RESEARCH REPORT

Date	*26.06.2018*
Revision	*B*
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Status	*Public*

Switching overvoltages of shunt reactors when opening the circuit breaker

IMPORTANT NOTICE: The simulations may contain inaccuracies due to the approximations made in the models or due to the estimated parameters. In order to verify the results measurements with actual system are recommended when possible. Authors do not assume any liability to anyone for any loss or damage caused by any errors or inaccuracies in this study.

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1 Introduction

In Finland the medium voltage (MV) networks in rural areas, which have traditionally been overhead lines, are being changed to cabled networks in order to improve the supply reliability. Long cable feeders produce relatively large amount of reactive power which need to be compensated by shunt reactors at least during the periods of light load. Thus the use of shunt reactors is increasing in medium voltage networks.

Earlier the use of shunt reactors has been rare so the it is necessary to review the technical behaviour and requirements of the shunt reactors as a part of the system. This study focuses on the swithching overvoltages related to the shunt reactors. The overvoltages are studied by a set of simulations with a transient simulation tool PSCAD. Before the simulation study this report includes a short literature survey of the topic in Chapter 2. Simulation model and the cases simulated are presented in Chapter 3 and the results are shown in Chapter 4. The results are briefly analysed and summarized in Chapter 5.

2 Switching overvoltages of shunt reactors

Relating to the switching of shunt reactors there exist two types of transient phenomenon. When energizing the reactor, there might be quite large inrush current arising from the magnetic characteristics of the core. On the other hand, there might be large overvoltage transient when disconnecting the reactor due to the characteristics of circuit breaker. The latter one is the phenomena that is studied with more details in this report.

2.1 Disconnecting the shunt reactor

Disconnection of a shunt reactor is in principle a situation where a small inductive current is switched off. Currents from few amperes to tens of amperes are considered as small currents. The circuit breakers applied in high and medium voltage networks can break the small inductive current before the natural zero crossing of the current. This is called current chopping. The arc between the circuit breaker contact becomes unstable in low enough current value and causes high frequency oscillations in the current (around 1 MHz). This in turn lead to passing the zero current before the 50 Hz current would have reached the zero value. This is illustrated in the following figure.

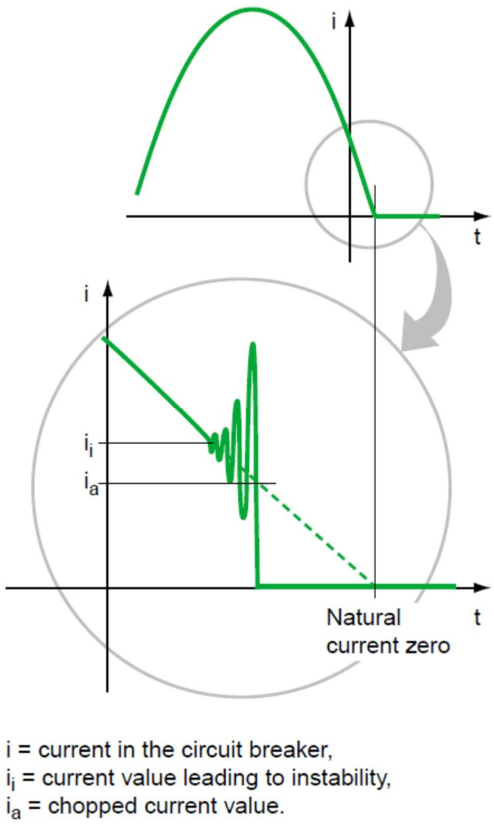


Figure 1. The high frequency oscillation phenomena leading to current chopping [1].

Due to the current chopping there remains some energy to the reactor, which then starts to oscillate with the capacitance in the circuit. For studying the switching transient, a simple equivalent circuit shown in Figure 2 can be applied. The inductance of the reactor is L and the total capacitance at the reactor side of the circuit breaker is C_L. The latter is considered to include all the capacitances of the bus, cabling, and bushings. The inductance L_b includes the series inductance of these elements. The source side inductance and capacitance (L_s and C_s) need to be considered only when studying the situation where the reactor is switched on by closing the circuit breaker. Also the stray capacitance and inductance between the breaker contacts (C_p and L_p) has been included in the figure for complete presentation. On the other hand, the losses, i.e. the resistances of the elements, are ignored in this simple equivalent circuit. In the simulations presented later in this report all the losses of the modelled system are accurately represented.

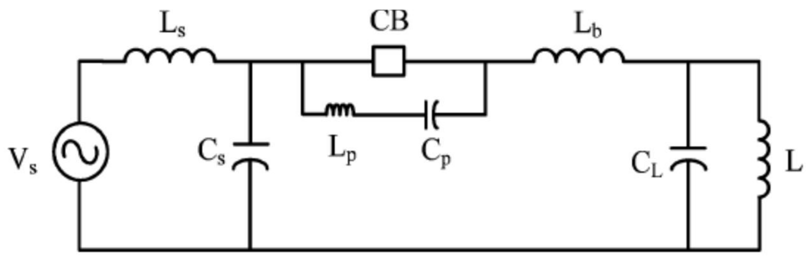


Figure 2. Single-phase equivalent circuit for shunt reactor switching transient analysis [2].

