TECHNICAL REPORT

Harmonic Resonances Associated with Wind Farms

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Summary

This report studies harmonic resonances are they occur due to wind farms that are connected to the transmission and subtransmission grid. The report contains a general theoretical description of harmonic resonances; more detailed calculations for an example wind farm, and an example of a harmonic filter to limit the impact of the resonances.

Harmonic resonances come in two types: harmonic series resonances and harmonic parallel resonances. Harmonic resonances occur always whenever both capacitive and inductive elements are present, which is always the case. A harmonic resonance results in an amplification of the harmonic voltage and/or current distortion. The amount of amplification depends mainly on the amount of resistive damping present in the system. For harmonic studies it is therefore important to know the amount of resistance present in the system.

A certain harmonic voltage or current level may be unacceptable because it results in damage to equipment, mal-operation of equipment, loss-of-life-of-equipment or other types of interference (light flicker or audible noise are examples). In that case there is no doubt that measures should be taken to reduce the distortion. In case of wind parks, high currents through the substation transformer and high voltages at the medium-voltage substation result, as was mentioned before.

The second type of unacceptability occurs when the limits set in standards or set by the network operator in the grid code are exceeded. In case of a wind farm this only concerns the currents through the substation transformer. The collection grid is a "private network" where it is up to the owner of that grid to decide about which levels are accepted. Using the voltage-distortion limits set in international standards like EN 50160 or IEC 61000-2-2 will in most cases prevent interference with equipment but it could also result in overdesign especially for non-characteristic harmonics and interharmonics.

Parallel resonances together with the broadband spectrum emitted by wind turbines, could result in emission limits being exceeded for non-characteristic harmonics and for interharmonics. This is a consequence of the limits being set in a time when the emission at these frequencies was almost non-existing. A discussion should be started, preferably at international level, to obtain reasonable limits at these frequencies.

Series resonances are normally only a concern when they are close to the fifth or seventh harmonic. The high currents through the substation transformer could result in overheating of the transformer; the high voltages at the medium-voltage bus could result in overheating of the capacitor banks. The fifth and seventh harmonic currents could also exceed the emission limits according to the grid code. This should however not be a reason for the network operator to disconnect the wind farm because the wind farm acts in this case as a harmonic filter reducing the voltage distortion in the grid. As long as the harmonic voltages or currents have no adverse effects within the wind

farm, there is no reason to take any measures.

The simulations presented in this report show clearly that the resonance frequency and the amplification depend strongly on the operational state of the wind farm and the grid. It is thus needed to consider the harmonics for all possible operational states. When designing filters, or other mitigation methods, again all possible operational states should be considered. In this report a possible design of a harmonic filter is presented that covers all (N-1) operational states. The described filter requires a central controller that chooses the optimal filter from the operational state.

The main uncertainty found during the calculations is the knowledge of the resistances around the resonance frequency. Detailed models exist for cables and overhead lines but application of these is rather complicated and time consuming. But from our studies we draw the preliminary conclusion that the main impact on the amplification is by the resistance of the transformers and the turbines around the resonance frequency. It may be worth the effort to have a closer look at this in the future.

Contents

1 Introduction

Harmonic distortion is the presence of components beyond the power-system-frequency (50 or 60 Hz) in the voltage or current waveform. In time domain harmonic distortion can be defined as the voltage and/or current waveform not being sinusoidal. Harmonic distortion is due to a range of causes, from the generator units not being fully rotational symmetric, through core saturation of power transformers, up to non-linear loads. The studies on harmonic distortion have very much concentrated on emission by non-linear load, especially load with power-electronic converters. For more details on the origin of harmonic distortion, the reader is referred to the literature on power-system harmonics, including the classic book by Jos Arrillaga [1]. Other books covering the subject include [2][3][4][5][6][7][8].

In this report we will not discuss the emission of harmonic currents by non-linear load, but instead concentrate on a phenomenon called "harmonic resonance", where the harmonic voltage or current distortion is amplified by a combination of capacitive and inductive elements. Most of the above-mentioned books discuss harmonic resonance as it is the main contributing factor in many cases with high harmonic levels. The most commonly-discussed case concerns capacitor banks in public distribution systems, but also in industrial systems resonances are often a cause for concern.

The basic theory behind harmonic resonances will be discussed in Chapter 2, where we will distinguish between parallel resonance and series resonance. Chapter 2 will also contain a number of practical examples where the impact of different parameters on resonance frequency and amplification is illustrated. Chapter 3 will continue the set of example with a number of wind farms: analytical calculations as well as simulation studies will be shown. Finally, Chapter 4 will present a brief discussion on the use of filters to limit the amplification due to harmonic resonances.

2 Harmonic Resonance

Normally, the most severe harmonics appears at the terminals of polluting elements and lessens along with the increase of distance from its source. However, resonances due to the presence of capacitive equipments can lead to amplification of harmonic levels. Two types of resonance should be distinguished: "parallel resonance" and "series resonance", which will be discussed in detail in Section 2.1 and Section 2.2, respectively.

2.1 Parallel resonance

2.1.1 Theory

Parallel resonance occurs due to the parallel connection of a capacitive and an inductive element in the source impedance of a source of harmonic current emission. With parallel resonance the high harmonic voltage and current levels occur between the capacitive element and the source of the harmonic currents.

The configuration leading to harmonic parallel resonance is shown in Figure 1, where the harmonics-emitting load is on the left and the grid on the right. The circuit elements hold for the harmonic frequency, so that there is no voltage source[1]. Resistance is neglected in this figure; we will consider the impact of resistance further on in this section.

The impedances of inductance and capacitance are both imaginary but of opposite sign. At the resonance frequency they are of equal magnitude, so that the impedance seen by the harmonic current source becomes infinite.

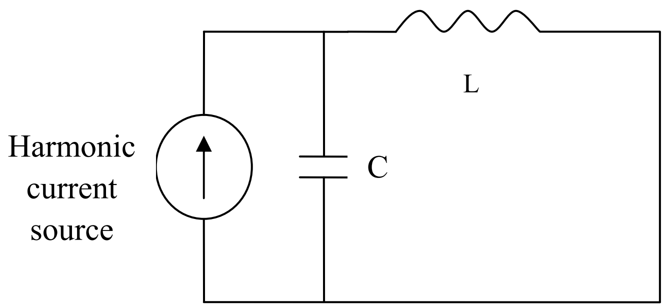


Figure 1, ***Equivalent circuit for parallel resonance without considering resistance***

[1] As a first approximation in harmonic studies, each harmonic frequency is treated independently of the others and the background distortion is neglected. This is sufficient to illustrate the phenomenon. In real-case studies all sources, including the background distortion, need to be considered.

When the resistances are neglected, the impedance seen by the harmonic source can be expressed as (1).

$$Z(\omega) = \frac{j\omega L}{1-\omega^2 LC} \tag{1}$$

$$\omega = 2\pi f_0 \tag{2}$$

At resonance frequency f_{rp}, the impedance becomes infinite.

$$f_{rp} = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

When the resonance is due to a capacitor bank, the harmonic order at which the resonance takes place can also be estimated by (4) with available system fault level S_{fault} and size of capacitor bank Q_{cap}.

$$n_{res} = \sqrt{\frac{S_{fault}}{Q_{cap}}} \tag{4}$$

Therefore, the harmonic source may result in an infinite harmonic voltage at the load bus. Meanwhile, two infinite harmonic currents with opposite direction will be produced in the branches of capacitor and the inductor. Assuming that the harmonic order of harmonic current source is *h*, the harmonic currents through the inductor and the capacitor can be expressed by (5) and (6) as follows.

$$i_{ind} = \frac{1}{1-h^2\omega^2 LC} I_h \tag{5}$$

$$i_{cap} = \frac{-h^2\omega^2 LC}{1-h^2\omega^2 LC} I_h \tag{6}$$

These parallel resonances are common with capacitor banks connected to low or medium-voltage networks. The capacitance is dominated by the capacitor bank and the inductance is dominated by the transformer feeding in from a higher voltage level.

The parallel resonance tends to occur in the medium-voltage bus at frequencies in the range of 250Hz to 500Hz. And the fifth harmonic has been proved to be the one most prone to resonance.

2.1.2 Some example calculations, neglecting resistance

Apart from rectifiers and capacitor banks, underground cables and motor loads are the main factors contributing to the resonance frequency, as well as to the impedance at different harmonic orders. According to (1) and (4), when the resistance is neglected, the resonance frequency and impedance depend on the equivalent inductance and capacitance seen by the harmonic current source. The parameters of cable and capacitor bank determine the capacitance, while the fault level contribution from the grid and the induction motors affect the inductance. The impedance at different harmonic orders can be expressed by using (7).

$$Z(\omega) = \frac{jh\omega L}{1 - h^2\omega^2 LC} \tag{7}$$

A sensitivity analysis is carried out here to study the impact of these parameters on both resonance frequency and impedance at different harmonic order using two examples, referred to as Example 1.1 and Example 1.2. Both examples are hypothetical cases, but using realistic parameters. Example 1.1 could be a typical medium-voltage public network, whereas Example 1.2 is more relevant for an industrial installation.

Example 1.1: A medium-voltage network is supplied by a 70/20 kV transformer with rated capacity of 30 MVA and per-unit impedance of 17%. Its fault level at 70 kV is 1850 MVA. A 5.8 Mvar capacitor bank is connected to the 20-kV bus on secondary side of the transformer. Four underground cables of 3 km length each are also connected to that bus. The cable capacitance is 0.21μF/km. The load connected to this substation is mainly domestic load, which does not contribute to the fault level.

1) Base case

The capacitance connected to the medium-voltage network is formed by the capacitor bank and the four cables. The size of the capacitor bank is 5.8 Mvar, while the cables correspond to a capacitor size equal to:

$$Q_{cab} = \omega C U^2 = 2\pi f \times 0.21 \cdot 10^{-6} \times 12 \times (20 \cdot 10^3)^2 = 316.8 \text{ kvar}$$

The transformer has a partial fault level of $\frac{30}{0.17} = 176.5 \text{ MVA}$

The total fault level at 20 kV is $\frac{1}{\frac{1}{1850} + \frac{1}{176.5}} = 161.1 \text{ MVA}$

According to (4), we obtain the resonance frequency order.

$$n_{res} = \sqrt{\frac{S_{fault}}{Q_{cap} + Q_{cab}}} = \sqrt{\frac{161.1}{5.8 + 0.32}} = 5.132$$

Therefore, the resonance frequency is $f_{rs} = n_{res} f = 5.132 \times 50 \text{ Hz} = 257 \text{ Hz}$

At fundamental frequency (50 Hz9, the equivalent inductance and equivalent capacitance are

$$L = \frac{U^2}{\omega S_{fault}} = \frac{20^2}{2\pi \times 50 \times 161.1} = 7.9 \times 10^{-3} H \ , \ \ C = C_{cab} + C_{cap} = 48.7 \times 10^{-6} F$$

$$C_{cable} = 0.21 \times 12 = 2.52 \mu F \ , \ \ C_{cap} = \frac{Q_{cap}}{\omega U^2} = \frac{5.8 \times 10^6}{2\pi \times 50 \times (20 \times 10^3)^2} = 46.2 \mu F$$

In order to study the effect of each parameter on the resonance frequency, the concerned parameter changes with certain steps, while the other parameters are kept unchanged.

2) Impact of cable length

As for the cable parameters, its capacitance per kilometre is assumed to be constant at 0.21μF. The cable length is changed between 0 and 100 km; the effect on the resonance frequency is shown in Figure 2. The resonance frequency decreases along with the increase of cable capacitance, but in all cases is the resonance frequency found around the fifth harmonics (250 Hz).

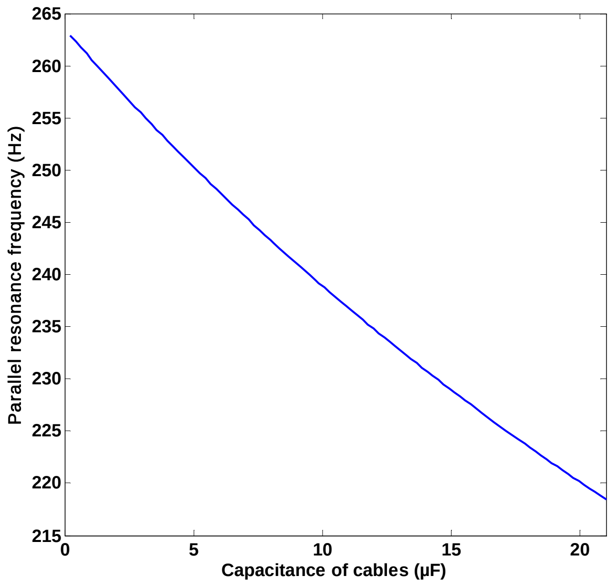
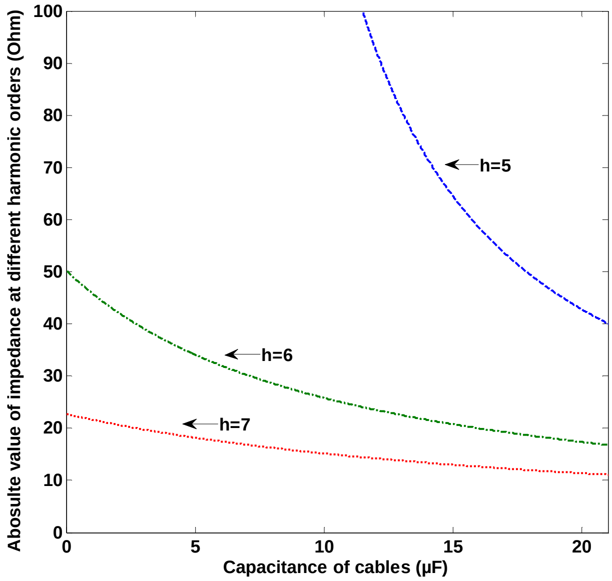


Figure 2. Resonance frequency as a function of the cable capacitance

As fifth and seventh harmonic sources are common in power systems, the impact of cables capacitance on the impedance at these harmonic orders has been studied and



the results are shown in

Figure 3. Harmonic order 6 is rarely emitted by existing equipment during normal operation. It is however present during a short time with transformer energizing. Also modern power electronic converters, like the ones used in wind parks, sometimes emit a certain level of 6th harmonic. Therefore harmonic 6 is added for completeness.

