) = 561.5 , THD= 12.05%

Figure 4.47: The case no.4 phase 2 with $200nF$ with/without extra inductor


Fundamental (50Hz) = 561.6 , THD= 10.69%

Fundamental (50Hz) = 561.6 , THD= 13.12%

Figure 4.48: The case no.4 phase 2 with $300nF$ with/without extra inductor

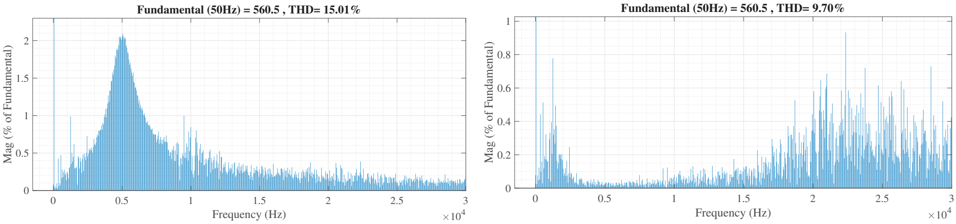


Figure 4.49: The case no.4 phase 3 with $100nF$ with/without extra inductor

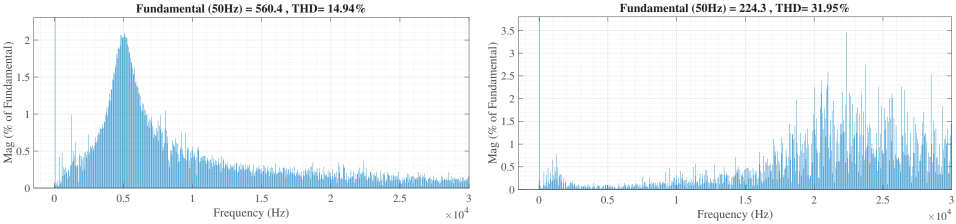


Figure 4.50: The case no.4 phase 3 with $200nF$ with/without extra inductor

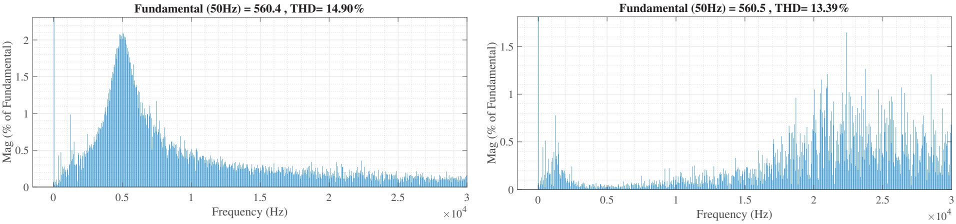


Figure 4.51: The case no.4 phase 3 with $300nF$ with/without extra inductor

4.7 Case 5

The case no.5 is based on the collected data at power plant from a 3-phase $400kW/50Hz$ motor with earthed star point that is in parallel with a several single IGBT based drive unit. The inductance of the motor is approximately $100\mu H$. the considered inductance is small due to the proportional power scale of the motor to the system that is connected to and high harmonic content (over 20%) of the case reflects this fact.

Due to this fact the motor is not able to minimize the high order harmonics entering the circuit, these high frequency harmonics circulate in the circuit and affect the snubber resistor. The exact values cannot be shared as it is counted considered as sensitive information of the ABB properties.

4.7.1 Input signal

The three phase input data in the common mode practice has been shown in the following figures (4.52, 4.53, and 4.54). These figures demonstrate the voltage in away that each phase had been grounded and the measurement criteria is between the phase and the ground. The sampling is done each $2\mu S$.