Due to the energy conservation, the opening of the circuit breaker in the above circuit means that the following equation if valid [2]:

$$\frac{1}{2}C_L V_a^2 = \frac{1}{2}C_L V_0^2 + \frac{1}{2}L i_{ch}^2 \quad (1)$$

where V_0 is the voltage across the shunt reactor at the instant of current interruption and i_{ch} is the chopping current. The voltage V_a is then the first peak value of the initiated oscillation [2].

Usually the V_0 can be assumed to be equal to the peak value of the normal system voltage [3]. The ratio for estimating the overvoltage, or actually the ratio of suppression peak voltage to the reactor voltage, can be defined using the following equation [3]:

$$k_a = \frac{V_a}{V_0} = \sqrt{1 + \left(\frac{i_{ch}}{V_0}\right)^2 \frac{L}{C_L}} \tag{2}$$

If the load side capacitance is assumed to be much larger than the other capacitances in the circuit then the frequency of the oscillation can be assumed to be:

$$f_L = \frac{1}{2\pi\sqrt{LC_L}} \tag{3}$$

The frequency of these oscillations is said to be in the range of 1 – 5 kHz [3].

The overvoltages caused are also seen over the breaker contacts and if the distance of the contacts is not enough to widhtstand the voltage, re-ignition occurs. This in turn causes transients with higher frequencies ranging between 50 to 1000 kHz [3].

2.2 Current chopping

Since the value of current where the current chopping takes place is critical when considering the level of the overvoltages in the studied case, it is worth to make short survey about the current chopping of various types of circuit breakers.

The current chopping level (CCL) depends on the on the total capacitance seen from the circuit breaker terminals and the so called chopping number λ as follows [3], [4]:

$$i_{ch} = \lambda\sqrt{NC_t} \tag{4}$$

where $C_t = C_p + C_L$ and the N refers to the number of interrupters in series (in MV circuit breakers only one).

The chopping number is not applicable for vacuum circuit breaker but for the other breaker types the following ranges of values are given [4]:

- Minimum oil: 5.8 – 10 $\cdot 10^4$ ($AF^{-0.5}$)
- Air blast: 15 – 20 $\cdot 10^4$ ($AF^{-0.5}$)
- SF_6 puffer: 4 – 19 $\cdot 10^4$ ($AF^{-0.5}$)
- SF_6 self-blast: 3 – 10 $\cdot 10^4$ ($AF^{-0.5}$)
- SF_6 rotating arc: 0.39 – 0.77 $\cdot 10^4$ ($AF^{-0.5}$)

The idea of the formulas above is that the manufacturer can provide the maximum chopping number and when system total capacitances are known, the maximum chopping current can be determined.

Using the above equation and given constants the chopping current of a SF6 circuit breaker in the systems modelled later in this report could reach the value of 19.5 A in the worst case. However, the puffer-technique represents the oldest technology and as can be seen in the chopping numbers given above the more advanced arc quenching techniques result in very low chopping number. In practice this would mean chopping current below 1 A. Furthermore, it seems that the MV SF6 circuit breaker manufacturers claim that they have reached the “soft switching” with no current chopping.

The first generation of vacuum circuit breakers had very high chopping current but the since that the values has been limited to 3 – 5 A [5]. In [6] a wider range is given: 3 – 21 A. In general the chopping current depends in the vacuum circuit breaker on the contact material and design. Naturally, the tendency is to have lower chopping current but there seems to be no indication that the current chopping can be totally avoided in vacuum circuit breakers.

There seems to be not much information available about the the current chopping charactersitics of minimum oil circuit breakers. They do represent the old technology and some early papers on the topic indicate even chopping current of several tens of amperes in specific test conditions [7]. However, calculating an approximation with the chopping number range given above the value would stay below 10 A in the simulation cases studied later in this report.

2.3 Managing the switching transients

The inductive load switching has the following transient phenomena [5]:

- normal current chopping
- virtual current chopping
- re-ingitions and
- pre-ingitions.

The normal current chopping was discussed above and it is the main concern in this study. The current chopping causes oscillating overvoltages which in turn may cause re-ingitions in the first pole to clear. In that situation the oscillating currents may in turn cause current zero at the other two poles of the circuit breaker. This is called virtual current chopping and it is specific to vacuum circuit breakers only [5]. Pre-ignitions happen when closing the circuit breaker and the contact gap becomes small enough so that its dielectric strength is exceeded. This causes a steep voltage surge reaching 3 pu at the terminal of inductive load [5].