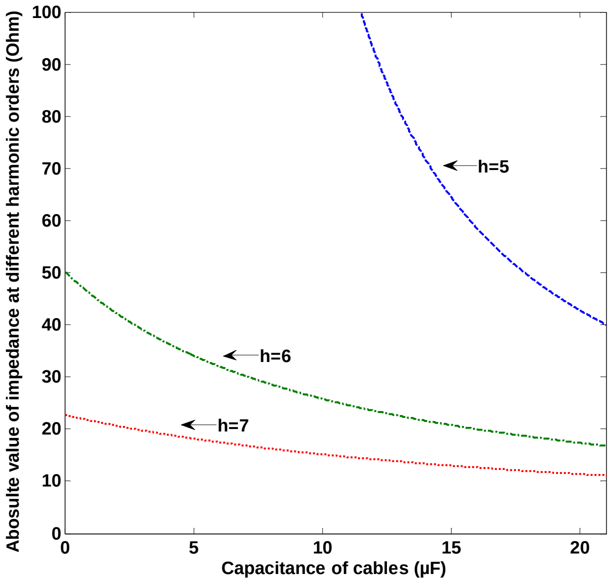
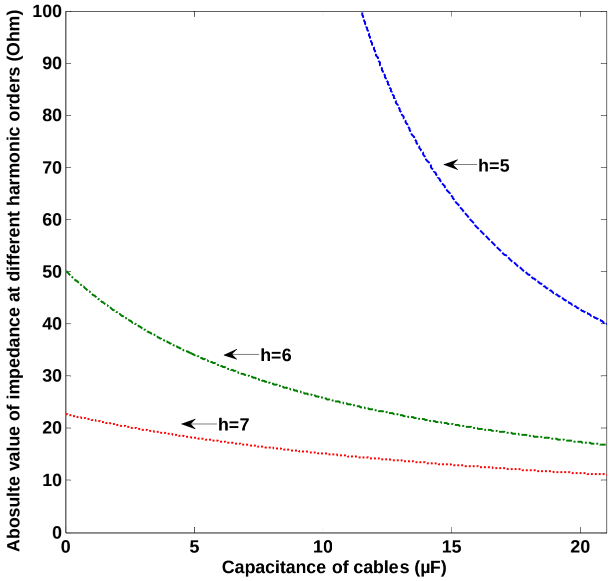


Figure 3. Impedance at different harmonic orders versus capacitance of cables



As shown in

Figure 3, the impedances at different harmonic orders decrease with the increase of cables' capacitance from zero to 21 μF. When resistance is neglected, the impedance at resonance frequency is infinite. Moreover, the amplification due to harmonic resonances is a factor of 2 to 5 in existing systems. Therefore, a vertical scale of zero to 100 Ω is selected to cut off the unrealistically high values of impedance.

3) Impact of the size of the capacitor bank

The size of the capacitor bank is the main contributing factor to the resonance frequency. It can vary in the range which results in resonance orders of 5, 6 and 7. The change of parallel resonance frequency along with capacity of capacitor bank is shown in Figure 4. Resonance occurs at harmonic orders 5, 6 and 7 for capacitor banks of size 6.13 Mvar, 4.16 Mvar and 2.97 Mvar, respectively. The impacts of capacitor banks on impedances at fifth, sixth and seventh harmonic has also been studied and is shown in Figure 5. The figure clearly shows that the harmonic impedance depends strongly on the size of the capacitor bank. Note that again damping has been neglected; the impact of damping will be studied in more detail in the next section.

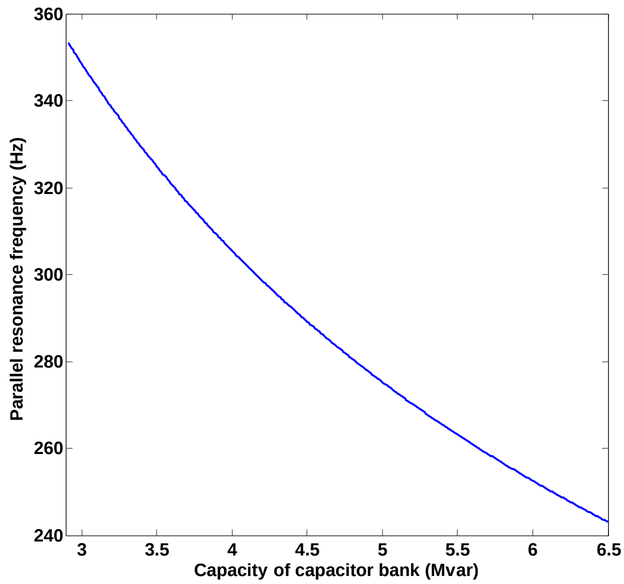


Figure 4. Parallel resonance frequency versus capacity of capacitor bank

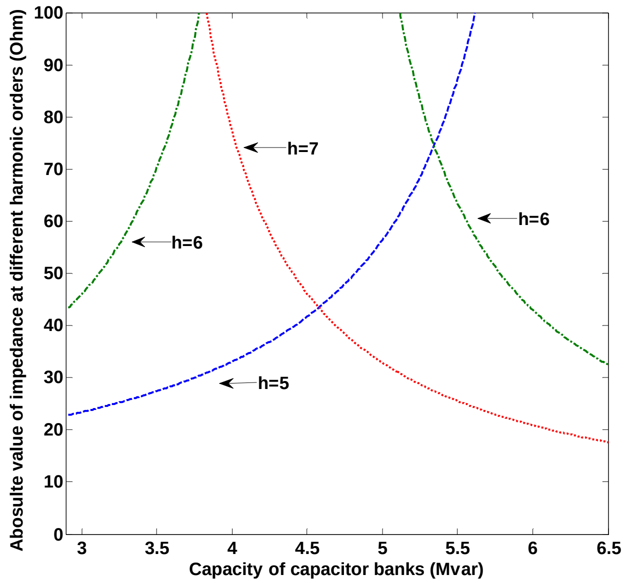


Figure 5. Impedance at different harmonic orders versus capacity of capacitor banks

4) Impact of fault level

With the same method as before, the effects of the fault level at the 70-kV bus has been studied. The results are shown in Figure 6 and Figure 7. For fault levels above about 750 kVA, the impact of the fault level (at 70 kV) is small. Here the fault level at 20 kV is determined mainly by the impedance of the 70/20-kV transformer. As the resonance frequency moves slowly towards the sixth harmonic, the impact of the fault level at 70 kV on the impedance at the sixth harmonic is non-negligible however.

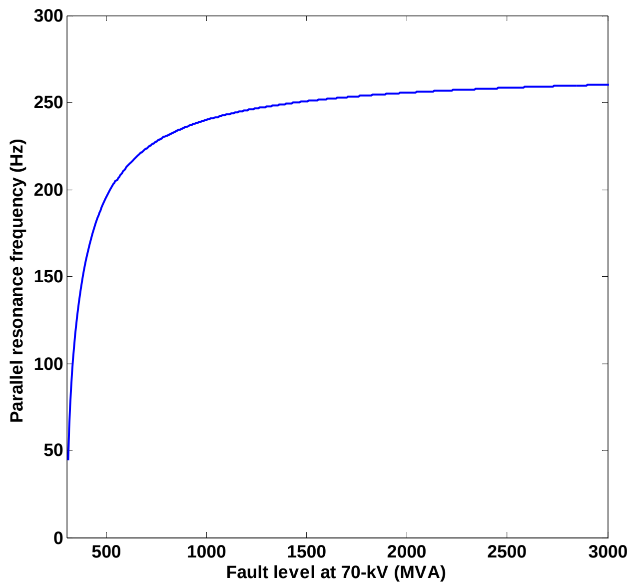


Figure 6. ***Parallel resonance frequency versus fault level***

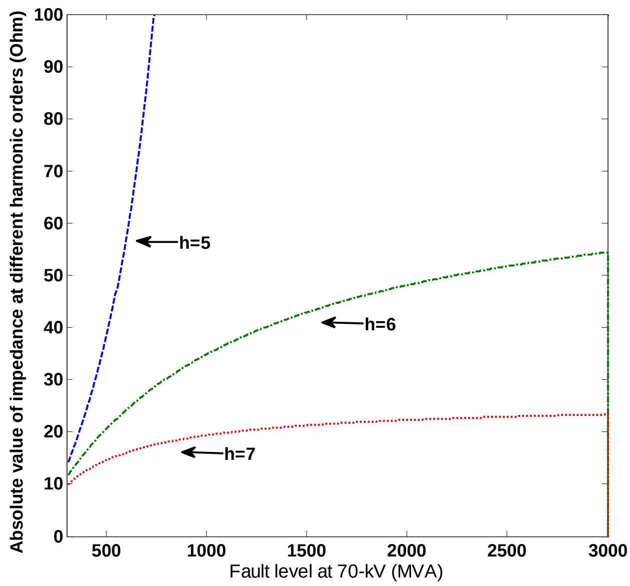


Figure 7. ***Impedance at different harmonic orders versus fault level***

Example 1.2: A 15-kV/690V transformer with capacity of 1200 kVA and per-unit impedance of 8% serves the low-voltage network of an industrial installation. The fault level at 15 kV side of the transformer is 147 MVA. A 450-kvar capacitor bank on secondary side is installed to compensate the reactive power consumed by the induction motors in the industrial plant. A total of 900 kVA of induction motors with leakage reactance of 17% is present. And a total of 3 km of underground cable with capacitance of 0.5μF/km is assumed to be connected to the bus (there are lots of motors, some of which are up to 150 meters from the transformer).

The capacitance connected to the low-voltage network consists of the capacitor bank and the underground cable. The size of the capacitor bank is 0.45 Mvar; while the reactive power (at fundamental frequency) produced by the cables is:

$$Q_{cab} = \omega C U^2 = 2\pi f \times 0.5 \cdot 10^{-6} \times 3 \times 690^2 = 224.4 \text{ var/km}$$

The total fault level at the secondary side of the transformer is:

$$S_{fault} = \frac{1}{\frac{1}{147} + \frac{0.08}{1.2}} + \frac{1}{0.17} \times 0.9 = 18.91 \text{ MVA}$$

According to (4), we can get the resonance frequency order.

$$n_{res} = \sqrt{\frac{S_{fault}}{Q_{cap} + Q_{cab}}} = \sqrt{\frac{18.91}{0.45 + 224.4 \times 10^{-6}}} = 6.48$$

Therefore, the resonance frequency is: $f_{rp} = n_{res} f_0 = 6.48 \times 50 \text{ Hz} = 324 \text{ Hz}$.

At fundamental frequency, the equivalent inductance and equivalent capacitance are

$$L = \frac{U^2}{\omega S_{fault}} = \frac{690^2}{2\pi \times 50 \times 18.91 \times 10^6} = 8 \times 10^{-5} H \quad C = C_{cab} + C_{cap} = 3 \times 10^{-3} F$$

$$C_{cap} = \frac{Q_{cap}}{\omega U^2} = \frac{450 \times 10^3}{2\pi \times 50 \times 690^2} = 3mF \quad C_{cable} = 0.5 \times 3 = 1.5 \mu F$$

5) Impact of induction motors

The impacts of cable, capacitor bank and transformer have been studied in example 1.1. In this example, the impact of the induction motor is studied in more detail. The sensitivity analysis is carried out by changing the total amount of induction motors from zero to the rating of the transformer, which is 1200 kVA. The results are shown as in Figure 8 and Figure 9. The scale of the vertical axis for absolute value of impedance is set to in the range of 0 to 10 Ω, in order to remove the unrealistic values that occur because damping is not considered. The amount of induction motor load has a significant influence on the resonance frequency and on the impedance at harmonic frequencies. The resonance frequency corresponds to the sixth and seventh harmonic for motor load equal to 440 kVA and 1440 kVA, respectively. The latter amount is beyond the horizontal scale of the figures; the total amount of motor load would exceed the rating of the transformer, which is an unlikely situation.

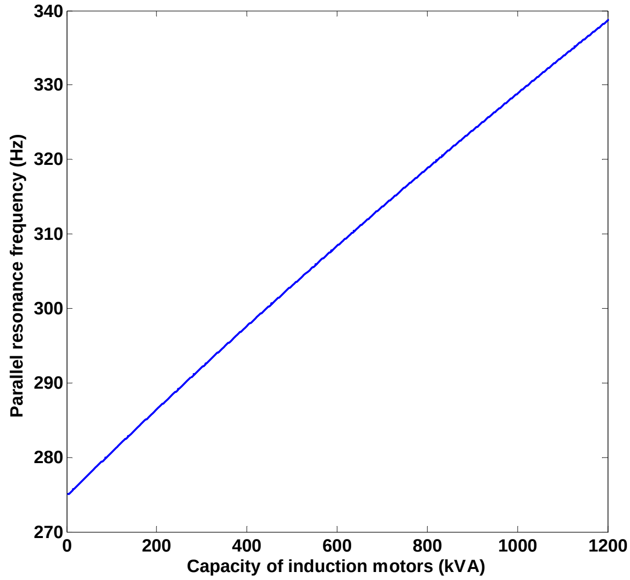


Figure 8. Parallel resonance frequency versus amount of induction motors.

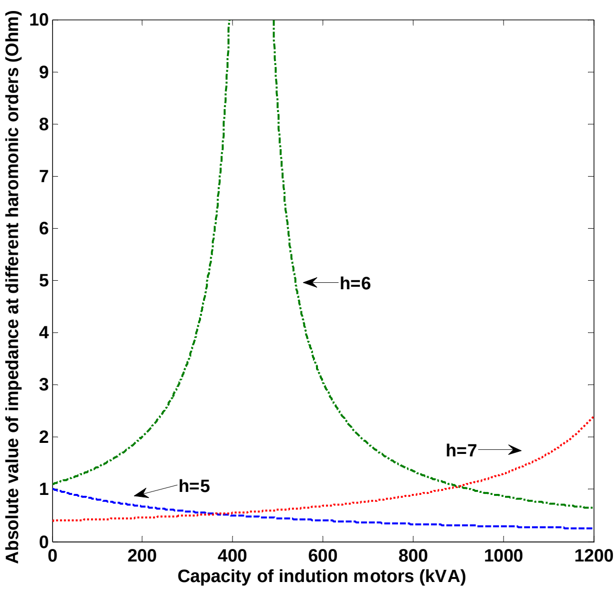


Figure 9. Impedance at different harmonic orders versus amount of induction motors

2.1.3 Influences of resistance on the impedance

Traditionally, high harmonic distortion levels were prevented by choosing the size lof the capacitor bank such that the resonance occurred close to harmonic order 5.5 or 6.5 where the harmonic emission was very small. Even a resonance frequency close to the sixth harmonic was often considered as acceptable because of the small amount of emission at even harmonics. However, a broadband spectrum is generated by using modern converters, like in wind turbines [9][10][11]. Therefore, the actual value of the impedance at resonance frequency should also be calculated, and the resistance cannot be neglected any longer. In this study, the series resistance of transformers is considered as well as shunt resistances due to the load.

2.1.4 Resistance due to transformer

An equivalent resistance, which represents the resistance of transformer, is added in series with the equivalent inductance as shown in Figure 10.

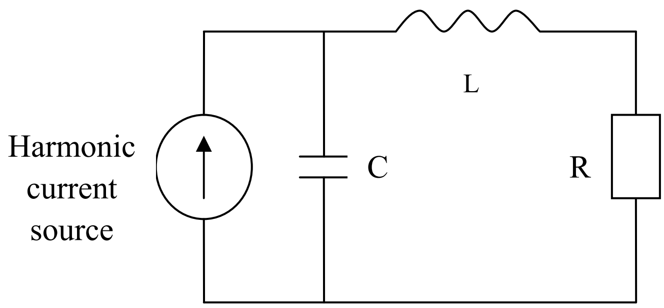


Figure 10. ***Equivalent circuit for parallel resonance with considering series resistance***

The resistance of transformers is considered proportional with frequency and the impedance of transformer can be expressed approximately by (8) [2][12].

$$Z_{tra}(h) = hR + jh\omega L \tag{8}$$

This is not an exact representation of the transformer impedance as a function of frequency, but it is the one commonly used in harmonic studies. Using (8), the impedance seen by harmonic current source is shown as in (9).

$$Z(h) = \frac{hR + jh\omega L}{\left(1-\omega^2 h^2 LC\right) + jh^2\omega RC} \tag{9}$$

At resonance frequency, the impedance reaches its maximum value which can be expressed by using (10).

$$Z_{\max} = \sqrt{\frac{L}{C}\left(1+\frac{\omega^2 L^2}{R^2}\right)} \tag{10}$$

And its resonance order is

$$n_{res} = \sqrt{\frac{L}{C}} \times \sqrt{\frac{1}{\omega^2 L^2 + R^2}} \tag{11}$$

The same two examples used before are studied here to analyze the impact of the series resistance on the impedance seen by a harmonic current source. For example 1.1, the equivalent inductance and capacitance is 7.9 mH and 48.7 µF, according to the earlier calculations. For an X/R ratio equal to 15 ($\frac{\omega L}{R} = 15$), the maximum impedance is 191.5 Ω at a resonance frequency of 256 Hz. The impedance at harmonic order of 5, 6 and 7 is calculated by using (9) and shown in Table I. Comparing the impedance for different values of *X/R*, there is little difference at harmonic order of 6 and 7. The difference at 5th harmonic is distinct, because it is close to the resonance order.