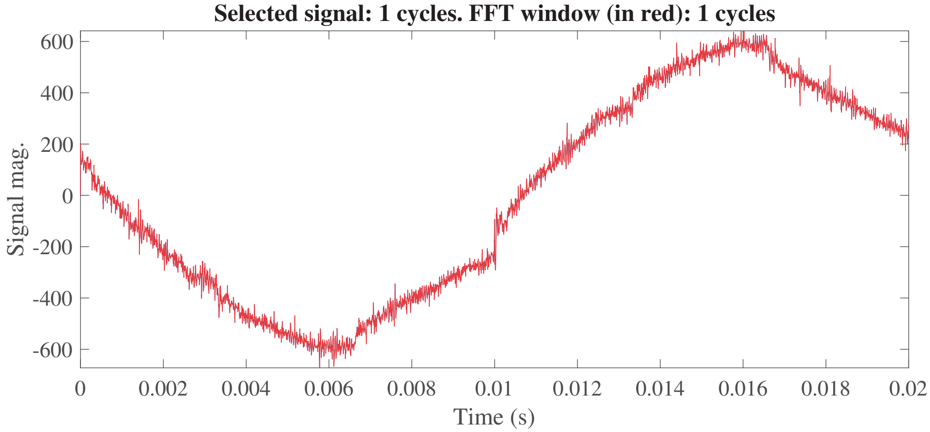


Figure 4.52: The input signal phase no.1

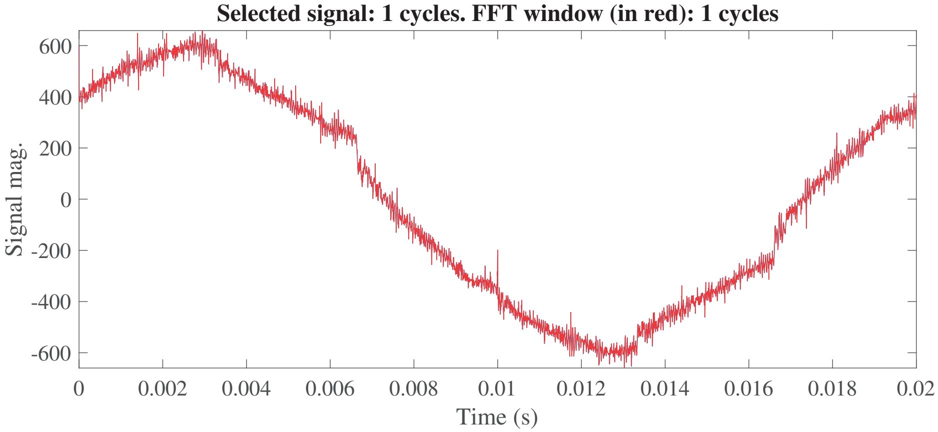


Figure 4.53: The input signal phase no.2

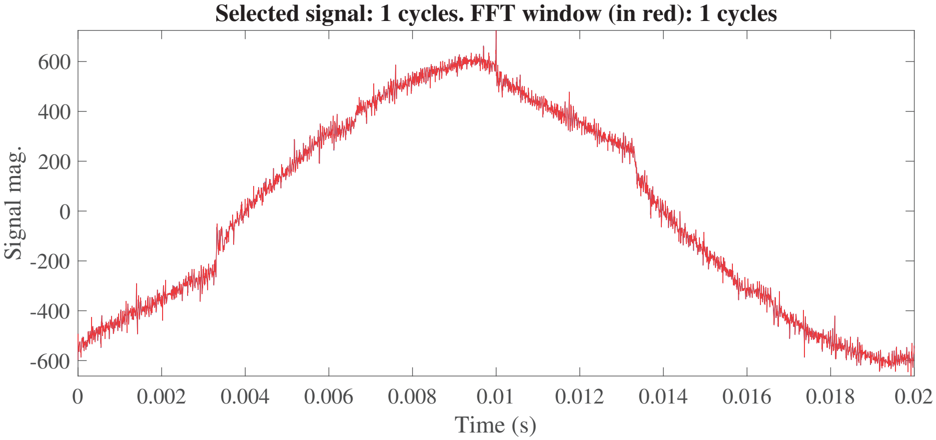


Figure 4.54: The input signal phase no.3

4.7.2 Results of the study

The study is done considering three different scenarios, in which every scenario has a different capacitor size (100, 200 and 300 nF) to simulate the equivalent capacitance of the motor as well as the cabling system. Each scenario is simulated with/without the inductor. As it is shown in the following figures (4.55, 4.56, 4.57, 4.58, 4.59, 4.60, 4.61, 4.62, and 4.63), adding the inductance could reduce the dissipated power significantly by reducing the current flow rate of the snubber resistor at the high harmonic contents. In other words, in high frequencies the inductor acts as a filter and compensates for the low impedance of the capacitor.

What we can see from the mentioned figures is that the magnitude of high frequency harmonics are reduced significantly by adding the inductor to the system. It is worth to mention that the effect is more significant for the case with $300nF$ capacitance than the case with $100nF$. For case no.5 there are few high frequency harmonics between $20kHZ$ and $30kHZ$. Consequently the $10mH$ inductor has the most effect on reducing of the harmonics. High frequency harmonics above $20kHZ$ cause the most power dissipation in the snubber resistor thus applying of an inductor has big effect on reducing these harmonics and as a result the power dissipation on the snubber resistor.

For all the scenarios of case no.5, the snubber resistors current is already below $264mA$ and no action is needed to save the snubber resistor, but still adding a $10mH$ inductor draws down the dissipated power of the snubber resistor. For case no.5 the harmonics are mostly distributed between $15kHZ$ and $25kHZ$ and unlike case no.1 and case no.2, which had harmonics distributed around $20kHZ$, adding a $10mH$ inductor plays a huge role and eliminates majority of the high frequency harmonics. Furthermore, the magnitude of the harmonics are below 7 volts and in turn the snubber resistor's current is below $264mA$ for all the scenarios. As it is shown in the following table, adding the inductance could reduce the dissipated power significantly by reducing the current flow rate of the resistor in the high frequency harmonic contents. In other words, in high frequencies the inductor acts as a filter and compensate the low impedance of the capacitor.