The main standards covering the shunt reactor switchgear are IEC 62271-110 [8] and IEEE Std C37.015 [4], which are both updated in 2017. The IEEE standard provides very detailed discussion about various switching oscillations and derives equations for estimating the overvoltage in various types of systems. The IEC standard seems to focus on switching devices and their testing. Earlier this standard has covered only higher voltage levels but since edition 2012 the voltage levels below 52 kV have also been included [5]. The standard describes the test procedures and test circuits for the switching devices. The standard IEC 62271-110 was not available when writing this report but according to [5] and [9] the specific type testing is not needed if the transient recovery voltage (TRV) values of the short circuit test duties T10 and T30 (common test for circuit breakers as defined in IEC 62271-100) are equal to or higher than in this standard. This is the fact in most cases but in the isolated neutral system specific type-tests for TRV are needed [5].

In the latest version of the IEC standard also the evaluation and reporting of a re-ignition-free arcing time window has been added. This has also been discussed in [10] and the idea is to start the contact separation early enough to avoid re-ignition after the current chopping (see the following figure).

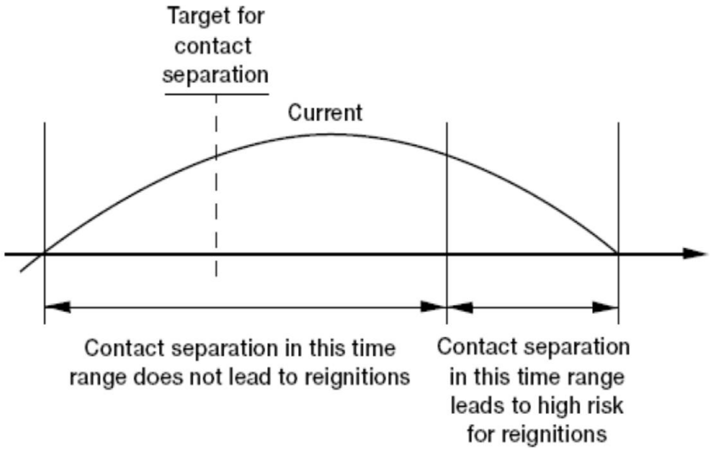


Figure 3. Target for contact separation to eliminate re-ingition [10].

The standards referred above considers only the circuit breaker so with proper test procedures it can be ensured that the circuit breaker can handle the transients. However, these standards do not consider the effects of the transients to the shunt reactor. In practice all breakers may experience single re-ingitions and they cause voltage stresses to the shunt reactors that can be detrimental. While the transient reaches levels up to 3 pu the surge arrester limits the voltage to values less than 2.5 pu. This implies that the surge arresters are always required for the shunt reactors. [11]

The standard tests for shunt reactors are presented in the standard IEC 60076-6 [12]. In the Appendix A.1.2 of the standard there is some further discussion about switching phenomena. A reactor is designed to tolerate certain level of switching overvoltages and this is referred as switching impulse widhstand level (SIWL). A surge arrestes used for protecting the reactor in turn has some surge impulse protection level (SIPL). In order to have proper protection the SIPL must be more than 30 % below the SIWL [12].

The current chopping leads typically re-ignitions, which result high frequency voltage oscillations in the range of MHz. These are similar to lightning impulses and the chopped wave test should be enough to verify the widhtstand of the reactors at voltage levels below 52 kV [12]. In this case the protection provided by the surge arresters will likely be sufficient [12].

Multiple re-ignitions are said to be possible for vacuum circuit breakers [11] but in reference [5] also other types of breakers are mentioned in this context. The occurrence of the multiple reignitions depends on the system characteristics. According to [5] the RC snubbers may be used to detune the system to avoid multiple reignitions. The capacitor applied also reduces the steepnes of the overvoltage surge. In [11] a detailed simulation study about the effects of various surge mitigation devices was made and the RC snubber, also called as RC surge suppressor, provided best solution against multiple reignitions. It is worth noting that in the study the RC circuit was recommended in addition with the usual surge arrester.

3 Simulation model and studies cases

3.1 Model structure

The model consists of

- 110 kV supplying grid equivalent model
- 110/20 kV main transformer
- two simple feeders with one cable model and load in each
- shunt reactor connected to the 20 kV bus at the substation.

The simulations are repeated with three reactor size: 1, 3 and 6 MVAr.

The reactor is connected to the bus with a short cable. It is assumed, that a major part of the total capacitance in the reactor side of the circuit breaker consist of the capacitance of the connection cable. The length of the cable has thus some effect and this is verified by repeating the simulations with two cable lengths: 15 and 50 m. The connection cable type in the cases with 1 or 3 MVAr reactors is HXCMK 3x1x35+16cu. For the 6 MVAr reactor the cable type is AHXAMK 3x95+35.

The basic model is shown in the following figure. This figure shows the main system of the model including the primary transformer, two background network feeders with loads and the reactor. At the terminal of the reactor there are also shown the surge arresters, which were included only in some special variants.