Table I. Magnitude of impedance at different harmonic orders for example 1.1

X/R	Resonance order	Amplitude of impedance (Ohm)			
		5	6	7	Resonance order
∞	5.132	224.7	40.58	20.19	∞
15	5.120	153.4	39.47	20.02	191.5

The sensitivity analyses also have been carried out with different value of *X/R* by changing both values of *X* and *R* and keeping their RMS value constant. As shown in the Figure 11, at harmonic order of 6 and 7, the impedance increases along with the increase of *X/R,* then it remains the same. As for the 5th harmonic, the impedance increases nonlinearly with *X/R.* The curve of harmonic with resonance frequency of 5.12 shows a linear relationship between the impedance and *X/R,* which is in accordance with the equation (4) and (9).

For frequencies close to the resonance frequency, the impact of the resistance on the impedance is big. It is therefore important that a good estimation of the resistance is used in the calculations.

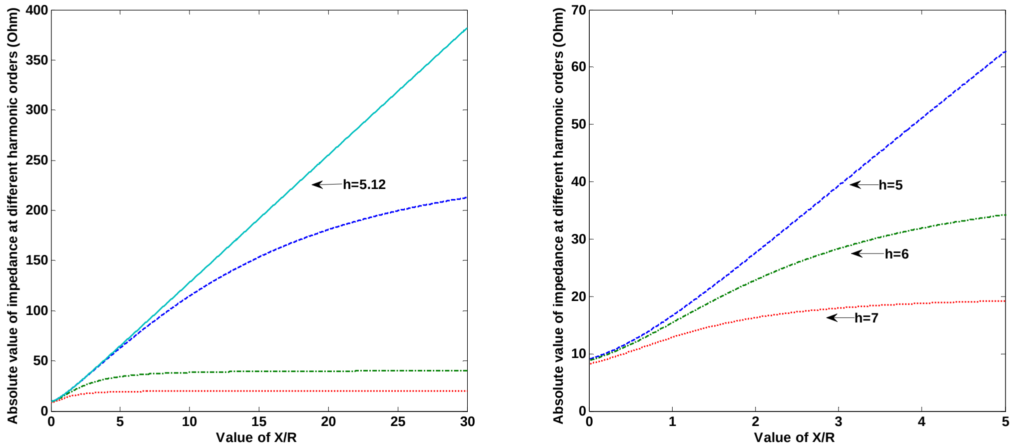


Figure 11 Magnitude of impedance at different harmonic orders versus X/R of the transformer; example 1.1.

For example 1.2, the equivalent inductance and capacitance is 80.16 μH and 3 mF. *X/R* of transformer is assumed to be 7, and its inductive impedance is 0.3174 Ω. At harmonic order of 5, 6 and 7, the specific values of impedance with different *X/R* are shown in Table II.

Table II Magnitude of impedance at different harmonic order for example 1.2

X/R	Resonance order	Amplitude of impedance (Ohm)			
		5	6	7	Resonance order
∞	6.480	0.2989	0.9429	1.1887	∞
7	6.426	0.3180	0.2301	0.1827	0.2069

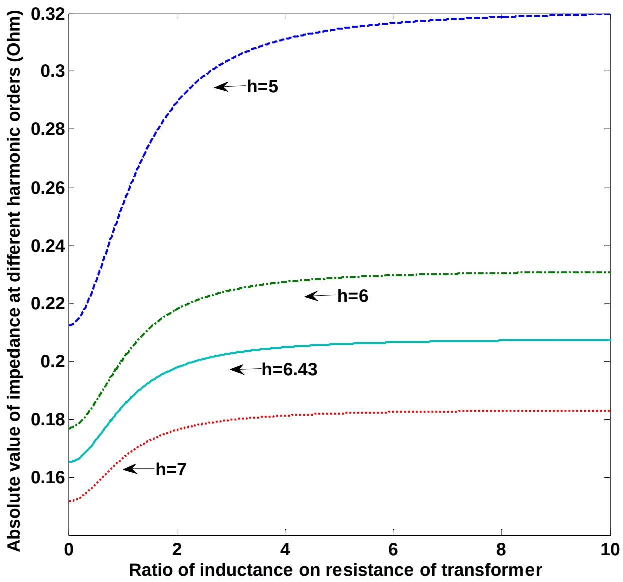


Figure 12 Magnitude of impedance at different harmonic orders versus X/R of the transformer; example 1.2.

And the sensitivity analyses also have been carried out with changing value of *X/R* as shown in Fig. 1-12. The impedance at different harmonic orders increases along the growth of *X/R* with different patterns. In this example the inductance is dominated by transformer and induction motors. Therefore, the impedance at different harmonic orders keeps constant when X/R is larger than about 3.

2.1.5 Resistance due to load

A resistance is added in parallel with the capacitor as shown in Figure 13. This resistance represents the damping due to all load supplied from the same bus as where the capacitor bank is connected.

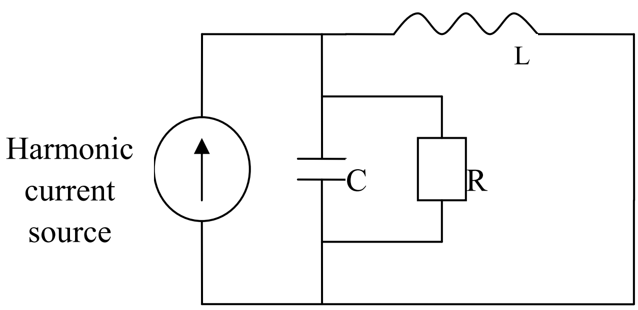


Figure 13. Equivalent circuit for parallel resonance with considering shunt resistance due to resistive load.

In our model we assume that the resistance representing the load does not change with frequency, so the impedance seen by the harmonic current source is

$$Z(\omega) = \frac{jh\omega RL}{R\left(1-\omega^2 h^2 LC\right) + jh\omega L} \tag{12}$$

The absolute value of the maximum impedance and the resonance order are

$$\left|Z_{\max}\right| = R\sqrt{1-\frac{L/C}{4R^2 - L/C}} \tag{13}$$

$$n_{res} = \frac{1}{\omega\sqrt{LC}} \bullet \sqrt{1-\frac{L/C}{2R^2}} \tag{14}$$

For example 1.1, a 5 MW resistive load is assumed to form the equivalent resistance, so the resulting maximum impedance is 80 Ω. As for example 1.2, 100 kW resistive load is assumed to form the equivalent resistance. The resulting maximum impedance is 4.761 Ω. At harmonic order of 5, 6 and 7, the impedance for both examples has been calculated by (11) and listed in the Table III and Table IV, respectively. And the sensitivity analyses have also been carried out with changing value of resistive load as shown in Figure 14 and Figure 15.

Table III Magnitude of impedance at different harmonic order for example 1.1

Load (MW)	Resonance order	Amplitude of impedance (Ohm)			
		5	6	7	Resonance order
0	5.132	224.7	40.58	20.19	∞
5	5.099	76.04	36.19	19.57	79.74

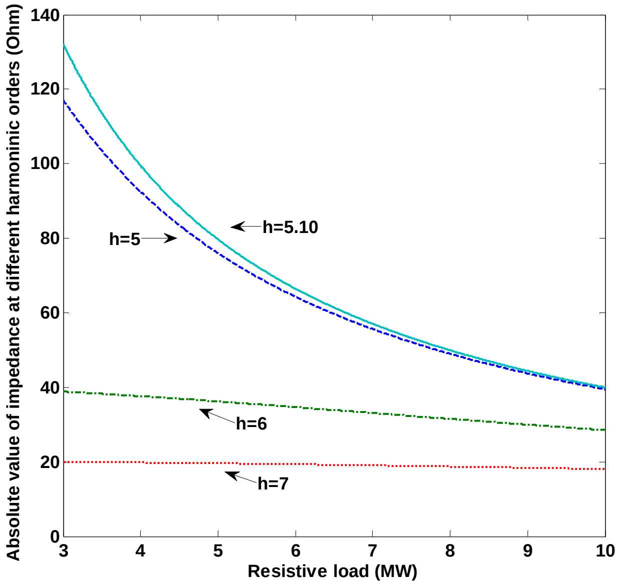


Figure 14. Magnitude of impedance at different harmonic orders versus resistive load; example 1.1.

Table IV. Magnitude of impedance at different harmonic order for example 1.2

Load (MW)	Resonance order	Amplitude of impedance (Ohm)			
		5	6	7	Resonance order
0	6.480	0.2989	0.9429	1.1887	∞
100	6.478	0.3023	0.9572	1.1135	4.4488

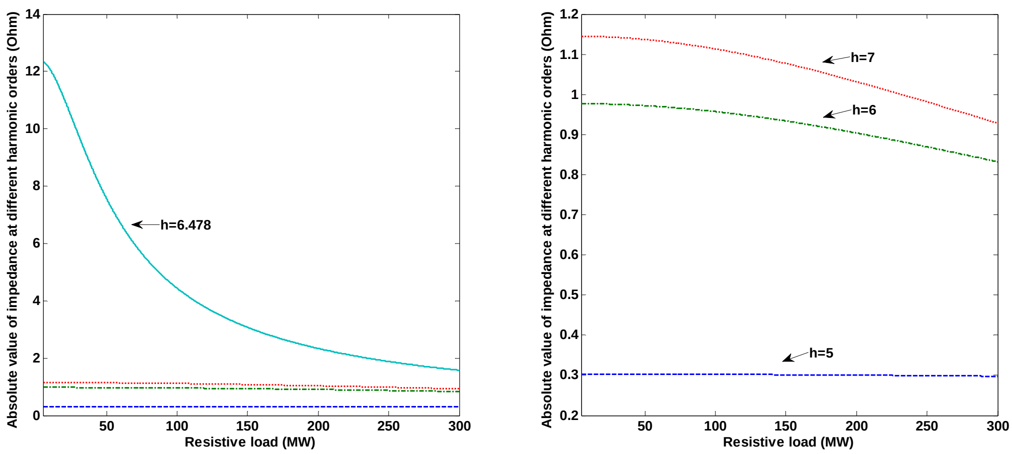


Figure 15. Magnitude of impedance at different harmonic orders versus resistive load; example 1.2.

As shown in Figure 14, the influence of the resistive load at harmonic 6 and 7 is small, because they are far away from the resonance frequency. Similarly, the curves for harmonic5, 6 and 7 shows little changes with different resistive load in Figure 15. A conclusion can be draw from these calculations: the resistance greatly affects the impedance close to the harmonic order where the resonance occurs.

2.2 Series Resonance

2.2.1 Theory

Series resonance leads to low impedance at the resonance frequency which results in a high voltage distortion even at locations where there is no or little harmonic emission from downstream sources [1][2]. Series resonance occurs when the local capacitance is in resonance with the inductance that connects the local bus to a remote bus with a high harmonic voltage. When the resistance is neglected, an equivalent circuit for series resonance is shown as in Figure 16.

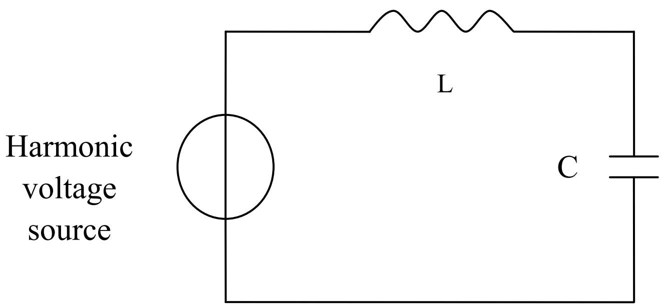


Figure 16. Equivalent circuit for series resonance, neglecting resistance.

The voltage at th local bus can be calculated by using (15).

$$U_h = \frac{1/jh\omega C}{jh\omega L + 1/jh\omega C} E_h = \frac{1}{1 - h^2\omega^2 LC} E_h \tag{15}$$

Where C is the total capacitance connected to the local bus, L is the inductance between the local bus and the remote bus, h is the harmonic order of the harmonic voltage at the remote bus. The current through the inductor and the capacitance can be expressed as (16).

$$I_h = \frac{E_h}{j\omega hL + 1/j\omega hC} = \frac{j\omega hC}{1 - \omega^2 h^2 LC} E_h \tag{16}$$

When $h^2\omega^2 LC$ gets close to 1, the voltage distortion at the local bus is amplified and can become much higher than at the remote bus.

The series resonance frequency is obtained from the following expression:

$$f_{rs} = \frac{1}{2\pi\sqrt{LC}} \tag{17}$$

Normally, the inductive equipment between local bus and remote bus is transformer. Assuming that the local capacitor size, transformer rating and transformer per-unit impedance are available, the resonance harmonic order can be calculated by (17) – (19) [2].

$$\omega C = \frac{Q_{cap}}{U^2} \tag{18}$$

$$\omega L = x_{tr}\frac{U^2}{S_{tr}} \tag{19}$$

$$n_{res} = \sqrt{\frac{S_{tr}}{x_{tr}Q_{cap}}} \tag{20}$$

When series resonance occurs, a high capacitor current will result, even if the harmonic voltages at the remote bus are relatively small [1].

Example 1.1 and example 1.2 are also studied here with the assumption that there is high harmonic voltage distortion at the primary side of the transformer. The series resonance frequency for each example is calculated as follows.

Example 1.1:

$$n_{res} = \sqrt{\frac{S_{tr}}{x_{tr}Q}} = \sqrt{\frac{30}{0.17\times\left(5.8+0.0264\times 12\right)}} = 5.3712$$

$$\omega L = x_{tr}\frac{U^2}{S_{tr}} = 0.17\times\frac{20^2}{30} = 2.27\,,\quad \omega C = \frac{Q}{U^2} = \frac{5.8+0.0264\times 12}{20^2} = 0.015$$

Example 1.2:

$$n_{res} = \sqrt{\frac{S_{tr}}{x_{tr}Q}} = \sqrt{\frac{1200}{0.08\times\left(450+3\times 74.8\times 10^{-3}\right)}} = 5.8$$

$$\omega L = x_{tr}\frac{U^2}{S_{tr}} = 0.08\times\frac{690^2}{1200\times 10^3} = 0.032\,,\quad \omega C = \frac{Q}{U^2} = \frac{450\times 10^3+3\times 74.8}{690^2} = 0.946$$

When the resistance is neglected, the voltage over the capacitor will be amplified to an infinite value at the series resonance frequency. In reality, there is always resistance associated with both transformer and load, which limits the maximum voltage amplification.

2.2.2 Impact of transformer resistance on the voltage amplification

When the resistance of the transformer is taken into account, the equivalent circuit for series resonance can be modified by adding a resistance in series with the equivalent inductor as shown in Figure 17.