As it is clear in the following tables (4.13, 4.14, and 4.15), the dissipation factor is improved between 1,87– 3,40 times for different scenarios by using a $10mH$ inductor. The total THD for all the scenarios in case no.5 is below 12%. The frequency with high harmonic between $10kHZ$ and $30kHZ$ is $2kHZ$ with the harmonic voltage of $6,01V$.

Case.5 phase.1	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	9,10	560	20000	0,55	0,103	1,06
Without inductor	8,53	560	20000	3,23	0,149	2,22
CM Capacitor=200nF						
With inductor 10mH	11,18	560	20000	0,77	0,149	2,22
Without inductor	9,75	560	20000	4,94	0,204	4,16
CM Capacitor=300nF						
With inductor 10mH	10,46	560	20000	0,87	0,127	1,62
Without inductor	10,54	560	20000	5,89	0,235	5,52

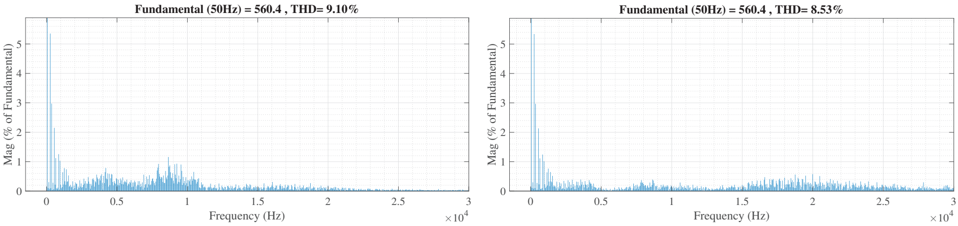
Table 4.13: Results of study in case no.5 phase no.1 with three different capacitor values and with/without inductor

Case.5 phase.2	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	8,99	560	20000	0,52	0,105	1,11
Without inductor	8,41	560	20000	3,48	0,158	2,51
CM Capacitor=200nF						
With inductor 10mH	11,05	560	20000	0,73	0,151	2,26
Without inductor	9,67	560	20000	5,58	0,212	4,52
CM Capacitor=300nF						
With inductor 10mH	10,41	560	20000	0,89	0,131	1,70
Without inductor	10,46	560	20000	6,01	0,242	5,88

Table 4.14: Results of study in case no.5 phase no.2 with three different capacitor values and with/without inductor

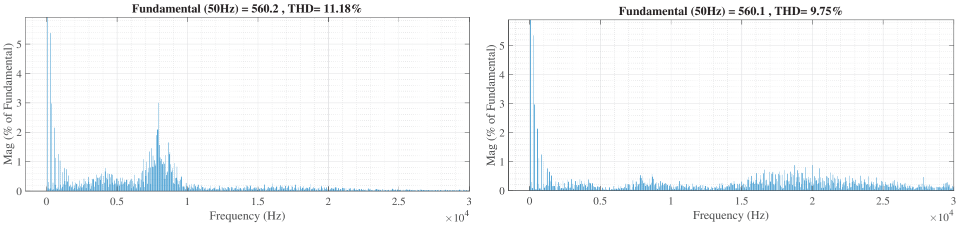
Case.5 phase.3	THD %	THD max	Frequency	THD volt	Current R	Power R
CM Capacitor=100nF						
With inductor 10mH	8,64	560	20000	0,51	0,101	1,00
Without inductor	8,19	560	20000	3,17	0,151	2,23
CM Capacitor=200nF						
With inductor 10mH	10,62	560	20000	0,74	0,145	2,10
Without inductor	9,34	560	20000	4,31	0,204	4,20
CM Capacitor=300nF						
With inductor 10mH	9,94	560	20000	0,85	0,124	1,55 heightWithout inductor
10,08	560	20000	5,13	0,234	5,49	

Table 4.15: Results of study in case no.5 phase no.3 with three different capacitor values and with/without inductor