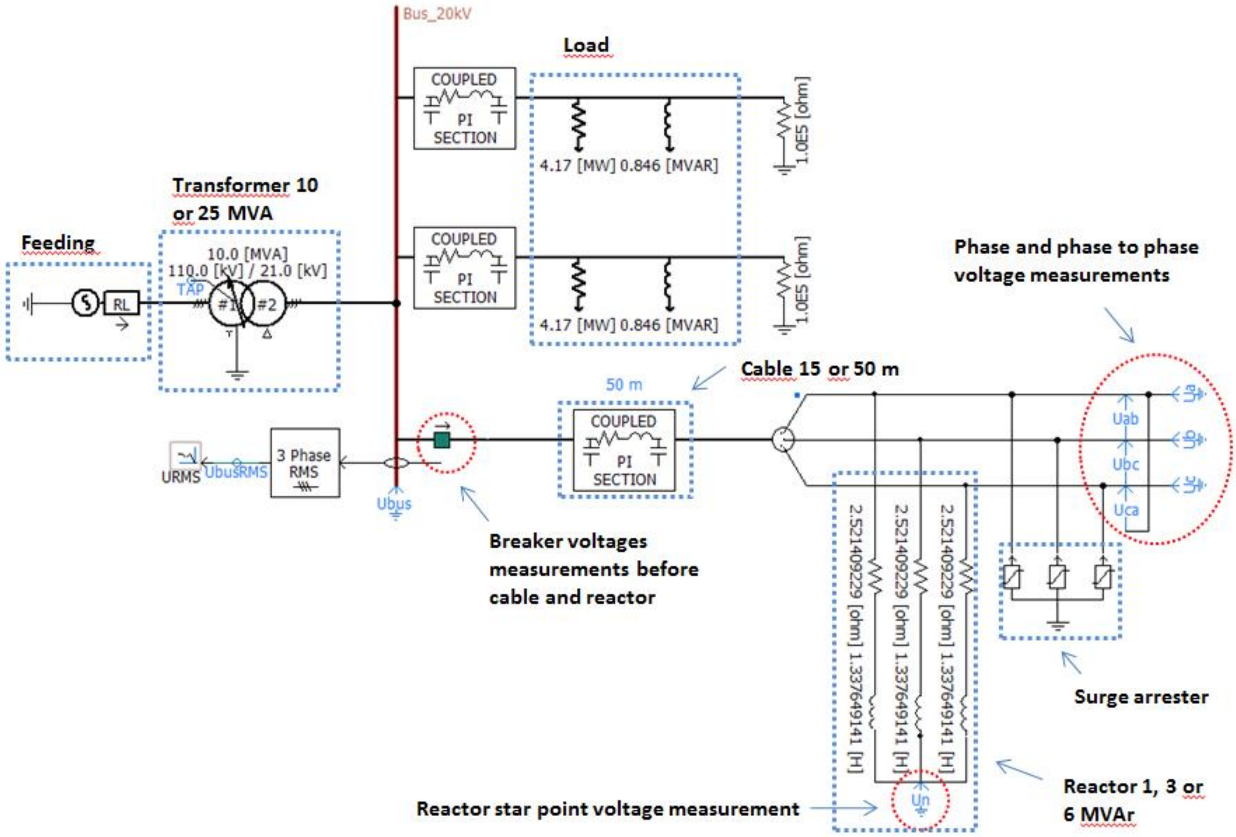


Figure 4. The simulation model.

The two feeders in the background network contain totally 175 km cables of type 95mm2 AHXAMK-W. The load in the background network is 1/3 of the main transformer rating and the power factor is assumed to be 0.98ind. At the 20 kV bus the target value for voltage control is 20.6 kV. In the model there is a control panel to adjust the transformer tap position manually.

The simulations are made with the main transformer rating of 25 MVA. The worst case scenarios (CLL that produces highest overvoltages, ie. 10 A) are repeated with the following special variants:

- Instead on 25 MVA transformer a 10 MVA main transformer is used.
- The load in the background network is removed.
- The reactor is equipped with surge arresters.

For comparison these simulations were repeated also with CCL of 5 A.

To model the current chopping all the poles of the three-phase circuit breaker were operated separately. The control logic applied in the model is shown in the figure below. After the timer provides the trip signal the breakers are opened immediately after the curren value is below the selected CCL (signal Ichop).

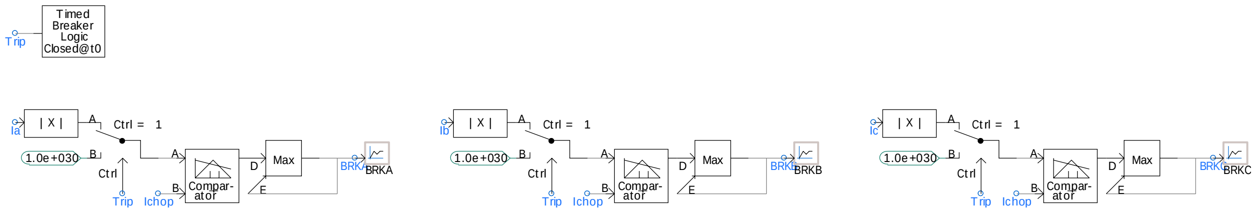


Figure 5. The control logic for modelling the current chopping.