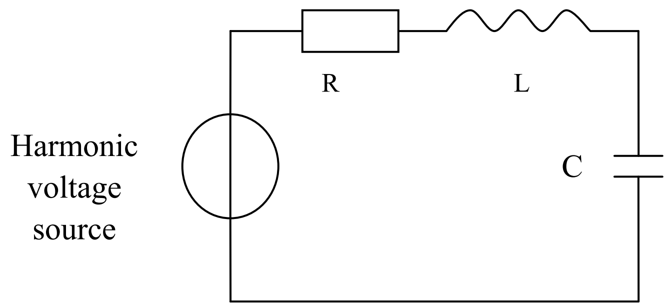


Figure 17. . Equivalent circuit for series resonance with considering resistance of the transformer.

According to (8), the resistance of the transformer is proportional with frequency, thus the voltage over the capacitor is:

$$U_h = \frac{E_h}{h\left(R + j\omega L\right) + \dfrac{1}{jh\omega C}} \bullet \frac{1}{jh\omega C} = \frac{E_h}{j\omega h^2 RC + \left(1 - \omega^2 h^2 LC\right)} \tag{21}$$

When the transformer resistance is taken into account, the resonance frequency turns into the expression of (22).

$$n_{res} = \sqrt{\frac{L}{C}} \bullet \sqrt{\frac{1}{\omega^2 L^2 - R^2}} \tag{22}$$

At resonance frequency, the maximum voltage distortion can be expressed as (23).

$$\left|\frac{U_h}{E_h}\right| = \left|\frac{\omega^2 L^2 - R^2}{R(R - j\omega L)}\right| = \frac{\dfrac{\omega^2 L^2}{R^2} - 1}{\sqrt{1 + \dfrac{\omega^2 L^2}{R^2}}} \tag{23}$$

For the example 1.1, the resonance order changes from 5.3712 to 5.4314, and the maximum voltage distortion is 14.9 (instead of infinite), when the transformer resistance is considered. Similarly, the maximum voltage distortion for example 1.2 is 6.79 at the resonance order of 5.81.

2.2.3 Impact of load resistance on the voltage amplification

In order to consider the impact of load resistance on voltage distortion, an equivalent load is added in parallel with the capacitor as shown in Figure 18.

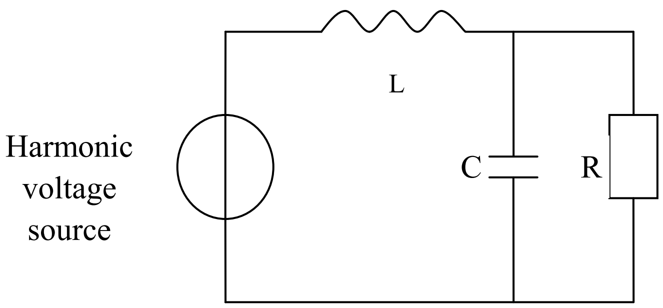


Figure 18. Equivalent circuit for series resonance with considering load resistance.

Then the voltage over the capacitor is

$$U_h = \frac{E_h}{jh\omega L + \frac{R/jh\omega C}{R + 1/jh\omega C}} \bullet \frac{R/jh\omega C}{R + 1/jh\omega C} = \frac{R}{R\left(1 - \omega^2 h^2 LC\right) + j\omega hL} E_h \tag{24}$$

When the load resistance is considered, the resonance order is

$$n_{res} = \frac{1}{\omega\sqrt{LC}} \bullet \sqrt{1 - \frac{L/C}{2R^2}} \tag{25}$$

At resonance frequency, the maximum voltage over the capacitor can be calculated by using (26).

$$\left|\frac{U_h}{E_h}\right| = \frac{2R^2}{\sqrt{\frac{L}{C}\left(4R^2 - \frac{L}{C}\right)}} \tag{26}$$

For example 1.1, the maximum voltage over the capacitor is 6.52 times the voltage at the remote bus, at a harmonic order of 5.39. As for example 1.2, at the resonance harmonic order of 5.75, the maximum ratio of the capacitor voltage and the voltage at the remote bus is 25.89.

3 Harmonic Resonance due to grid-connected wind farms

In the previous chapter we introduced the two types of harmonic resonances: parallel and series resonance. Both types occur in wind farms. In this chapter we will use an example configuration of wind farm to illustrate the occurrence of both types of resonance in wind farms. This chapter will start with some analytical calculations, along the same line as the calculations in the previous chapter. The main calculations will however be performed in a power-system analysis package.

3.1 Configuration of wind farm and wind turbine

When a wind farm is integrated into the power system, step-up transformers and capacitor banks are added as well as the cables for collecting power, as shown in Figure 19. These additional inductive and capacitive elements will produce new harmonic resonances or change resonance frequencies of existing harmonic resonances.

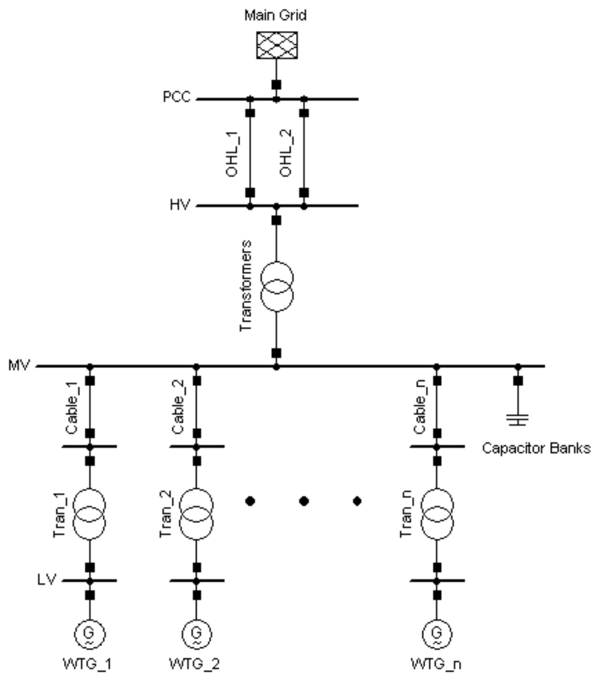


Figure 19. Typical configuration of a grid-connected wind farm.

The electrical power generated from each wind turbine generator (WTG) is first stepped up by a turbine transformer and collected to the medium-voltage (MV) substation by the underground cables. Normally, the wind farm is located in a remote area. In order to decrease energy loss, the electrical power is transmitted to the power grid by high voltage overhead lines after its voltage is increased by the substation transformers installed in the MV substation.

3.2 Modeling of wind farm for harmonic resonance analysis

3.2.1 Induction machine

The induction machine is used in most of the wind turbine generators as their electrical part. An equivalent circuit of the induction machine for harmonic analysis has been used in for example in [13]; the simplified equivalent circuit for harmonic resonance study is shown in Figure 20. In the circuit diagram R_s and R_r are the stator resistance and rotor resistance, while X_s and X_r are the stator leakage reactance and rotor leakage reactance; X_m represents the magnetizing reactance.

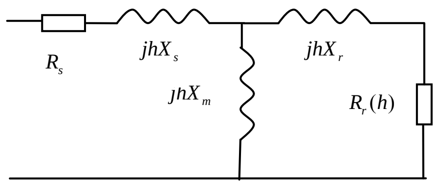


Figure 20. Equivalent circuit of an induction machine for harmonic resonance analysis.

In some publications the slip-dependence of the apparent rotor resistance is specifically mentioned and the resistance on the right in Figure 20 is replaced by $R_r(h)\left(1+\frac{1}{s}\right)$. The slip at harmonic frequencies is however much larger than unity so that the approximation used here is very well acceptable. The uncertainty in the actual resistance at the harmonic frequency is much larger than the error made by neglecting the impact of the slip.

3.2.2 Collecting system

The Collecting system for a wind farm contains medium-voltage (MV) cables, high-voltage (HV) overhead lines and transformers. The cables can be modelled as an equivalent capacitor, while the overhead lines and transformers can be modelled as a series combination of equivalent inductor and resistance. Both capacitance and inductance can be assumed frequency independent. The frequency dependency of the resistance should be considered in the calculations, as was clearly pointed out in the previous chapter. Where possible this relation should be obtained from detailed calculations. This is however not always practical; further may the uncertainty in the estimated amount of resistive load dominate the uncertainty in the results. Therefore simplified expressions are often used, which we will discuss in the next section.

3.2.3 Wind farm

Based on the equivalent circuits of the components in the wind farm, the grid-connected wind farm in Figure 19 can be modelled as an equivalent circuit shown as in Figure 21, where the magnetizing reactance of the induction machine has been neglected.

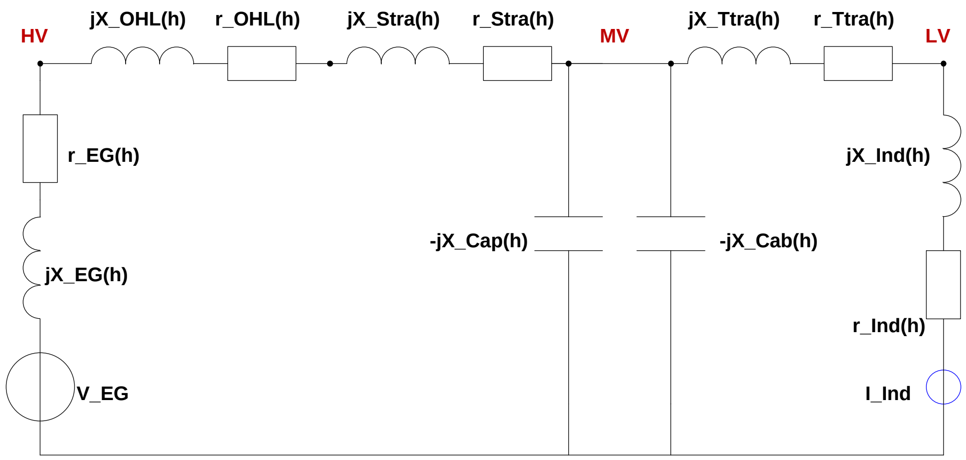


Figure 21. Equivalent circuit for the grid-connected wind farm.

3.3 Harmonic resonance analysis

Based on the above proposed modelling and the resonance theory in Chapter 2, several case studies are carried out to illustrate the harmonic resonances introduced by a wind farm. The wind farm used for the studies is based on the example presented in [13]: it consists of 100 wind turbines with rated power of 2 MW and terminal voltage of 690 V each. 100 turbine transformers and underground cables of 34.5 kV are used to connect the wind turbines to the MV substation. A total of 72 Mvar capacitor banks, switchable in steps of 12 Mvar, are also installed in the MV substation. The power from the wind farm substation is transmitted to the main grid through two 115/34.5 kV transformers and two parallel 115 kV overhead lines. The detailed parameters are supplemented and shown in Table V.

Table V. Parameters of the wind farm used in the study.

Equipments	Voltage (kV)	Capacity/Fault level	Impedance	*X/R*
Transformer	115/34.5	250MVA×2	18%	12
Turbine Transformer	34.5/0.69	2.5MVA×100	5%	5
Induction machine	0.69	2MW×100	17.12%	8.5
Underground cables	34.5	/	0.13 Ω/km,0.25 μF/km	18
Capacitor banks	34.5	72Mvar (6 steps)	/	/
Overhead lines	115	/	0.36 Ω/km×35km	/
External Grid	115	3500MVA	/	18

The 100 wind turbines are assumed to be located in 10 rows and 10 columns, as shown in Figure 22. The wind farm substation is in the centre place with a vertical distance of 500 m to the centre of the first row. In order to decrease the wake effect, the distance between two rows is 320 m, while the distance between two columns is 640 m. The length of the 10 cables for the wind turbines in the same column can be calculated according to the Pythagorean Theorem, resulting in Table VI. The total cable length is the summation of all cables' length.

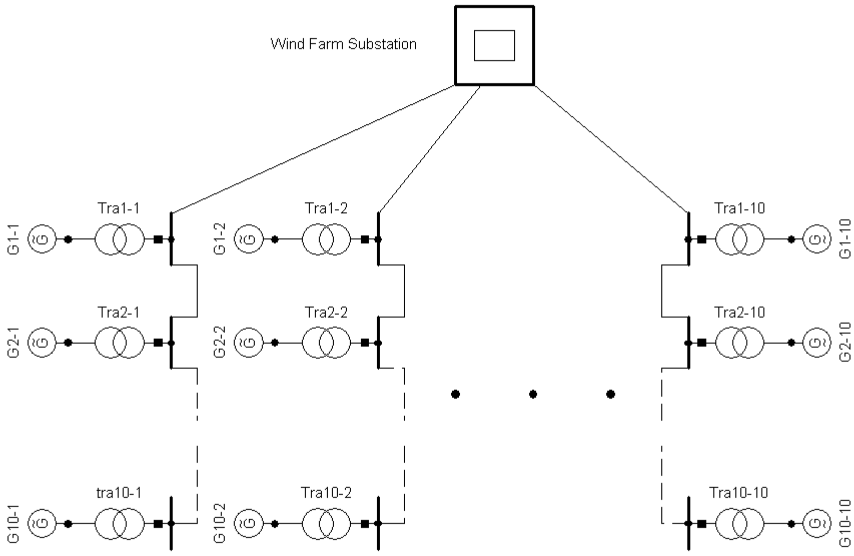


Figure 22. Layout of wind farm used in the case study.

Table VI. Length of underground cables in the wind farm.

Cable	Length (m)	Cable	Length (m)
Cab1	5803	Cab 10	5803
Cab 2	5175	Cab 9	5175
Cab 3	4556	Cab 8	4556
Cab 4	3962	Cab 7	3962
Cab 5	3474	Cab 6	3474
Total cables		45.94km	

3.3.1 Analytic method

The equivalent parameters for all the equipments are calculated to the same voltage level of 34.5 kV and listed in Table VII.

Table VII. Equivalent parameters of wind farm.

Equipments	Impedance (Ω)	Capacitor banks	Impedance (Ω)
Substation transformer	0.07117+j0.8540	12 Mvar	-j99.19
Turbine transformer	4.669+j23.34	24 Mvar	-j49.59
Induction machine	10.92+j92.83	36 Mvar	-j33.06
Underground cables	-j277.2	48 Mvar	-j24.80
Overhead lines	0.05936+j0.5639	60 Mvar	-j19.84
External Grid	0.01886+j0.3396	72 Mvar	-j16.53

3.3.2 Series resonance at the HV substation

The aim to study series resonance at the HV substation is to obtain the voltage distortion in the MV substation, due to voltage harmonics at the HV substation. The high voltage distortion might damage the electrical equipments installed in the MV substation, such as capacitor banks. The high harmonic current through the transformer may also result in overheating of the transformer or cause an unwanted trip of the transformer protection.

To identify the series resonance frequency is to find the minimum impedance value at the HV substation. According to the equivalent circuit in Figure 21, the impedance at the HV bus is:

$$Z_{HV}(h) = Z_{EG}(h) // \left(Z_{OHL}(h) + Z_{Sub-Tra}(h) + Z_{WF}(h) // Z_C(h)\right)$$

$$= \frac{Z_{EG}(h) \times \left(Z_{OHL}(h) + Z_{Sub-Tra}(h) + Z_{WF}(h) // Z_C(h)\right)}{Z_{EG}(h) + \left(Z_{OHL}(h) + Z_{Sub-Tra}(h) + Z_{WF}(h) // Z_C(h)\right)} \tag{27}$$

$$Z_C(h) = -j(X_{Cab}(h) // X_{Cap}(h)) \tag{28}$$

So the series resonance occurs at the frequency where the impedance seen from the HV bus reaches its minimum absolute value. The amplification of voltage distortion at the MV substation can also be obtained by using (29) as follows.

$$\frac{U_{MV}}{U_{HV}}(h) = \frac{\left(Z_C(h) // Z_{WF}(h)\right)}{\left(Z_{OHL}(h) + Z_{Sub-Tra}(h)\right) + Z_C(h) // Z_{WF}(h)} \tag{29}$$

The resonance frequency can also be defined as the frequency at which the amplification is highest. This is not the same frequency as the one at which the impedance seen from the HV substation is lowest, but the two frequencies are close.