Fundamental (50Hz) = 560.4 , THD= 9.10%

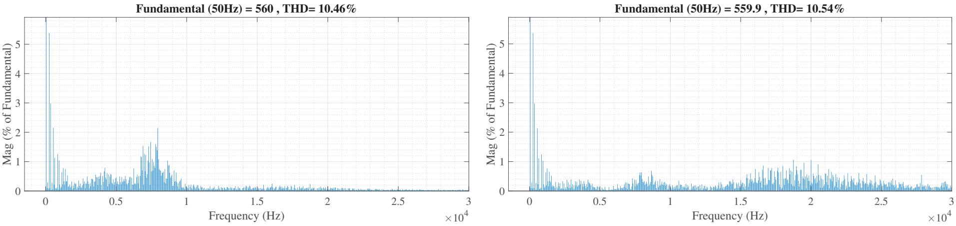
Fundamental (50Hz) = 560.4 , THD= 8.53%

Figure 4.55: The case no.5 phase no.1 with $100nF$ with/without extra inductor


Fundamental (50Hz) = 560.2 , THD= 11.18%

Fundamental (50Hz) = 560.1 , THD= 9.75%

Figure 4.56: The case no.5 phase no.1 with $200nF$ with/without extra inductor


Fundamental (50Hz) = 560 , THD= 10.46%

Fundamental (50Hz) = 559.9 , THD= 10.54%

Figure 4.57: The case no.5 phase no.1 with $300nF$ with/without extra inductor

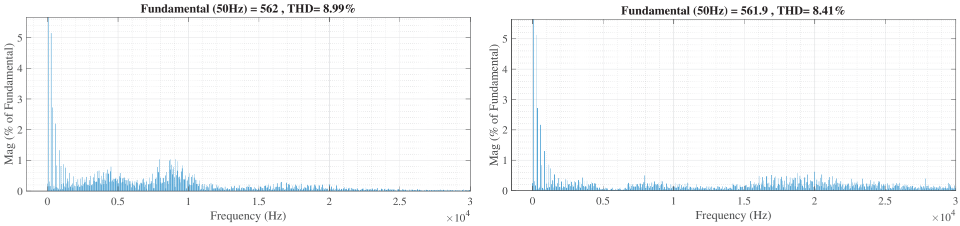


Figure 4.58: The case no.5 phase no.2 with $100nF$ with/without extra inductor

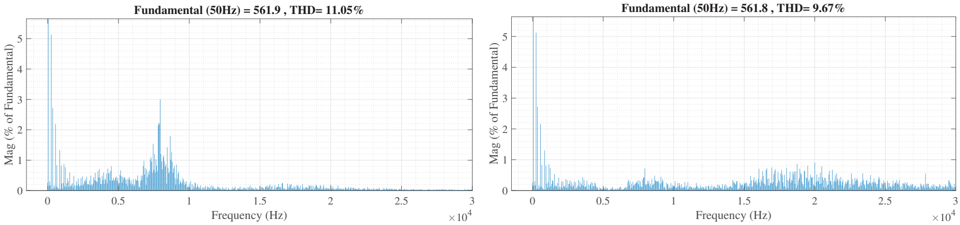


Figure 4.59: The case no.5 phase no.2 with $200nF$ with/without extra inductor

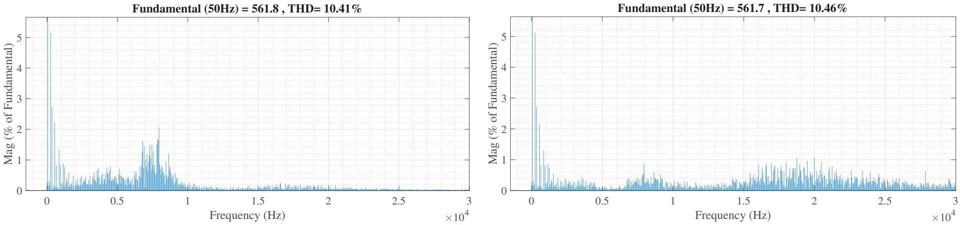


Figure 4.60: The case no.5 phase no.2 with $300nF$ with/without extra inductor

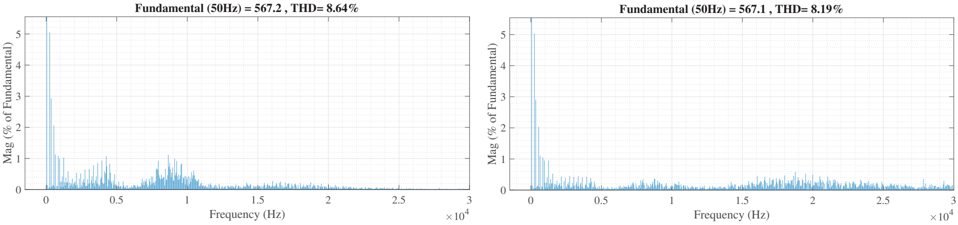


Figure 4.61: The case no.5 phase no.3 with $100nF$ with/without extra inductor

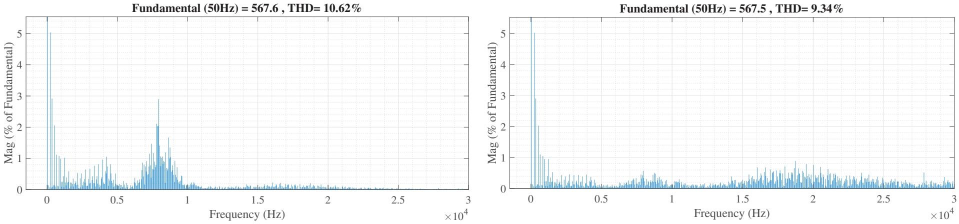


Figure 4.62: The case no.5 phase no.3 with $200nF$ with/without extra inductor

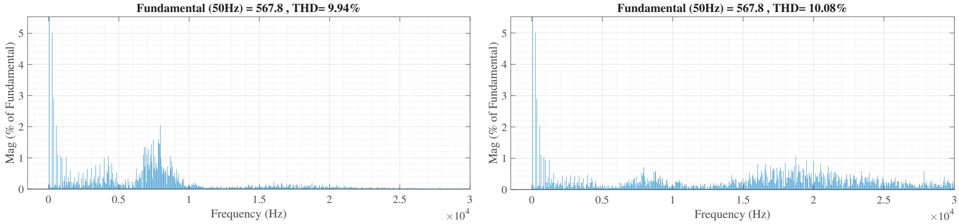


Figure 4.63: The case no.5 phase no.3 with $300nF$ with/without extra inductor

4.8 Measurements on a 37kW motor

As one of the test systems, a set of measurement data is done on a $37kW$ motor. In these set of measurements on a $37kW$ motor device, all the harmonics lie around $1kHZ$ and due to this, there is not a surge temperature rising at the snubber resistor. At this regard, it is really important to verify the Simulink model through the data that is measured. Further, determining the dissipation factor of the snubber capacitor to get an accurate result of the simulation is anther issue to be tackled.

In our case of study, determining the equivalent series resistance of the capacitor is a challenging issue since there is two types of data to get the dissipation factor. First of all, it could be taken from the capacitor graphs which shows 10Ω at $1kHZ$. Second of all, it could be given by a way that it calculates the ESR factor from the data sheet which states the dissipation factor to be 1,3% at $1kHZ$.

Dissipation factor = ESR/Impedance => 1,3%=ESR/1500 ESR=20Ω

According to the temperature measurements at FIDRI, the temperature raised from room temperature ($23^\circ C$-$66^\circ C$), after 10 minutes, to around ($70^\circ C$) and after 20 minutes or more, it doesn't raise more than ($75^\circ C$). Maximum temperature ($75^\circ C$) is a safe region for the resistor since it does not get too hot. The next stage is to find the current and voltage over the resistor while the resistor reaches almost ($75^\circ C$).

In the softstarter in the RND lab in Västerås, three voltage levels, $12V$, $10V$ and $9V$, have been applied over a 100Ω resistor and the temperature is measured after 2 minutes, after 5 minutes, after 10 minutes and after 20 minutes (4.16, 4.17, and 4.18). $10V$ voltage shows the closest results to the lab results from FIDRI. The snubber resistor's temperature stays at around ($74^\circ C$), 30 minutes later when $10V$ is applied over the snubber resistor, the current could be calculated as follows: $V = RI => I = 10/100 = 100mA$.