In all simulated cases the circuit breaker first opens phase C and then phase A and last phase B. Figure 6 shows the single pole operation and the current chopping. In this example case the current chopping limit was set to 10 A.

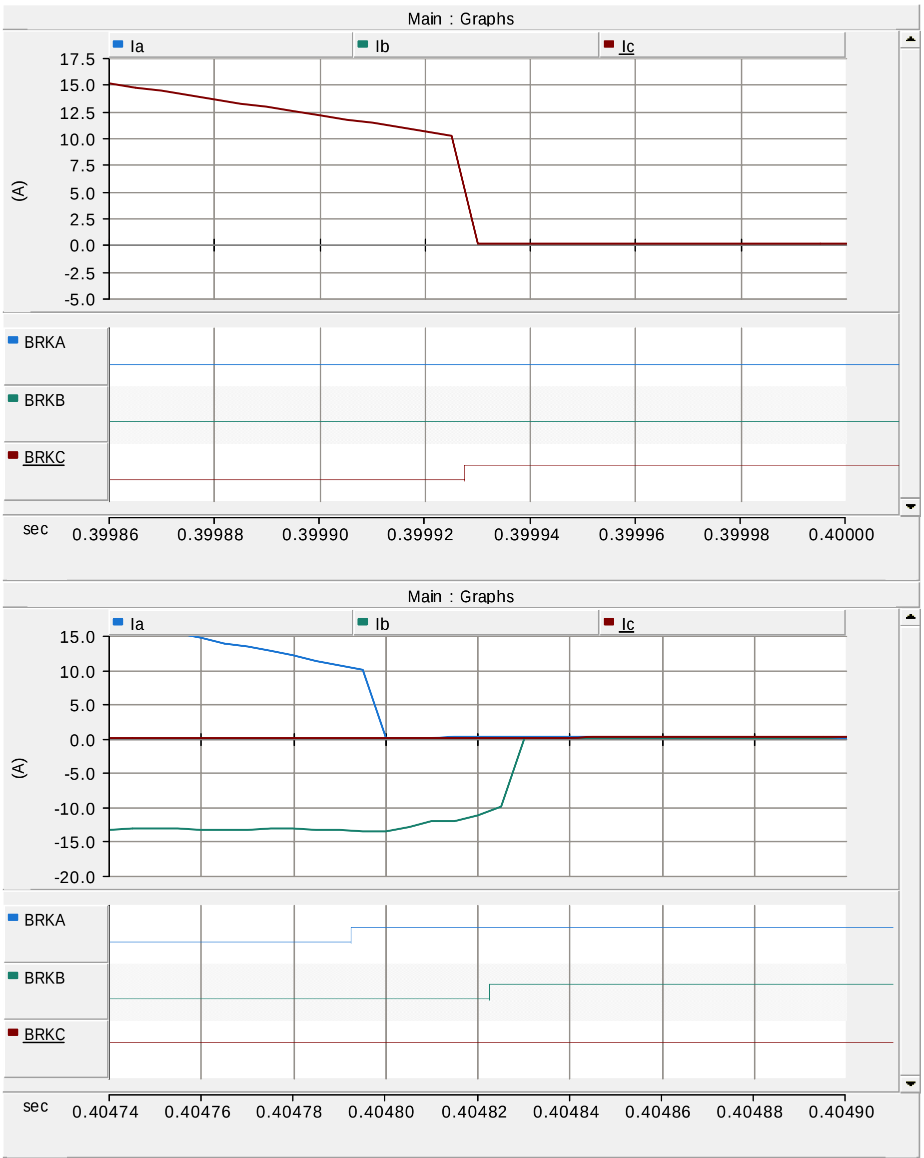


Figure 6. Single pole circuit breaker operation and current chopping in action.

3.2 PSCAD model component parameters

On simulation cases the cable length (15 m or 50 m) and reactor size (1, 3 or 6 MVAr) was varied. In special variants transformer size 10 MVA was also used instead of regular 25 MVA size and various combinations with/without surge arrester and load were examined. The parameters of the components in the model are shown in the following figures. In Figure 7 the reactor equivalent circuits are shown with parameter values. The circuit consist of inductance and resistance in series. The values of these elements were calculated so that the target reactive power is achieved while the losses are 0,6 %.