In order to simplify the calculation, the resistance of all components in the power grid is assumed to be linearly proportional to the frequency. Under these assumptions, the parameters in the equivalent circuit for the series resonance analysis are obtained as follows.

1) The impedance of the main grid is:

$$Z_{EG}(h) = h \times (0.01886\text{+j}0.3396)\ \Omega$$

2) The impedance of two parallel overhead lines and two parallel substation transformers is:

$$Z_{OHL}\left(h\right) + Z_{Sub-Tra}\left(h\right) = h \times \left(0.09494 + j0.9909\right)\Omega$$

3) The impedance of the parallel connection of 100 wind turbines and turbine transformers is:

$$Z_{WF}\left(h\right) = (Z_{Tur}\left(h\right) + Z_{Tur-Tra}\left(h\right)) / N_{WTG}$$

$$= h \times \frac{4.669 + j23.34 + 10.92 + j92.83}{100} = h \times (0.1559 + j1.162)\Omega$$

4) When all capacitor banks are switched on, the capacitive reactance in the circuit is:

$$X_C\left(h\right) = X_{cab}\left(h\right) // X_{cap}\left(h\right) = \frac{277.2 \times 16.53}{277.2 + 16.53} \Big/ h = \frac{15.60}{h}\Omega$$

In this case, the reactance of wind turbines and turbine transformers cannot be neglected and the resonance order cannot be calculated by using equation (14) or (17) in Section 2.2. However, the resonance order and amplification can be obtained by sensitivity analysis with MATLAB. Using such sensitivity analysis the resonance order was shown to be about 5.4; the impedance and amplification as a function of frequency are shown in Figure 23 and Figure 24.

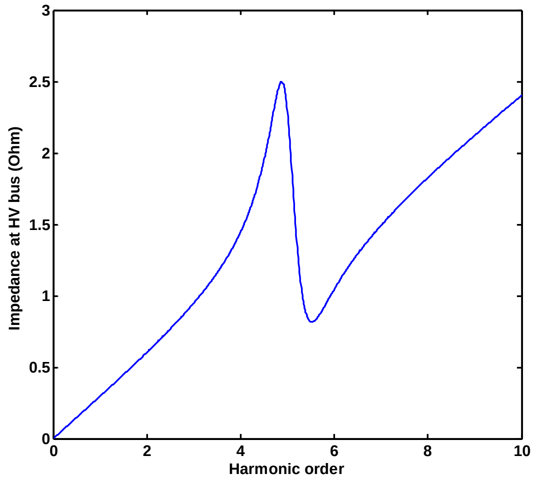


***Figure 23. Impedance at the HV bus versus harmonic orders** (Q_{cap}=72 Mvar).*

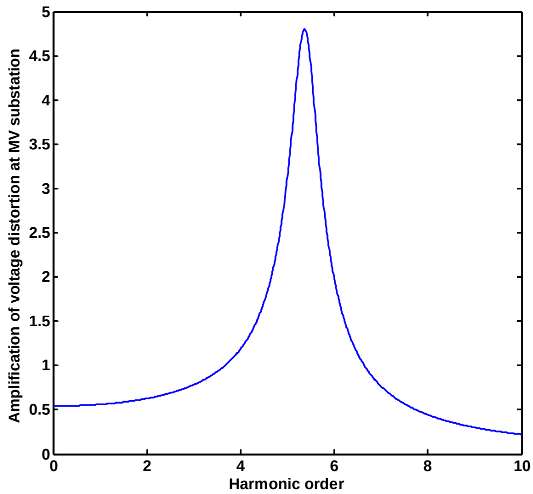


***Figure 24. Amplification of voltage distortion at the MV bus versus harmonic order** (Q_{cap}=72 Mvar).*

The different resonance orders with different number of switched-on capacitor banks are shown in Table VIII. The results agree with equation (23) deduced in Section 2.2. This indicates that the size of the capacitor bank does not affect the amplification of the voltage distortion at resonance order, when the resistance in the power grid is assumed to be linearly proportional to the frequency.

Table VIII. Series resonance analysis with different size of the capacitor bank.

Capacitor Banks	Resonance Order	$\lvert U_{MV}(h)/U_{HV}(h) \rvert$			
		Resonance order	3	5	7

0 Mvar	22.8	4.801	0.5505	0.5683	0.5974
12 Mvar	11.7	4.801	0.5791	0.6619	0.8420
24 Mvar	8.88	4.801	0.6108	0.7920	1.411
36 Mvar	7.45	4.801	0.6461	0.9842	3.584
48 Mvar	6.54	4.801	0.6857	1.295	2.701
60 Mvar	5.89	4.801	0.7305	1.870	1.213
72 Mvar	5.41	4.801	0.7814	3.134	0.7654

3.3.3 Parallel resonance at the MV substation

When the harmonic current sources connected to the MV bus emit a current close to the parallel resonance frequency, a large voltage distortion will result at the MV substation, as well as a large harmonic current through the capacitor banks.

The impedance seen by a current source connected to the MV bus is:

$$Z_{MV}(h) = \left(Z_{EG}(h) + Z_{OHL}(h) + Z_{Sub-Tra}(h)\right) // \left(Z_{WF}(h) // Z_C(h)\right)$$

$$= \frac{\left(Z_{EG}(h) + Z_{OHL}(h) + Z_{Sub-Tra}(h)\right) \times \left(Z_{WF}(h) // Z_C(h)\right)}{Z_{EG}(h) + Z_{OHL}(h) + Z_{Sub-Tra}(h) + Z_{WF}(h) // Z_C(h)} \qquad (30)$$

The parallel resonance occurs at the frequency where the impedance seen from the MV bus reaches its maximum absolute value. And the amplification of harmonic current flow in the capacitor banks can also be obtained by using (31) as follows.

$$\left|\frac{I_{cap}(h)}{I_{MV}(h)}\right| = \left|\frac{\dfrac{Z_{EG}(h) + Z_{OHL}(h) + Z_{Sub-Tra}(h)}{Z_{WF}(h)}}{Z_{EG}(h) + Z_{OHL}(h) + Z_{Sub-Tra}(h) + \dfrac{Z_{WF}(h)}{Z_C(h)}}\right|$$

(31)

In this case, the equivalent inductance is formed by the main grid, the 115 kV overhead lines, the 115/34.5 kV transformers, and all the induction machines and turbine transformers in the wind farm. The equivalent capacitance consists of the capacitor banks and all underground cables. When all capacitor banks are switched on, the equivalent parameters are calculated as follows.

1) The total inductive impedance seen at the MV bus is:

$$Z_L(h) = \left(Z_{EG}(h) + Z_{OHL}(h) + Z_{Sub-Tra}(h)\right) // Z_{WF}(h) = h \times (0.0691 + j0.6206)\Omega$$

$$Z_{EG}(h)+Z_{OHL}(h)+Z_{Sub-Tra}(h)=h\times(0.09494+j0.9909+0.01886+j0.3396)$$

$$=h\times(0.1138+j1.331)\Omega$$

$$Z_{WF}(h)=h\times(0.1559+j1.162)\Omega$$

2) The capacitive impedance connected to the MV bus is the parallel connection of the capacitive impedance of the cables and the capacitor banks.

$$X_C(h)=X_{cab}(h)//X_{cap}(h)=\frac{277.2\times16.53}{277.2+16.53}\Big/h=\frac{15.60}{h}\Omega$$

3) The ratio of reactance to resistance for the equivalent circuit is:

$$\frac{X_L}{R}=\frac{0.6206}{0.0691}=8.981$$

The resonance order can be calculated by using (11) in Section 2.1 as follows.

$$n_{res}=\sqrt{\frac{L}{C}}\times\sqrt{\frac{1}{\omega^2L^2+R^2}}=\sqrt{\frac{0.6206}{1/15.6}}\times\sqrt{\frac{1}{0.6206^2+0.0691^2}}=4.983$$

and the impedance of the MV substation at the resonance frequency is:

$$Z_{\max}=Z(n_{res})=\sqrt{\frac{L}{C}\left(1+\frac{\omega^2L^2}{R^2}\right)}=\sqrt{\frac{0.6206}{1/15.6}\times\left(1+8.981^2\right)}=28.12\Omega$$

When resonance occurs, the ratio of the current through the capacitor banks and the harmonic current source is:

$$\frac{I_{cap}(n_{res})}{I_h}=\frac{Z_{\max}}{X_{Cap}(n_{res})}=\frac{28.12}{16.53/4.983}=8.476$$

The results with different number of switched-on capacitor banks are obtained with the same method and shown in Table IX.

Table IX. Parallel resonance analysis with different size of the capacitor banks.

Capacitor Banks	Resonance Order	$\lvert I_{cap}(h)/I_h(h)\rvert$			
		Resonance order	3	5	7
0Mvar	21.7	0	0	0	0
12Mvar	10.8	6.647	0.0613	0.1997	0.5268

24Mvar	8.21	7.655	0.1306	0.4997	2.138
36Mvar	6.88	8.064	0.2095	0.9871	7.820
48Mvar	6.04	8.285	0.3001	1.924	3.358
60Mvar	5.44	8.412	0.4052	4.211	2.309
72Mvar	5	8.518	0.5285	8.518	1.901

3.3.4 Simulation

Further studies been carried out by using the harmonics analysis tool of DIgSILENT PowerFactory 14.0 [14]. The connections between the 10 wind turbines and turbine transformers in the first column of the wind farm are modelled in detail to study the harmonic resonance at the point near to the wind turbines. The remaining 90 wind turbines and turbine transformers are merged into 9 combinations, in which 10 wind turbines and 10 turbine transformers are connected in parallel. The model built in the simulation package is shown in Figure 25.

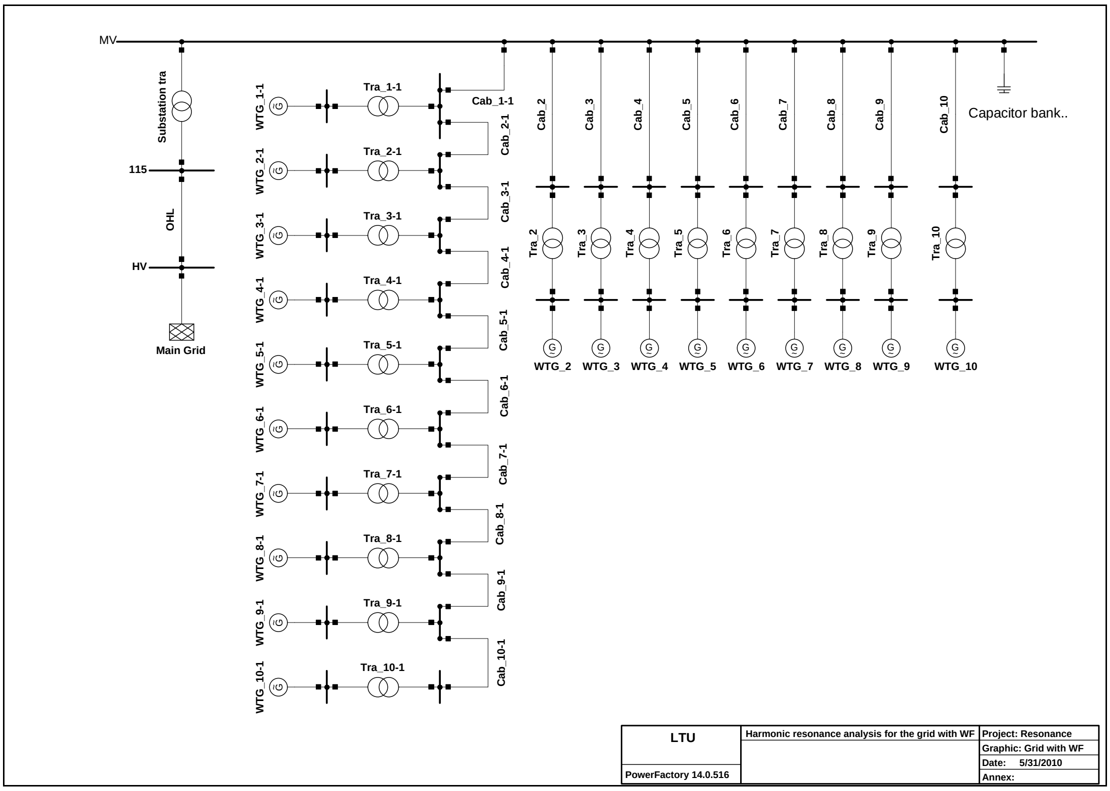


Figure 25. Modelling of grid-connected wind farm in the simulation package.

As for the simulation, the resistance for different components can be modelled separately by associating a "frequency characteristic" to these quantities [14]. This characteristic is defined by a polynomial formula as (32).

$$y(f_h) = (1-a) + a \bullet \left(\frac{f_h}{f_1} \right)^b \tag{32}$$

The resulting value of resistance or inductance is obtained by:

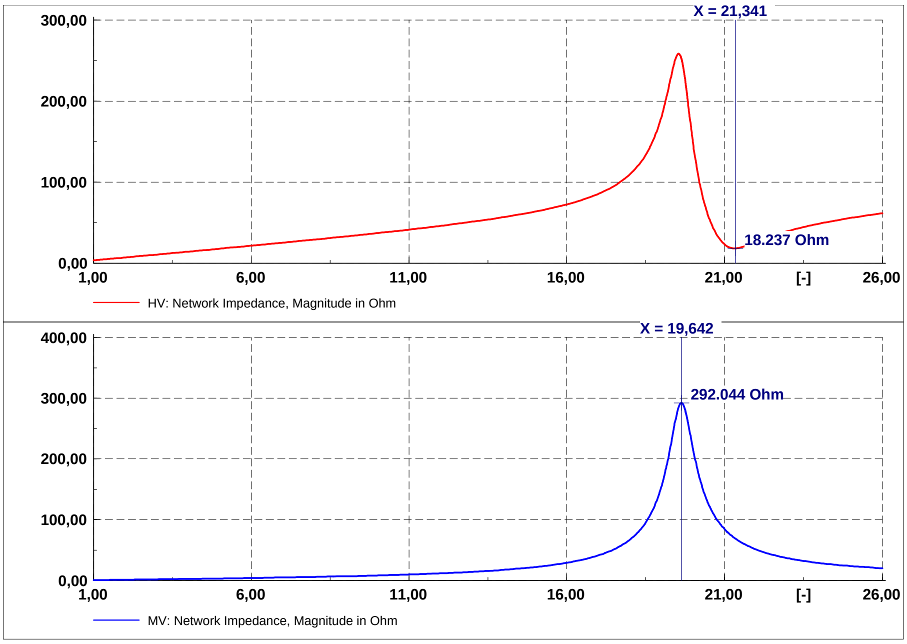
$$Val(f_h) = Val(f_1) \times y(f_h) \tag{33}$$

Therefore, the resistance of each component can be set to the values as shown in the Table X, separately.