4.8.1 Verification

The components of the circuit in the simulation environment would be chosen in a way that, in turn, the simulation gave the laboratory results ($100mA$) with minimum error. In simulation test, when the sample input data is applied to the circuit, the current that is passing through snubber resistor should be around $100mA$. The current equal to $100mA$ shows that the components should be chosen considering the values for the resistor current. To determine the components, the input data is simulated at both LT-Spice and MATLAB Simulink, which gives more accurate verification. The simulation result show that 20Ω resistor with $0.5mH$ inductor for a $37kW$ motor and $20nF$ as common mode capacitor equivalent for cabling results in almost $100mA$ when input data is applied. $100mA$ current is the optimum current to not allow the snubber resistor to pass the safe heat region.

Voltage	Start	after 2′	after 5′	
§ height12	25°	62°	77°	

Table 4.16: The temperature values in different times while the input voltage is $12v$

Voltage	Start	after $8'$	after $13'$	after $20'$	after $30'$
10	$25°$	$69°$	$72.3°$	$73.3°$	$74.8°$

Table 4.17: The temperature values in different times while the input voltage is $10v$

Voltage	Start	after $2'$	after $5'$	after $10'$	after $20'$
9	$25°$	$43.9°$	$53°$	$58°$	$60°$

Table 4.18: The temperature values in different times while the input voltage is $9v$

4.8.2 Analysis of the results

The simulation results show very low harmonics above $10kHZ$ for the labe cases no.6 and 7. During the laboratory test measurements in the FIDRI lab, the temperature of the snubber resistor didn't pass $70°C$. Due to the low network harmonics, the snubber resistor didn't heat up much and there was no need for employing a solution to control the temperature of the resistor. On the other hand, these two sets of measurements are done on smaller motor ($37kW$) which has more series inductance and creates less common mode capacitance compared to a larger motor ($400kW$). Lager inductance of the motor can additionally eliminate part of high frequency harmonics.

The simulations showed that there is just a slight difference in the snubber resistor's current assuming 10Ω or 20Ω as dissipation factor.

4.9 Case 6 – lab drives

At this part, to confirm the previous simulations thoughts, the authors have considered two real tests in the laboratory. The utilized components are as follows: 20Ω and 10Ω dissipation factor, $20nF$ for cabling capacitor, $0.5mH$ motor inductor. Like the previous simulations, common mode practice has considered in all the phases.

4.9.1 inputs

The three phase input data in the common mode practice, for both types with $20\Omega/10\Omega$ dissipation factor, has been shown in the following figures 4.64, 4.65, and 4.66). These figures demonstrate the voltage in a way that each phase had been grounded and the measurement criteria is between the phase and the ground. The sampling is done each $2\mu S$.