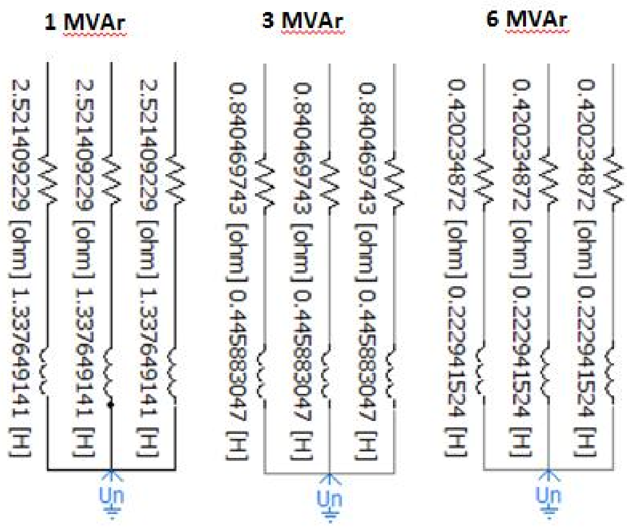
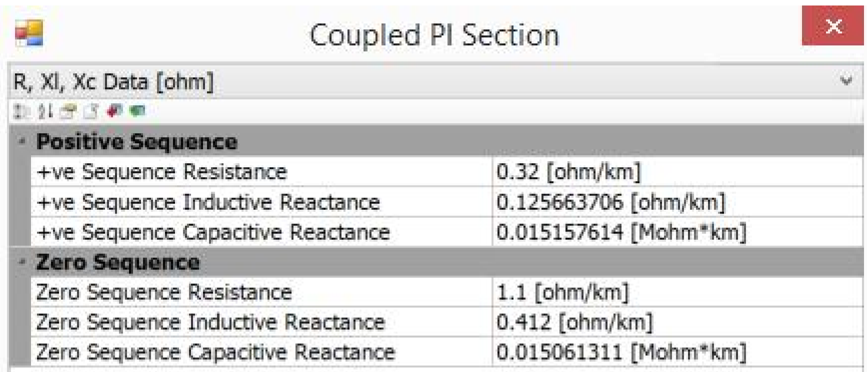


Figure 7. Simulation models for all three reactors



Coupled PI Section

R, Xl, Xc Data [ohm]

Positive Sequence	
+ve Sequence Resistance	0.32 [ohm/km]
+ve Sequence Inductive Reactance	0.125663706 [ohm/km]
+ve Sequence Capacitive Reactance	0.015157614 [Mohm*km]
Zero Sequence	
Zero Sequence Resistance	1.1 [ohm/km]
Zero Sequence Inductive Reactance	0.412 [ohm/km]
Zero Sequence Capacitive Reactance	0.015061311 [Mohm*km]

Figure 8. AHXAMK-W 3x95 cable parameters

Coupled PI Section

R, Xl, Xc Data [ohm]

Positive Sequence	
+ve Sequence Resistance	0.524 [ohm/km]
+ve Sequence Inductive Reactance	0.20106193 [ohm/km]
+ve Sequence Capacitive Reactance	0.019894368 [Mohm*km]
Zero Sequence	
Zero Sequence Resistance	4.124 [ohm/km]
Zero Sequence Inductive Reactance	0.804247719 [ohm/km]
Zero Sequence Capacitive Reactance	0.020377068 [Mohm*km]

Figure 9. HXCMK 3x1x35 cable parameters

25 MVA

3 Phase 2 Winding Transformer — Configuration

General	
Transformer Name	T1
3 Phase Transformer MVA	25.0 [MVA]
Base operation frequency	50.0 [Hz]
Winding #1 Type	Y
Winding #2 Type	Delta
Delta Lags or Leads Y	Lags
Positive sequence leakage reactance	0.101411736 [p.u.]
Ideal Transformer Model	No
Eddy current losses	0.000496 [p.u.]
Copper losses	0.004232 [p.u.]
Tap changer on winding	#1
Graphics Display	Single line (circles)
Display Details?	Yes

3 Phase 2 Winding Transformer — Winding Voltages

General	
Winding 1 Line to Line voltage (RMS)	115.0 [kV]
Winding 2 Line to Line voltage (RMS)	21.0 [kV]

3 Phase 2 Winding Transformer — Saturation

General	
Saturation enabled	No
Place saturation on winding	#1
Hysteresis	None
Inrush decay time constant	1.0 [sec]
Time to release flux clipping	0.1 [sec]
Air core reactance	0.2 [p.u.]
Magnetizing current	0.2 [%]
Knee voltage	1.25 [p.u.]

Figure 10. 25 MVA transformer parameters

10 MVA

3 Phase 2 Winding Transformer — Configuration

General	
Transformer Name	T1
3 Phase Transformer MVA	10.0 [MVA]
Base operation frequency	50.0 [Hz]
Winding #1 Type	Y
Winding #2 Type	Delta
Delta Lags or Leads Y	Lags
Positive sequence leakage reactance	0.102825094 [p.u.]
Ideal Transformer Model	No
Eddy current losses	0.00112 [p.u.]
Copper losses	0.006 [p.u.]
Tap changer on winding	#1
Graphics Display	Single line (circles)
Display Details?	Yes

3 Phase 2 Winding Transformer — Winding Voltages

General	
Winding 1 Line to Line voltage (RMS)	110.0 [kV]
Winding 2 Line to Line voltage (RMS)	21.0 [kV]

3 Phase 2 Winding Transformer — Saturation

General	
Saturation enabled	No
Place saturation on winding	#1
Hysteresis	None
Inrush decay time constant	1.0 [sec]
Time to release flux clipping	0.1 [sec]
Air core reactance	0.2 [p.u.]
Magnetizing current	0.2 [%]
Knee voltage	1.25 [p.u.]