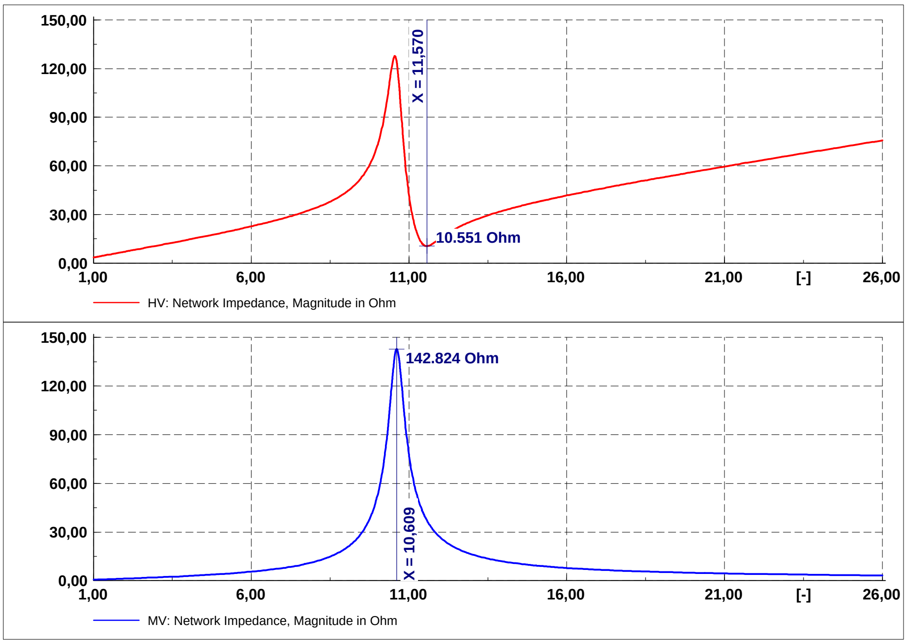
Table X. Parameters of resistance frequency characteristics for the different components.

Components	a	b
WTG	1	0.5
Main Grid	1	0.5
Transformer	1	0.9
Overhead lines	1	0.3
Cables	1	0.5

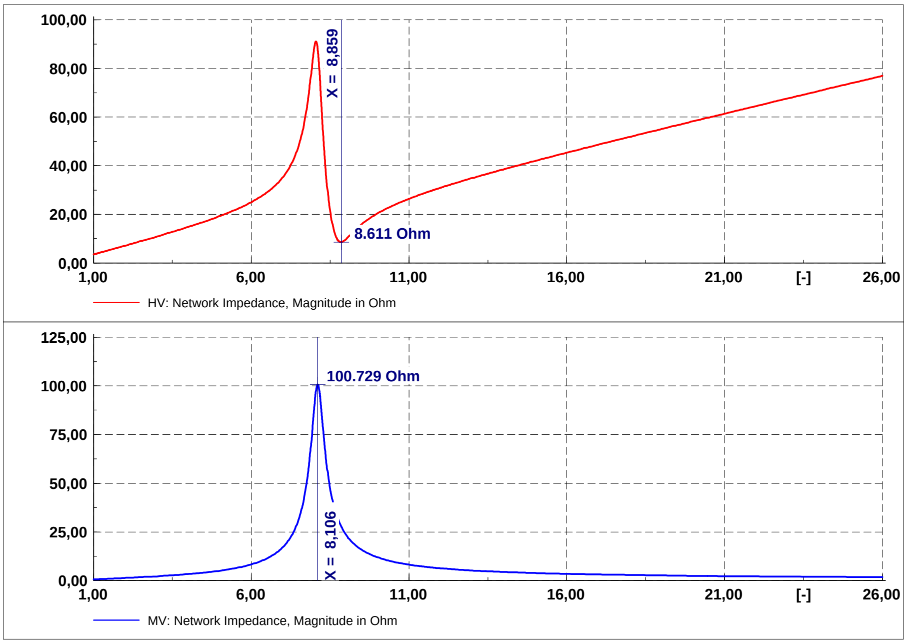
The resonance order can be obtained from a frequency sweep, i.e. the impedance as a function of frequency. The simulation results with different amount of the capacitor banks connected are shown in Figure 26. In all cases, the upper curve is the impedance at the HV bus and the lower one is the impedance at the MV bus.



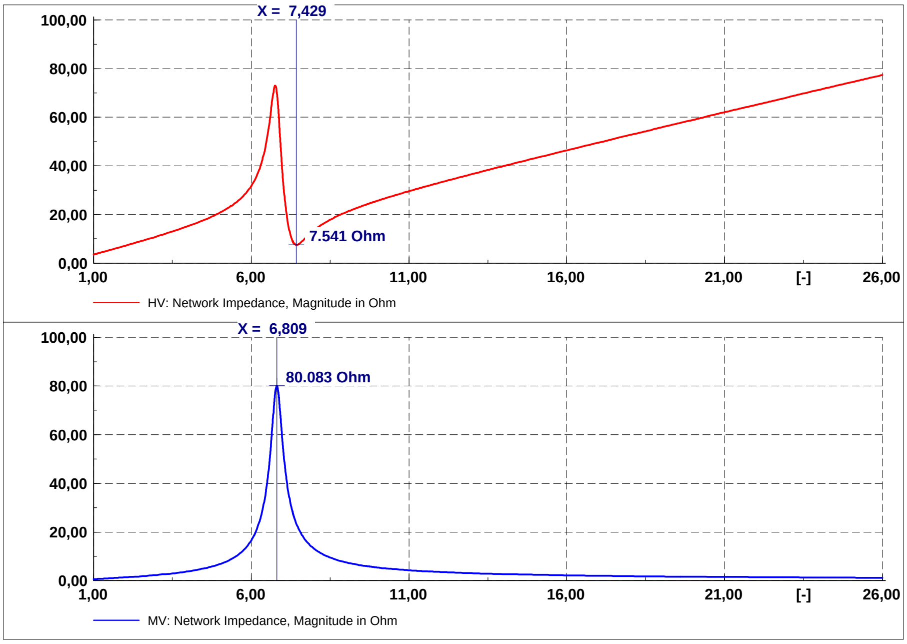
(a) $Q_{cap} = 0$ Mvar



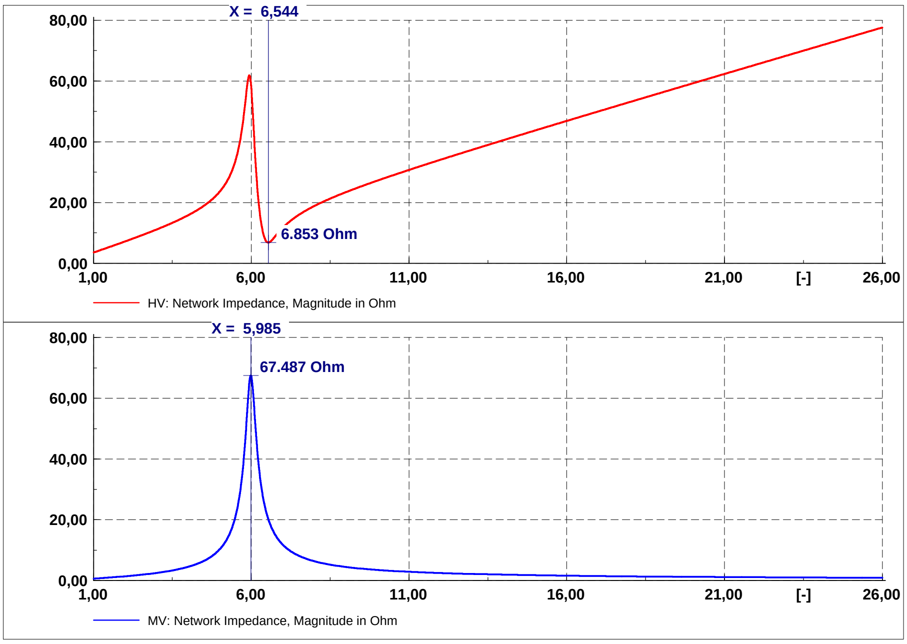
(b) $Q_{cap} = 12$ Mvar



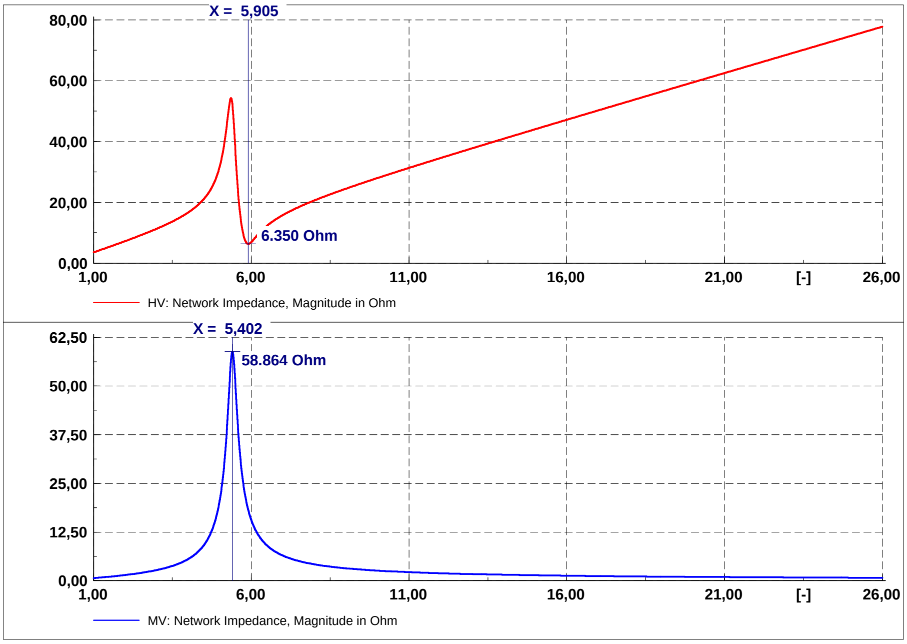
(c) $Q_{cap} = 24$ Mvar



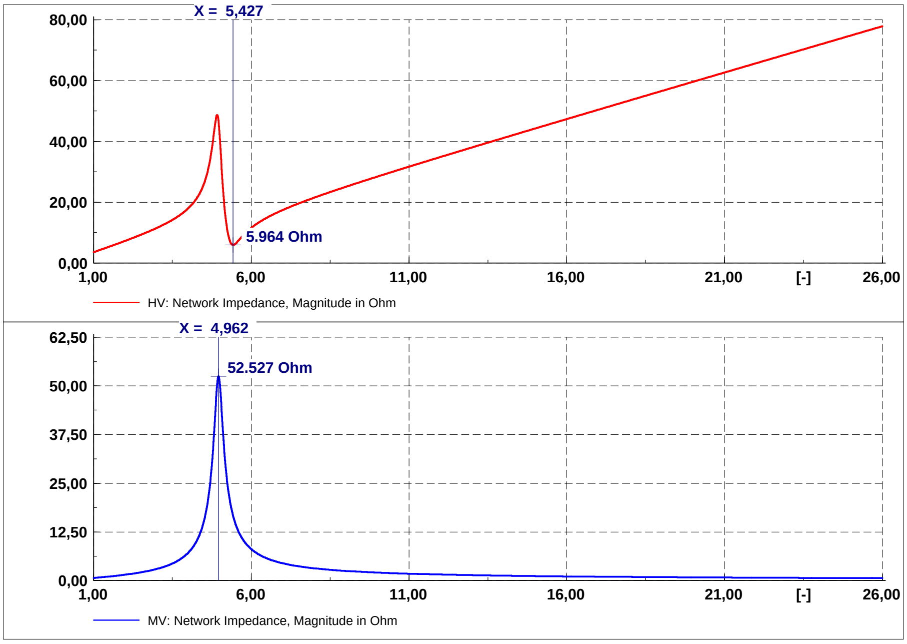
(d) $Q_{cap} = 36$ Mvar



(e) $Q_{cap} = 48$ Mvar



(f) Q_{cap} = 60 Mvar



(g) Q_{cap} = 72 Mvar

Figure 26. Impedance versus frequency at the HV bus and at the MV bus.

Without capacitors connected, resonances occur around harmonic order 20 (1 kHz), whereas the resonance frequency goes down to below 300 Hz when all 72 Mvar of capacitor banks is connected. Seen from the MV bus only a series resonance is visible, which will cause an increased voltage distortion due to emission by the wind turbines. This is normally of minor concern due to the rather small emission from the wind turbines, but it is worth checking in all cases. Seen from the HV bus both a series and a parallel resonance are visible; the concern is with the series resonance (the low impedance value) because this is where the background distortion gets amplified to the MV bus.

The resonance orders for different amounts of capacitance connected are listed in Table IX. There is little difference between simulation results and calculations. The different treating methods for resistances of the electrical components do not affect the resonance order significantly, for the resistances are rather small compared to the reactance. The resonance frequencies vary a lot with different amounts of capacitance connected to the MV bus.

Table XI. Harmonic resonance order with different capacities of capacitor banks.

Capacitor banks	HV		MV	
	Simulation	Calculation	Simulation	Calculation
0Mvar	21.34	22.8	19.64	21.7
12Mvar	11.57	11.7	10.61	10.8
24Mvar	8.859	8.88	8.106	8.21
36Mvar	7.429	7.45	6.809	6.88
48Mvar	6.544	6.54	5.985	6.04
60Mvar	5.905	5.89	5.402	5.44
72Mvar	5.427	5.41	4.962	5

The parallel resonances at the high voltage side of the 10 turbine transformers in the first column have also been analyzed by simulation, when the capacity of capacitor banks is 72 Mvar. The results are shown in Table XII. The results indicate that the cable is not the main factor impacting the harmonic resonances. A similar result was obtained in Chapter 2 where it was shown that the impact of the medium-voltage cables on the resonance frequency was small.

Table XII. Harmonic resonance orders at the bus near to the turbine transformers.

Near to the transformer	Resonance orders	Near to the transformer	Resonance orders
1-1	4.958	6-1	4.956
2-1	4.957	7-1	4.956
3-1	4.957	8-1	4.955
4-1	4.957	9-1	4.954

5-1	4.956	10-1	4.954

The operation modes of the 115-kV overhead lines and the 115/34.5-kV substation transformers are changed to study their influence on the series resonance. When series resonance occurs, the voltage distortion might be amplified at the MV bus. The 5th and 7th harmonics are the dominant harmonics in most transmission system. These harmonics originate from domestic and commercial customers [1][2][7]. Meanwhile, the similar analysis is also carried out for the 3rd harmonics, since the 3rd harmonic is often emitted by power transformers when the operating voltage is several percent above nominal. So the amplifications of voltage distortion with 3rd, 5th and 7th harmonics are calculated as well as the resonance orders with different capacity of capacitor banks, based on the simulation results. The simulation results are shown in Table XIII, Table XIV, and Table XV.

Table XIII. Amplification of voltage distortion under full operation.

Capacitor Banks	Resonance Order	$\left\|U_{MV}(h)/U_{HV}(h)\right\|$			
		Resonance order	3	5	7
0Mvar	21.3	10.81	0.5530	0.5727	0.6053
12Mvar	11.6	9.965	0.5816	0.6671	0.8531
24Mvar	8.86	9.059	0.6134	0.7968	0.5089
36Mvar	7.43	8.735	0.6485	0.9353	2.943
48Mvar	6.54	8.246	0.6878	0.6530	3.004
60Mvar	5.91	8.003	0.7321	0.0015	1.227
72Mvar	5.43	7.747	0.7817	1.7947	0.7657

Table XIV. Amplification of voltage distortion with one overhead line.