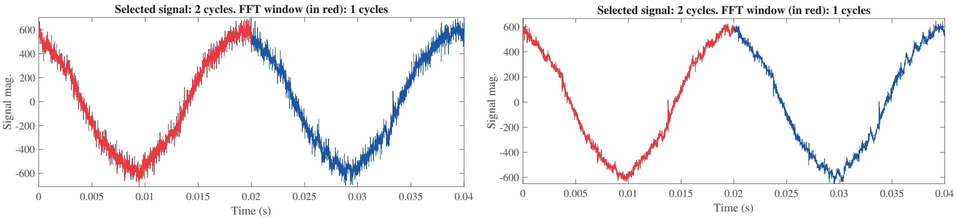


Figure 4.64: The input signal of lab case no.6 phase no.1

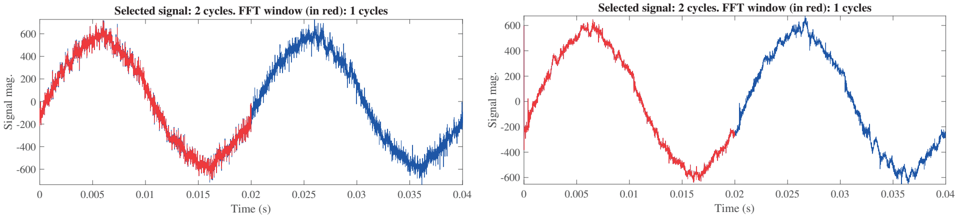


Figure 4.65: The input signal of lab case no.6 phase no.2

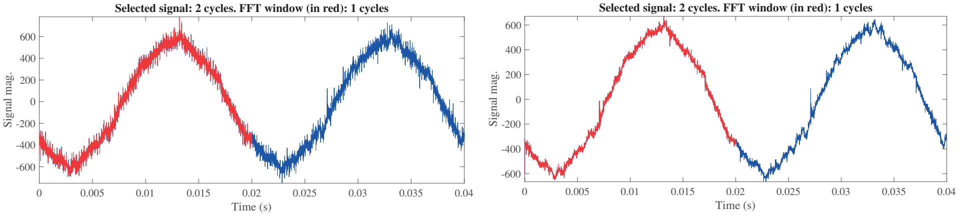


Figure 4.66: The input signal of lab case no.6 phase no.3

The frequency responses of the test are listed in the following plots (4.67, 4.68, and 4.69). Every two plots in a raw is consist of both 10Ω (in the left side) and 20Ω (in the right side) dissipation factor, respectively. As it has been previously mentioned, there are not a lot harmonics at these cases, which is obvious from the frequency response plots. It should be mentioned that since, here, we analyzed a $37kW$ motor which has a bigger inductor and it doesn't need extra inductor. Therefore the responses don't show a huge amount of harmonics in the high frequencies.