Figure 11. 10 MVA transformer parameters

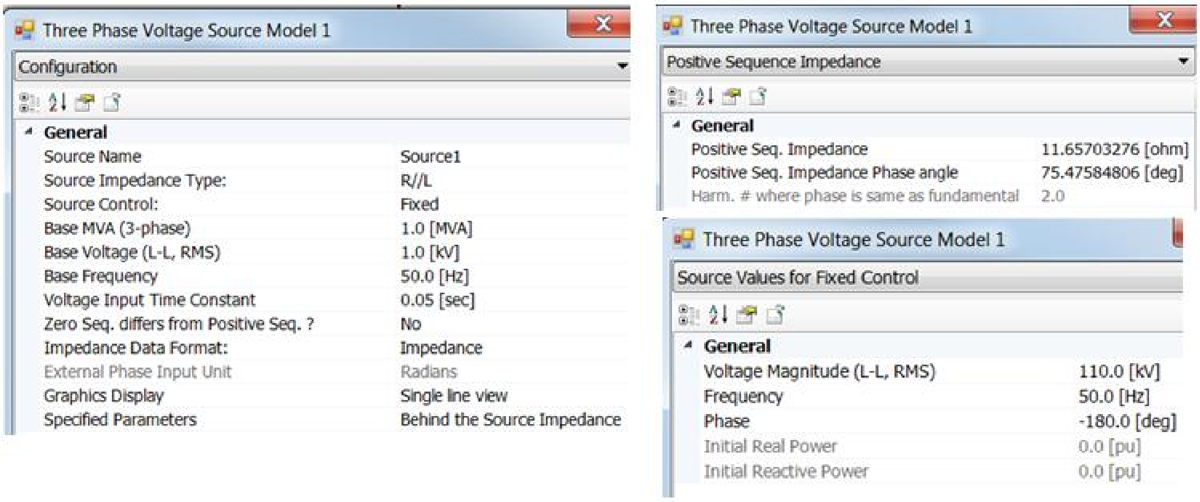


Figure 12. Voltage source parameters

In the special cases with surge arresters the surge arresters were connected between the reactor terminals and earth. The type of the used surge arrester is RSTI-CC-58SA2405, for which the rated voltage is 30 kV and continuous operating voltage was 24 kV. For the surge arrester modelling a detailed voltage-current curve would have been needed, but that was not available. However in ref. [13] a sample figure of the curve from a surge arrester with the same rating (30 kV) was found (see figure below) and that was used as a basis of adjusting the parameters. At this point it should be noted that since exact data was missing the modelling of surge arrester is only approximate.