Capacitor Banks	Resonance Order	$\left\|U_{MV}(h)/U_{HV}(h)\right\|$			
		Resonance order	3	5	7
0Mvar	19.26	8.393	0.4401	0.4597	0.4935
12Mvar	10.42	7.321	0.4691	0.5599	0.7863
24Mvar	7.978	6.572	0.5020	0.7134	0.9563
36Mvar	6.702	6.231	0.5397	0.8985	3.110
48Mvar	5.902	5.847	0.5834	0.3350	0.9355

60Mvar	5.329	5.633	0.6344	2.134	0.5451
72Mvar	4.896	5.502	0.6945	4.504	0.3842

Table XV. Amplification of voltage distortion with one substation transformer.

Capacitor Banks	Resonance Order	$\left\|U_{MV}(h)/U_{HV}(h)\right\|$			
		Resonance order	3	5	7
0Mvar	19.67	7.617	0.4634	0.4833	0.5170
12Mvar	10.65	6.806	0.4926	0.5830	0.8017
24Mvar	8.136	6.378	0.5254	0.7322	0.1247
36Mvar	6.846	5.994	0.5629	0.9075	4.336
48Mvar	6.029	5.676	0.6060	0.9257	1.1162
60Mvar	5.411	5.494	0.6559	1.309	0.6267
72Mvar	5.004	5.686	0.7105	5.377	0.4348

In all three cases the amplification is highest at the resonance frequency. This could be a problem with high levels of interharmonics being presented in the transmission system or when a power-line communication signal has a frequency close to the resonance frequency. The amplification at the resonance frequency is more than a five in all cases.

A more general concern is the amplification at the fifth and seventh harmonic, because these frequencies are always present in the transmission system. Here we see that the amplification varies strongly based on the operational state. With both lines and both transformers in operation, the seventh harmonic may be amplified up to three times when 36 or 48 Mvar of capacitance in connected. For 72 Mvar of capacitance, the fifth harmonic is amplified by a factor of 1.8. When one line or one transformer is out of operation, the maximum amplification increases for both the 5th and the 7th harmonics. As for the 3rd harmonic orders, the amplifications are all less than one under any operation modes, because the resonance orders are far away from the 3rd order with any steps of capacitor banks switched on.

With the same method, when there is a harmonic current source connects to the MV bus, the amplification of harmonic current flow in the capacitor banks is studied. The detailed results are shown in the Table XVI, Table XVII, and Table XVIII.

Table XVI. Amplification of harmonic current under full operation.

Capacitor Banks	Resonance Order	$\left\|I_{cap}(h)/I_h(h)\right\|$

		Resonance order	3	5	7
0Mvar	19.64	0	0	0	0
12Mvar	10.61	15.28	0.06222	0.2041	0.5498
24Mvar	8.106	16.46	0.1327	0.5123	2.413
36Mvar	6.809	16.49	0.2130	1.305	11.79
48Mvar	5.985	16.29	0.3056	2.079	3.331
60Mvar	5.402	16.03	0.4135	5.192	2.278
72Mvar	4.962	15.77	0.5421	15.39	1.879

Table XVII. Amplification of harmonic current with one overhead line.

Capacitor Banks	Resonance Order	$\left\| I_{cap}(h)/I_h(h) \right\|$			
		Resonance order	3	5	7
0Mvar	18.31	0	0	0	0
12Mvar	9.871	14.51	0.07289	0.2469	0.7215
24Mvar	7.539	15.53	0.1573	0.6544	4.908
36Mvar	6.334	15.51	0.2558	1.452	4.684
48Mvar	5.567	15.27	0.3726	3.664	2.455
60Mvar	5.027	15.00	0.5133	14.74	1.904
72Mvar	4.617	14.73	0.6860	5.891	1.655

Table XVIII. Amplification of harmonic current with one substation transformer.

Capacitor Banks	Resonance Order	$\left\| I_{cap}(h)/I_h(h) \right\|$			
		Resonance order	3	5	7
0Mvar	18.56	0	0	0	0
12Mvar	10.01	13.51	0.07065	0.2377	0.6920
24Mvar	7.647	14.63	0.1521	0.6224	4.109
36Mvar	6.425	14.72	0.2466	1.349	5.282
48Mvar	5.646	14.58	0.3581	3.206	2.577
60Mvar	5.097	14.39	0.4913	12.15	1.962
72Mvar	4.681	14.18	0.6533	6.791	1.692

At any operation mode, the amplification of harmonic current flow in capacitor banks at resonance orders is in the range of 13.51 to 16.49. The harmonic current amplification is also strongly affected by the operational state. With all equipment in operation, the 7th harmonic is amplified 12 times with 36 Mvar of capacitors, and the 5th harmonic is amplified 15 times with 72 Mvar of capacitors. When one line or one transformer is out of operation, the maximum amplification decreases for both the 5th and the 7th harmonic. As for the 3rd harmonic orders, the amplification is less than one under any operation modes (i.e. the third harmonic is actually damped).

4 Harmonic Filters

In Chapter 3, we have discussed the harmonic resonances that occur in a grid-connected wind farm. The parallel resonance will amplify the harmonic current from the equipment in the wind farm. The series resonance can lead to high voltage distortion in the wind farm substation due to amplification of the voltage distortion from the transmission grid.

A number of mitigation methods are possible to limit the impact of the resonances. We saw from the simulation example that different resonances occur for different operational states. It is thus difficult to prevent resonances is all operational states. Avoiding the use of capacitor banks altogether would prevent resonances at lower frequencies (like fifth and seventh harmonic). In that case the reactive-power control should be done in another way, for example using a central SVC or Statcom or by using power-electronic converters with the wind turbines.

In this chapter we will study the possibility of designing a set of passive harmonic filters that cover all operational states. The design criteria are the amplification of voltage distortion and the amplification of current distortion.

4.1 Attenuating the voltage distortion due to series resonance

According to the simulation results shown in Table XIII, Table XIV, and Table XV, the amplification of 5th and 7th harmonics from the HV bus to the MV bus is larger than 3 under certain operating conditions. The amplification at the resonance frequency is more than five under any operation modes, which will lead to high voltage distortion due to interharmonics being present in the transmission system.

In order to solve this resonance problem, passive filters are designed by adding reactance in series with the capacitor banks. In this way the resonance orders are shifted to a less problematic frequency. For the case when all the equipment is in operation and 36 Mvar of capacitor banks is connected, a filter is designed to shift the resonance. The simulation has been carried out using the same model as in Chapter 3 and the results are shown in Table XIX.

Table XIX. Amplification of voltage distortion under full operation (Q_{Cap} =36 Mvar).

Added reactance	Resonance Order	$\lvert U_{MV}(h)/U_{HV}(h)\rvert$			
		Resonance order	3	5	7
L=0, R=0	7.43	8.735	0.6485	0.9353	2.943
L=1.1mH, R =0	6.01	8.020	0.6603	0.6258	0.7249
L =1.1mH, R =0.1Ω	6.04	5.188	0.6601	0.6208	0.7127
L =1.1mH, R =0.2Ω	6.07	3.702	0.6598	0.6158	0.6966
L =1.1mH, R =0.3Ω	6.10	2.830	0.6595	0.6108	0.6769
L =1.1mH, R =0.5Ω	6.19	1.848	0.6587	0.6013	0.6286

Installing an inductor of 1.1 mH in series with the capacitor banks shifts the resonance order from 7.43 to 6. By moving the resonance order away from 5 and 7, the amplification of 5th and 7th harmonics becomes less than 3 in any operation state. However, merely adding inductor will not significantly affect the amplification at the resonance frequency; this requires adding resistance to damp the resonance. When the resistance value reaches 0.5 Ω, the amplification will be less than 2. But higher resistance will cause more power loss. Therefore, the value of the resistor should be selected based on the amplification limits.

If the filter cannot be tuned, the simulations with the same added reactance have been carried out for different operation conditions. Part of the results is listed in Table XX.

Table XX. Amplification of voltage distortion at resonance frequency.

Added reactance	Full operation Q_{Cap} (Mvar)		One overhead lines Q_{Cap} (Mvar)		One substation transformer Q_{Cap} (Mvar)	
	36	48	36	72	36	72
L=0, R =0	8.735	8.246	6.232	5.503	5.994	5.686
L =1.1mH, R =0	8.074	8.120	5.831	3.914	5.712	5.030
L =1.1mH, R =0.1Ω	5.195	4.730	4.037	3.095	3.965	3.061
L =1.1mH, R =0.2Ω	3.743	3.311	2.941	2.156	2.953	2.163
L =1.1mH, R =0.3Ω	2.885	2.460	2.322	1.616	2.071	1.632
L =1.1mH, R =0.5Ω	1.889	1.549	1.576	1.025	1.586	1.032

Meanwhile, if the installed reactance can be adapted to the operational state, the specific value of inductance and resistance for the above-mentioned operation modes is obtained and shown in Table XXI. For different operation conditions, inductor with different values is added to shift the resonance order close to 4 or 6, and a resistor is added to decrease the voltage amplification at the resonance frequency.

Table XXI. Design of reactance for different operation conditions.

Operation modes		Added reactance		Resonance order	Amplification times at resonance order
		L(mH)	R(Ω)		
Full operation	36	1.1	0.3	6.1	2.830
Q_{Cap}(Mvar)	48	0.4	0.3	6.1	2.818
One overhead line	36	0.7	0.3	6.05	2.481
Q_{Cap}(Mvar)	72	1.2	0.15	4.01	2.513
One substation transformer	36	0.8	0.25	6.04	2.703
Q_{Cap}(Mvar)	72	1.3	0.15	4.02	2.437

4.2 Attenuating the current amplification due to parallel resonance

The analysis for parallel resonance at the MV bus has been carried out in the Chapter 3. The current amplification from the harmonic source to the capacitor banks has been calculated and shown in Table XVI, Table XVII, and Table XVIII. Similarly, adding reactance in series with capacitor banks can also affect the parallel resonance. When all the equipments work and connected capacity of the capacity is 36 Mvar, a filter is designed and connected with capacitor banks in series to shift the resonance order close to 6. The simulation results are shown in the Table XXII.

Table XXII. Amplification of harmonic current through capacitor banks under full operation. (Q_{Cap} =36 Mvar).

Added reactance	Resonance Order	$\left\|I_{Cap}(h)/I_{MV}(h)\right\|$			
		Resonance order	3	5	7
L=0, R=0	6.81	16.49	0.2130	1.030	11.79
L=0.7mH, R =0	6.02	12.37	0.2159	1.293	1.820
L =0.7mH, R =0.1Ω	6.01	8.898	0.2159	1.286	1.803

L =0.7mH, R =0.2Ω	6.01	6.953	0.2158	1.277	1.783
L =0.7mH, R =0.3Ω	6.01	5.706	0.2157	1.266	1.761
L =0.7mH, R =0.5Ω	6.00	4.208	0.2156	1.239	1.711

The resonance order is shifted to 6 by adding series reactance with a specific value. The added inductance significantly affects the resonance order, while the added resistance impacts the amplification at the resonance frequency. If the filter is tunable, the parameters of the filter are designed to shift the resonance order to 4 or 6 for different operation conditions. Part of results is shown in Table XXIII.

Table XXIII. Design of reactance for different operation conditions

Operation modes		Added reactance		Resonance order	Amplification times of harmonic current at resonance order
		L(mH)	R(Ω)		
Full operation	36	0.7	0.5	6.01	4.208
Q_{Cap} (Mvar)	72	1.1	0.2	4.05	4.640
One overhead line Q_{Cap}=60 Mvar		1.4	0.2	4.04	4.727
One substation transformer Q_{Cap}=60 Mvar		1.5	0.2	4.03	4.398

4.3 Overall filter design

In Section 4.1 and Section 4.2, filters have been designed for either decreasing the voltage amplification due to series resonance or for decreasing the current amplification to parallel resonance. This could be a solution when just one of the two types of resonance results in excessive voltage and/or current distortion. However, ideally, the filter should solve the problems brought by series resonance and parallel resonance at the same time. In this section, the filters are designed to decrease both the voltage amplification and the current amplification. Based on the simulation results, the parameters of filter should be adjusted to satisfy all limits set to the amplification.

The case when all equipment is in operation and 36 Mvar of capacitor banks is connected is taken here as an example. The designed filter for weakening the consequences of series resonance and parallel resonance is L=1.1 mH, R=0.3 Ω and L=0.7 mH, R=0.5 Ω, respectively. The amplification times of voltage distortion and harmonic current have been simulated for these two filters. Meanwhile, the case with a filter of L=0.9 mH, R=0.4 Ω, which is the average value of the parameters of the two designed filters, has also been studied. The simulated results are shown in Table

XXIV.

Table XXIV. Filter design for full operation (Q_{Cap} =36 Mvar).

Parameters of filter	Reactance at fundamental frequency (Ω)	Series resonance		Parallel resonance	
		Resonance order	Maximum $\lvert U_{MV}(h)/U_{HV}(h)\rvert$	Resonance order	Maximum $\lvert I_{Cap}(h)/I_{MV}(h)\rvert$
L=0, R =0	0	7.4	8.735	6.8	16.49
L =0.7mH, R =0.5Ω	0.5+j0.22	5.2	1.456	6.0	4.208
L =0.9mH, R =0.4Ω	0.4+j0.28	5.0	1.698	4.6	2.164
L =1.1mH, R =0.3Ω	0.3+j0.35	6.1	2.830	4.4	2.369

According to the results in Table XXIV, the reactance value of the filter at fundamental frequency is low. Hence, the reactive power supplied by the capacitor banks will remain largely unchanged. All three filters can effectively depress the amplification to an acceptable value. Moreover, the cost of filter inductors depends greatly on the construction method instead of the different rating, and the cost of resistor is also independent of the power rating. In this case, the filter with the lowest resistance is selected because of the lower power loss at fundamental frequency.

With the same method, the filter is designed for different operation conditions. The detailed simulation results and filter parameters are shown in the Table XXV, Table XXVI, and Table XXVII.

Table XXV. Filter design for full operation

Q_{Cap} (Mvar)	Filter	Reactance at 50 Hz (Ω)	Series resonance		Parallel resonance	
			Resonance order	Maximum $\lvert U_{MV}(h)/U_{HV}(h)\rvert$	Resonance order	Maximum $\lvert I_{Cap}(h)/I_{MV}(h)\rvert$
12	L =0mH, R =1.3Ω	1.3	12	2.463	10.6	4.895
24	L =0mH, R =0.9Ω	0.9	9.2	1.984	8.1	4.815
36	L =1.1mH, R =0.3Ω	0.3+j0.35	6.1	2.830	4.4	2.369
48	L =0.5mH, R =0.6Ω	0.6+j0.16	6.1	1.493	5.4	4.438
60	L =0mH, R =0.6Ω	0.6	6.2	1.532	5.4	4.424
72	L =0mH, R =0.5Ω	0.5	5.7	1.625	5.0	4.705

Table XXVI. Filter design for the operation case with one overhead line.