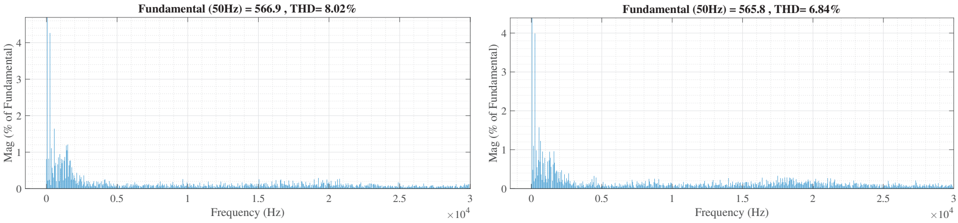


Figure 4.67: The case no.6 phase no.1 with dissipation factor equal 10 and 20 Ω

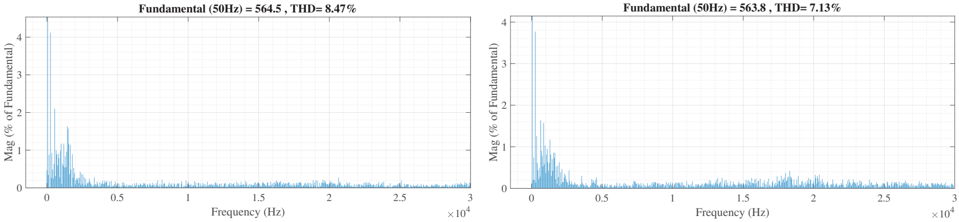


Figure 4.68: The case no.6 phase no.2 with capacitors equal 10 and 20 Ω

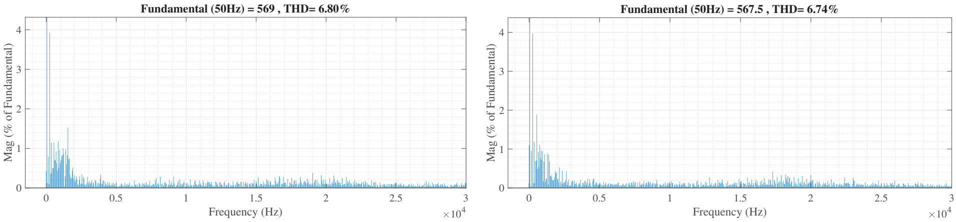


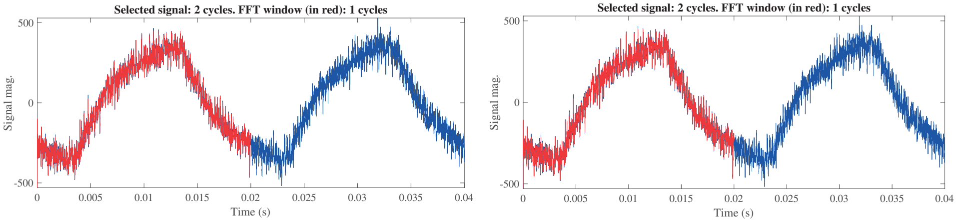
Figure 4.69: The case no.6 phase no.3 with capacitors equal 10 and 20 Ω

4.10 Case 7 – lab drives

Here, to corroborate the previous simulations, two real tests in the laboratory have been well considered. The used elements are as follows: 20Ω and 10Ω dissipation factor,$20nF$ for cabling capacitor,$0.5mH$ motor inductor. The following details have been applied at the present test: measurement set 1- phase no. 1 Common mode (line to ground); measurement set 2- phase no. 2 on the snubber circuit(over snubber); and measurement set 3- phase no. 3 on the snubber circuit.

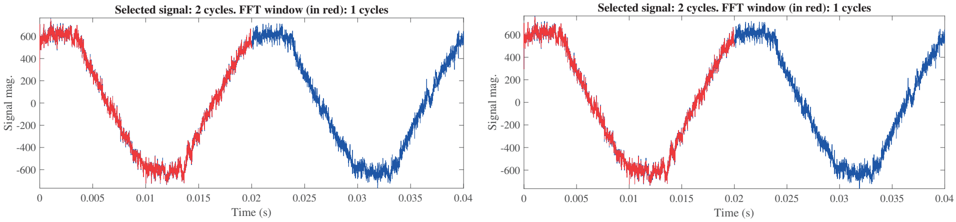
4.10.1 inputs

Here, again, the three phase input data in the common mode test, for both types with $20\Omega/10\Omega$ dissipation factor, has been shown in the following figures (4.70, 4.71, 4.72). These figures show the voltage where each phase has been grounded and the measurement criteria is between the phase and the ground. The sampling is done each $2\mu S$.


Selected signal: 2 cycles. FFT window (in red): 1 cycles

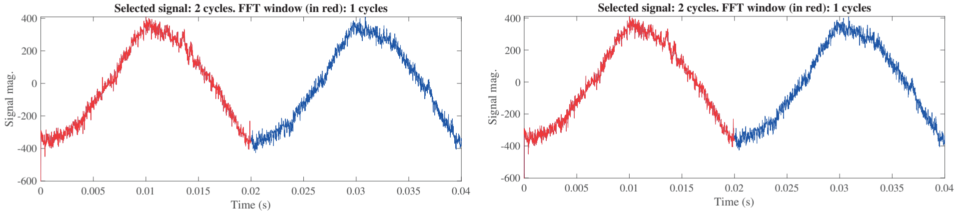
Selected signal: 2 cycles. FFT window (in red): 1 cycles

Figure 4.70: The input signal of lab case no.7 phase no.1


Selected signal: 2 cycles. FFT window (in red): 1 cycles

Selected signal: 2 cycles. FFT window (in red): 1 cycles

Figure 4.71: The input signal of lab case no.7 phase no.2


Selected signal: 2 cycles. FFT window (in red): 1 cycles

Selected signal: 2 cycles. FFT window (in red): 1 cycles

Figure 4.72: The input signal of lab case no.7 phase no.3

The frequency responses of the test are listed in the following plots (4.73, 4.74, and 4.75). Every two plots in a raw is consist of both 10Ω (in the left side) and 20Ω (in the right side) as dissipation factor, respectively. Like previous laboratory case, here there is not a lot harmonic sign in the frequency responses since the tested motor has a bigger value of induction by itself.