Q_{Cap} (Mvar)	Filter	Reactance at 50 Hz (Ω)	Series resonance		Parallel resonance	
			Resonance order	Maximum $\lvert U_{MV}(h)/U_{HV}(h)\rvert$	Resonance order	Maximum $\lvert I_{Cap}(h)/I_{MV}(h)\rvert$
12	L =0mH, R =1.5Ω	1.5	10.8	2.024	9.9	4.586
24	L =0mH, R =0.9Ω	0.9	8.2	1.643	7.5	4.975
36	L =0.8mH, R =0.6Ω	0.6+j0.25	6.0	1.649	5.6	4.997
48	L =0mH, R =0.6Ω	0.6	6.1	1.470	5.6	4.992
60	L =1.5mH, R =0.4Ω	0.4+j0.47	4.3	1.287	4.0	4.943
72	L =1.1mH, R =0.5Ω	0.5+j0.35	4.2	1.003	3.8	4.148

Table XXVII. Filter design for the operation case with one transformer.

Q_{Cap} (Mvar)	Filter	Reactance at 50 Hz (Ω)	Series resonance		Parallel resonance	
			Resonance order	Maximum $\lvert U_{MV}(h)/U_{HV}(h)\rvert$	Resonance order	Maximum $\lvert I_{Cap}(h)/I_{MV}(h)\rvert$
12	L =0mH, R =1.5Ω	1.5	11.0	1.775	10.0	4.444
24	L =0mH, R =0.9Ω	0.9	8.5	1.626	7.6	4.830
36	L =0.8mH, R =0.6Ω	0.6+j0.25	6.1	1.409	5.7	4.864
48	L =0mH, R =0.6Ω	0.6	6.3	1.476	5.7	4.878
60	L =1.5mH, R =0.4Ω	0.4+j0.47	4.3	1.288	4.0	4.815
72	L =1.1mH, R =0.4Ω	0.4+j0.35	4.2	1.252	3.9	4.718

According to the results, the required ratings of filter inductor are 0.5 mH, 0.8 mH, 1.1 mH and 1.5 mH; and the ratings of filter resistors are 0.3 Ω, 0.4 Ω, 0.5 Ω, 0.6 Ω, 0.9 Ω, 1.3 Ω and 1.5 Ω. For different operation modes, the different combinations of inductor and resistor are needed. Therefore, the configuration of filters are designed and shown in the Figure 27.

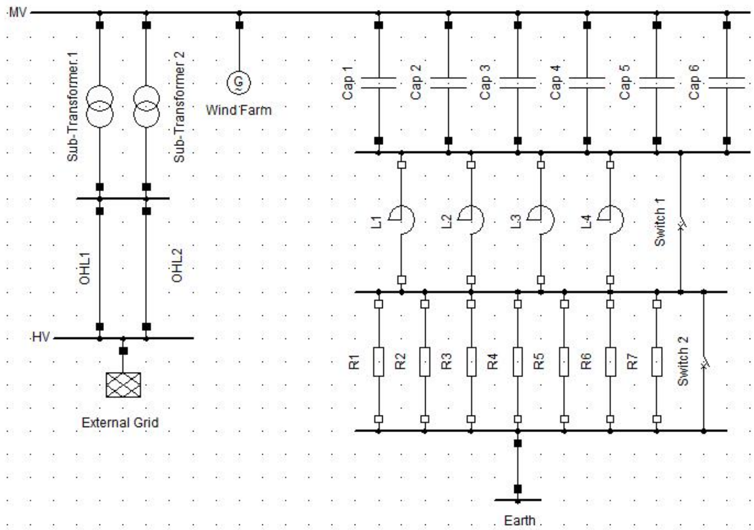


Figure 27. Configuration of filters.

By solving the following equations sets, the design values for inductors and resistors in Figure 27 is obtained as follows:

$$\begin{cases} L_1 = 1.5 \\ L_1 // L_2 = 1.1 \\ L_1 // L_2 // L_3 = 0.8 \\ L_1 // L_2 // L_3 // L_4 = 0.5 \end{cases} \longrightarrow \begin{cases} L_1 = 1.5 \\ L_2 = 4.125 \\ L_3 = 2.930 \\ L_4 = 1.333 \end{cases}$$

$$\begin{cases} R_1 = 1.5 \\ R_1 // R_2 = 1.3 \\ R_1 // R_2 // R_3 = 0.9 \\ R_1 // R_2 // R_3 // R_4 = 0.6 \\ R_1 // R_2 // R_3 // R_4 // R_5 = 0.5 \\ R_1 // R_2 // R_3 // R_4 // R_5 // R_6 = 0.4 \\ R_1 // R_2 // R_3 // R_4 // R_5 // R_6 // R_7 = 0.3 \end{cases} \longrightarrow \begin{cases} R_1 = 1.5 \\ R_2 = 9.750 \\ R_3 = 2.925 \\ R_4 = 1.8 \\ R_5 = 3 \\ R_6 = 2 \\ R_7 = 1.2 \end{cases}$$

Based on the calculation results, the inductors and resistors are selected as shown in the Table XXVIII and Table XXIX.

Table XXVIII. Design parameters for filter inductors.

Inductor	Value (mH)

L_1	1.5
L_2	4
L_3	3
L_4	1.4

Table XXIX. Design parameters for filter resistors.

Resistor	Value (Ω)
R_1	1.5
R_2	10
R_3	3
R_4	1.8
R_5	3
R_6	2
R_7	1.2

Therefore, the required inductance and resistance for different operation modes of power grid with wind farm can be met by different combinations of connected inductors and resistors. The detailed working states of filter are summarized in the Table XXX, Table XXXI, and Table XXXII.

Table XXX. Filter elements for full operation

Q_{Cap} (Mvar)	Objective Value of Filter	Real Value	
		Connected elements	Filter
12	L =0mH, R =1.3Ω	R_1, R_2	L =0mH, R =1.304Ω
24	L =0mH, R =0.9Ω	R_1, R_2, R_3	L =0mH, R =0.9092Ω
36	L =1.1mH, R =0.3Ω	L_1, L_2, R_1, R_2, R_3, R_4, R_5, R_6, R_7	L =1.0909mH, R =0.3010Ω
48	L =0.5mH, R =0.6Ω	L_1, L_2, L_3, L_4, R_1, R_2, R_3, R_4	L =0.5090mH, R =0.6041Ω
60	L =0mH, R =0.6Ω	R_1, R_2, R_3, R_4	L =0mH, R =0.6041Ω
72	L =0mH, R =0.5Ω	R_1, R_2, R_3, R_4, R_5	L =0mH, R =0.5028Ω

Table XXXI. Filter elements for the operation case with one overhead line.

Q_{Cap} (Mvar)	Objective Value of Filter	Real Value	
		Connected elements	Filter
12	L =0mH, R =1.5Ω	R_1	L =0mH, R =1.5Ω
24	L =0mH, R =0.9Ω	R_1, R_2, R_3	L =0mH, R =0.9092Ω
36	L =0.8mH, R =0.6Ω	L_1, L_2, L_3, R_1, R_2, R_3, R_4	L =0.8000mH, R =0.6041Ω
48	L =0mH, R =0.6Ω	R_1, R_2, R_3, R_4	L =0mH, R =0.6041Ω
60	L =1.5mH, R =0.4Ω	L_1, R_1, R_2, R_3, R_4, R_5, R_6	L =1.5mH, R =0.4018Ω
72	L =1.1mH, R =0.5Ω	L_1, L_2, R_1, R_2, R_3, R_4, R_5	L =1.0909mH, R =0.5028Ω

Table XXXII. Filter elements for the operation case with one transformer.

Q_{Cap} (Mvar)	Objective Value of Filter	Real Value	
		Connected elements	Filter
12	L =0mH, R =1.5Ω	R_1	L =0mH, R =1.5Ω
24	L =0mH, R =0.9Ω	R_1, R_2, R_3	L =0mH, R =0.9092Ω
36	L =0.8mH, R =0.6Ω	L_1, L_2, L_3, R_1, R_2, R_3, R_4	L =0.8000mH, R =0.6041Ω
48	L =0mH, R =0.6Ω	R_1, R_2, R_3, R_4	L =0mH, R =0.6041Ω
60	L =1.5mH, R =0.4Ω	L_1, R_1, R_2, R_3, R_4, R_5, R_6	L =1.5mH, R =0.4018Ω
72	L =1.1mH, R =0.4Ω	L_1, L_2, R_1, R_2, R_3, R_4, R_5, R_6	L =1.0909mH, R =0.6041Ω

According to the results shown in the above three tables, the selected inductors and resistors can results in the values, which are close enough to the expected values of filter, with different switch combinations. A central controller is needed that gets as input the state of the capacitor banks, of the 115-kV overhead lines and of the substation transformers. From this information and a look-up table, the optimal combination of inductance and resistance is determined.

5 Discussion and Conclusions

Harmonic resonances come in two types: harmonic series resonances and harmonic parallel resonances. Harmonic resonances occur always whenever both capacitive and inductive elements are present, which is always the case. A harmonic resonance results in an amplification of the harmonic voltage and/or current distortion. The amount of amplification depends mainly on the amount of resistive damping present in the system. For harmonic studies it is therefore important to know the amount of resistance present in the system. Ideally, the resistance of all elements as a function of frequency would be needed, but for practical studies it is sufficient to know the resistance values around the resonance frequency. Of importance for the impact of a harmonic resonance is not only the amplification but also the emission level. Emission levels are highest for harmonics 5 and 7 so that the concern traditionally has been most with resonance frequencies below about 400 Hz (in a 50-Hz system).

The presence of capacitor banks at a low-voltage or medium-voltage substation will often result in resonances around harmonic 5 or 7. This holds for public distribution systems as well as for the distribution system in a wind farm (typically referred to as the “collection grid”). The case studies show that the capacitance of the medium-voltage cables has only a minor impact on the resonance frequency. The inductance of induction machines has a more significant impact on the resonance frequency and should not be neglected. With other types of turbines (double-fed induction machines, full-power converter) the inductance to be used for harmonic studies is similar so that also these should not be neglected.

In most practical cases, the resonance frequencies for parallel and series resonance are close. The difference is however in the source of the distortion and in the consequences. A parallel resonance amplifies the current distortion from any source downstream of the resonance point (which is mostly the capacitor bank). The result is high voltage distortion over the capacitor bank and high current distortion through the substation transformer connecting the wind farm to the grid. In case of a wind farm the emission from the turbines is amplified by a parallel resonance. Measurements have shown that wind turbines often produce a broadband spectrum superimposed on the characteristic harmonics of a six-pulse converter (5, 7, 11, 13, etc). The emission at the characteristic harmonics is rather low. The impact of a parallel resonance with low damping will therefore likely be unacceptably high levels of non-characteristic harmonics and of interharmonics. We will continue this discussion below, especially with reference to the term “unacceptable”.

A series resonance will amplify the harmonic voltage distortion from the HV bus to the MV bus. The result will again be high currents through the substation transformer and high voltages at the medium-voltage substation in the wind farm. The source of the emission is in this case the voltage distortion in the transmission or transmission grid to which the wind farm is connected. The main distortion present in these grids is at the fifth and seventh harmonic. Any resonance close to these frequencies might result in unacceptably high voltage and/or current distortion. From the case study we saw that amplification factors above three are not unlikely.

At this stage we should make a distinction between two types of unacceptability; a distinction that is often blurred in discussions on harmonic distortion. A high distortion level may result in damage or other adverse consequences or it may exceed a limit set in a standard or by the network operator.

A certain harmonic voltage or current level may be unacceptable because it results in damage to equipment, mal-operation of equipment, loss-of-life-of-equipment or other types of interference (light flicker or audible noise are examples). In that case there is no doubt that measures should be taken to reduce the distortion. In case of wind parks and parallel or series resonance, high currents through the substation transformer and high voltages at the medium-voltage substation result, as was mentioned before. The currents through the transformer could result in excessive heating especially through the forming of hot-spots. The so-called K-factor model in IEEE Std C57-110 can be used to estimate the impact of a non-sinusoidal current on the transformer and to determine a corrected rating. For heavily-distorted currents this corrected rating may be exceeded for large wind-power production. A temporary solution in that case is to limit the production. A more suitable solution is to overrate the transformers during the design of the windpark or to install suitable harmonic filters.

High levels of harmonic voltage at the medium-voltage bus will result in excessive heating of the capacitor bank. Again model calculations of the capacitor bank should be used to estimate the impact and this is most appropriately done in the design stage of the wind farm. When excessive heating is expected, either the capacitor bank can be overrated or the harmonics can be filtered.

High harmonic current distortion may also result in unwanted tripping of protection relays. In fact, several cases of this have been reported. The distortion level at which these unwanted trips occur depends on the details of the protection algorithm used and no general conclusions can be drawn about this. A discussion with manufacturers of protection relays may be started to take up this issue when it is confirmed that unwanted trips are due to the way in which the protection relay treats harmonic distortion.

The second type of unacceptability occurs when the limits set in standards or set by the network operator in the grid code are exceeded. In case of a wind farm this only concerns the currents through the substation transformer. The collection grid is a “private network” where it is up to the owner of that grid to decide about which levels are accepted. Using the voltage-distortion limits set in international standards like EN 50160 or IEC 61000-2-2 will in most cases prevent interference with equipment but it could also result in overdesign especially for non-characteristic harmonics and interharmonics.

It is difficult to give general conclusions here because each installation is different; but we still want to use the following basic assumptions:

- ✓ The emission from individual wind turbines is low and in the form of a broadband spectrum.
- ✓ The background voltage distortion in the transmission and subtransmission grid is almost exclusively in the form of integer harmonics with harmonic five and seven dominating.
- ✓ Interharmonics may be occasionally used by network operators for power-line communication.

Parallel resonances together with the broadband spectrum emitted by wind turbines, could result in emission limits (set in the grid code, for the wind farm as a whole) being exceeded for non-characteristic harmonics and for interharmonics. This is a consequence of the limits being set in a time when the emission at these frequencies was almost non-existing. A discussion should be started, preferably at international level, to obtain reasonable limits at these frequencies. It should be noted that the broadband character of the emission makes that actual location of the resonance frequency no longer matters. We do not expect the harmonic voltages or currents with parallel resonance to cause any actual damage. However, any installation is different and it is recommended to perform a detailed study in any case during the design of the installation.

Series resonances are normally only a concern when they are close to the fifth or seventh harmonic. The high currents through the substation transformer could result in overheating of the transformer; the high voltages at the medium-voltage bus could result in overheating of the capacitor banks. The fifth and seventh harmonic currents could also exceed the emission limits according to the grid code. This should however not be a reason for the network operator to disconnect the wind farm because the wind farm acts in this case as a harmonic filter reducing the voltage distortion in the grid. As long as the harmonic voltages or currents have no adverse effects within the wind farm, there is no reason to take any measures.

The main case of interharmonics present in the grid is with power-line communication. When the communication frequency used is close to the series resonance the communication signal may disappear in the wind farm and communication may become difficult or impossible. The duration of the communication signals used is normally limited to a few seconds and no thermal effects are expected.

The simulations presented in this report show clearly that the resonance frequency and the amplification depend strongly on the operational state of the wind farm and the grid. It is thus needed to consider the harmonics for all possible operational states. When designing filters, or other mitigation methods, again all possible operational states should be considered. In this report a possible design of a harmonic filter is presented that covers all (N-1) operational states. The described filter requires a central controller that chooses the optimal filter from the operational state.

The main uncertainty found during the calculations is the knowledge of the resistances around the resonance frequency. Detailed models exist for cables and overhead lines but application of these is rather complicated and time consuming. But from our studies we draw the preliminary conclusion that the main impact on the amplification is by the resistance of the transformers and the turbines around the resonance frequency. It may be worth the effort to have a closer look at this in the future.

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