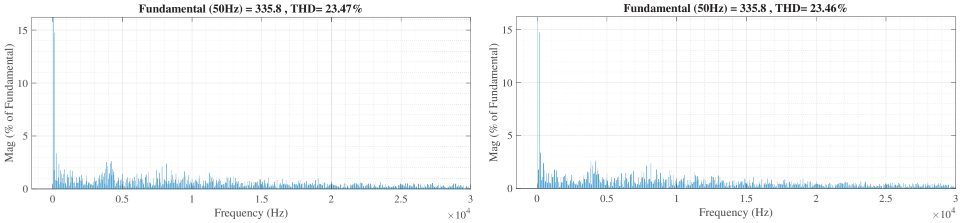


Figure 4.73: The case no.7 phase no.1 with dissipation factor equal to 10 and 20 Ω

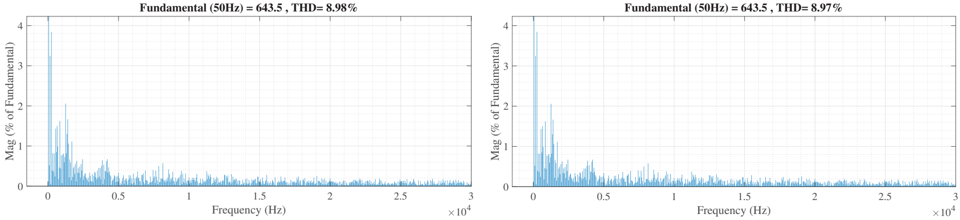


Figure 4.74: The case no.7 phase no.2 with capacitors equal to 10 and 20 ohm

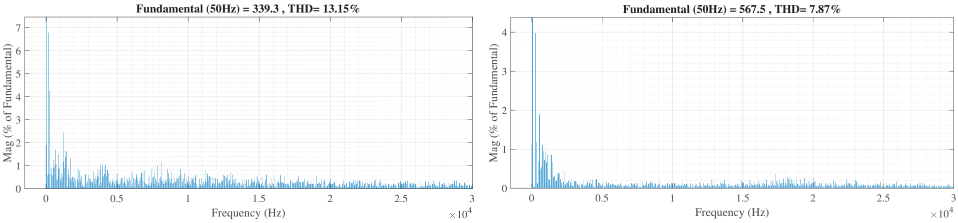


Figure 4.75: The case no.7 phase no.3 with capacitors equal to 10 and 20 ohm

Chapter 5

Conclusion

To sum up, harmonics at high frequencies are destructive which the operators must cope with. The most exacerbating harmonics are between 15KHz and 20 kHz and in the common mode operation, which is why the authors have chosen to analyze harmonics of this specific mode. To tackle the harmonics around $20kHz$ an inductor should be used in series with the snubber resistor. It should be mentioned that using an inductor in series with the snubber circuit is not a general solution and it is not effective for low harmonics. At this regard, for harmonics around $5kHz$ that heat up the resistor, a more complicated way is needed, a contactor in parallel with the snubber circuit. The presented thesis have well analyzed the high frequency harmonics and their function on the motor's snubber circuit which let the snubber resistor heating up in the high frequencies. Due to the thesis results, it is necessary to change the previous standard and use the proposed novel design to refine the softstarter's function. Furthermore to test the model, 5 simulation studies plus 2 practical laboratory tests have been presented to verify the thesis claims. Using an extra inductor have made high frequency harmonics less in all studied cases.

As a part of the thesis process, there are several finding related to the scope of the study which could be listed as follow:

- To have reliable fault measurement, as one of the most import part of the analysis, the best time-step to use for the measurements is $2\mu S$.
- As the input of the circuit, the voltage measurement should be done both across the snubber circuit and common mode.
- The voltage measurement procedure should be done both at idle and ramp-up phase.
- Heat camera should be used both at idle and ramping up of the voltage to monitor the temperature of the snubber circuit.
- Revise ABB's recommendation to the customers for the cable length between the motor and softstarter.
- As for big motors larger than 200kW, inside delta connection is often used, as a solution, changing the position of bypass switch prevents the snubber resistor from getting too hot. To do so, a highly effective inside-delta connection model have proposed over the previous (original) model in figure 5.1.

Moreover, to continue research at this area, the future works related to the thesis could summarised as follows:

- Using a contactor across the resistor at snubber circuit to by-pass the snubber at stand-by state.

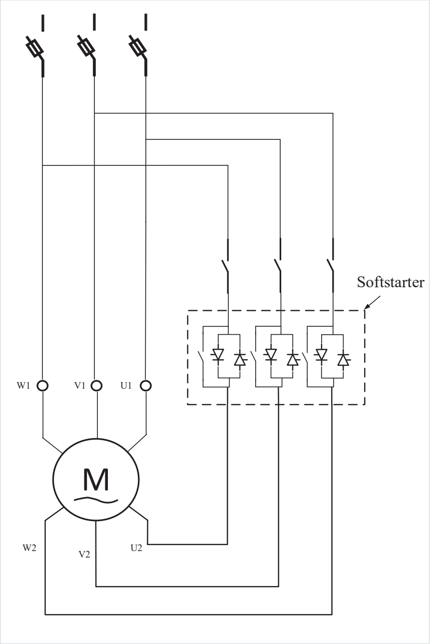


Figure 5.1: proposed inside-delta connection

- A bypass switch over snubber resistor can be used when the softstarter is not conducting. But it is complicated and needs a detailed software programming besides hardware implementation.
- Since ABB produces both 2-phase and 3-phse softstarters, the effect of harmonics on snubber resistor for these types can be studied respectively.

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