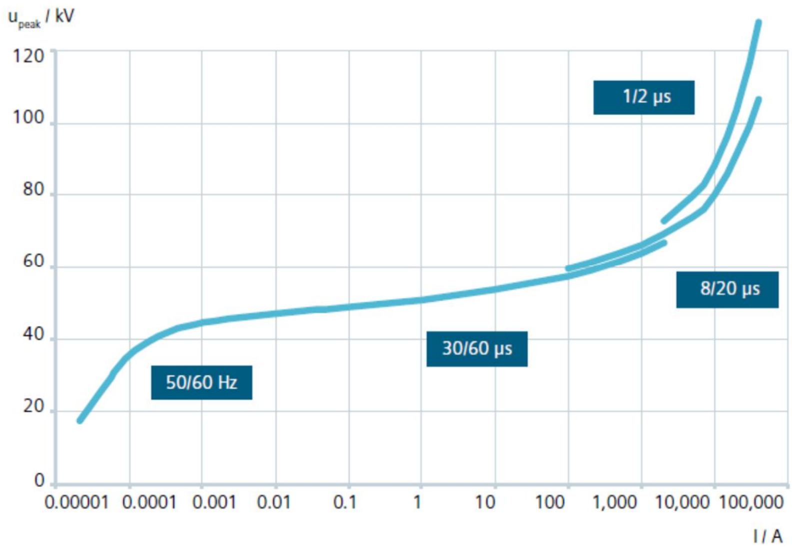
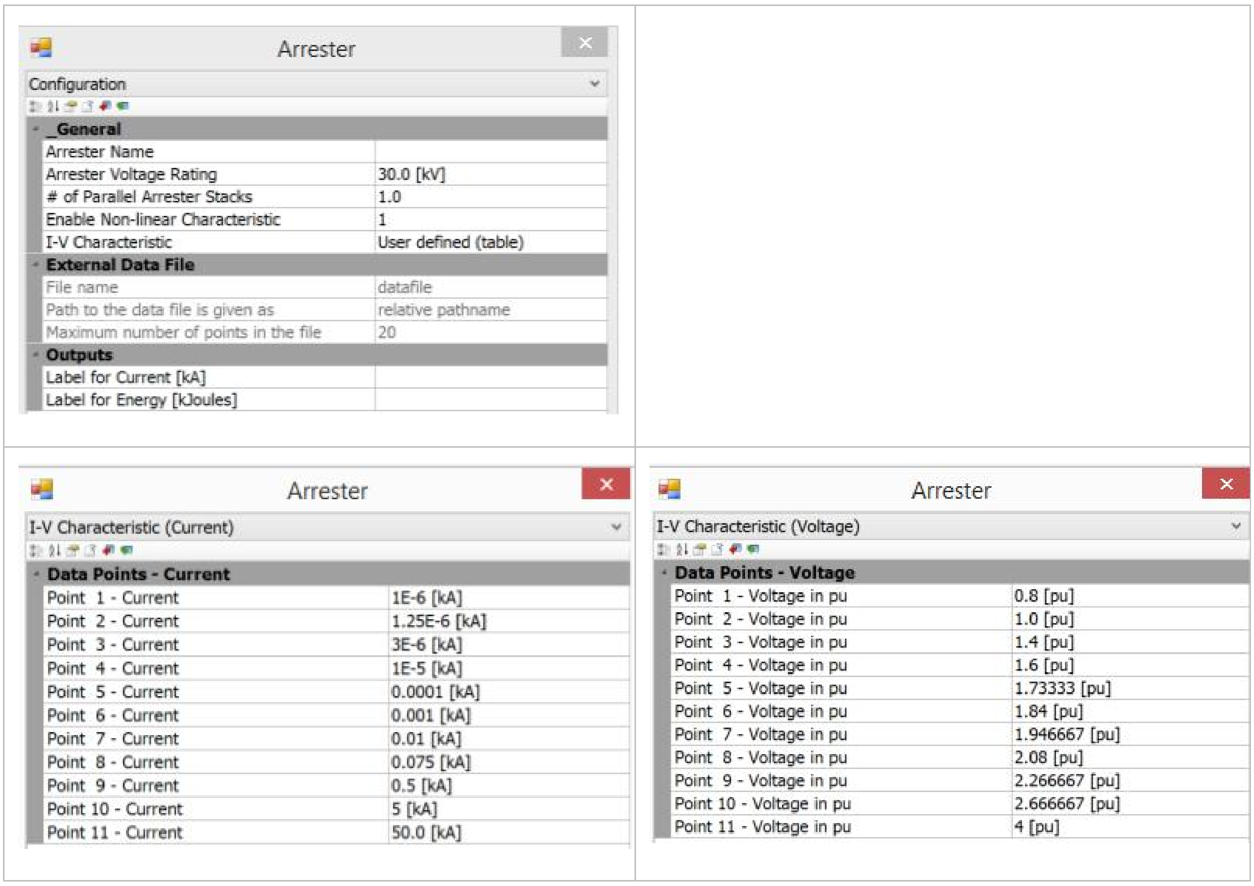


Figure 13. Example of voltage-current characteristic of a 30 kV surge arrester.

The data used in PSCAD model of the surge arrester is shown in the following figure.



Arrester

Configuration

_General	
Arrester Name	
Arrester Voltage Rating	30.0 [kV]
# of Parallel Arrester Stacks	1.0
Enable Non-linear Characteristic	1
I-V Characteristic	User defined (table)
External Data File	
File name	datafile
Path to the data file is given as	relative pathname
Maximum number of points in the file	20
Outputs	
Label for Current [kA]	
Label for Energy [kJoules]	

Arrester

I-V Characteristic (Current)

Data Points - Current	
Point 1 - Current	1E-6 [kA]
Point 2 - Current	1.25E-6 [kA]
Point 3 - Current	3E-6 [kA]
Point 4 - Current	1E-5 [kA]
Point 5 - Current	0.0001 [kA]
Point 6 - Current	0.001 [kA]
Point 7 - Current	0.01 [kA]
Point 8 - Current	0.075 [kA]
Point 9 - Current	0.5 [kA]
Point 10 - Current	5 [kA]
Point 11 - Current	50.0 [kA]

Arrester

I-V Characteristic (Voltage)

Data Points - Voltage	
Point 1 - Voltage in pu	0.8 [pu]
Point 2 - Voltage in pu	1.0 [pu]
Point 3 - Voltage in pu	1.4 [pu]
Point 4 - Voltage in pu	1.6 [pu]
Point 5 - Voltage in pu	1.73333 [pu]
Point 6 - Voltage in pu	1.84 [pu]
Point 7 - Voltage in pu	1.946667 [pu]
Point 8 - Voltage in pu	2.08 [pu]
Point 9 - Voltage in pu	2.266667 [pu]
Point 10 - Voltage in pu	2.666667 [pu]
Point 11 - Voltage in pu	4 [pu]

Figure 14. Surge arrester parameters

These values produce the following characteristic, which is quite close to the one shown in the Figure 13 above.

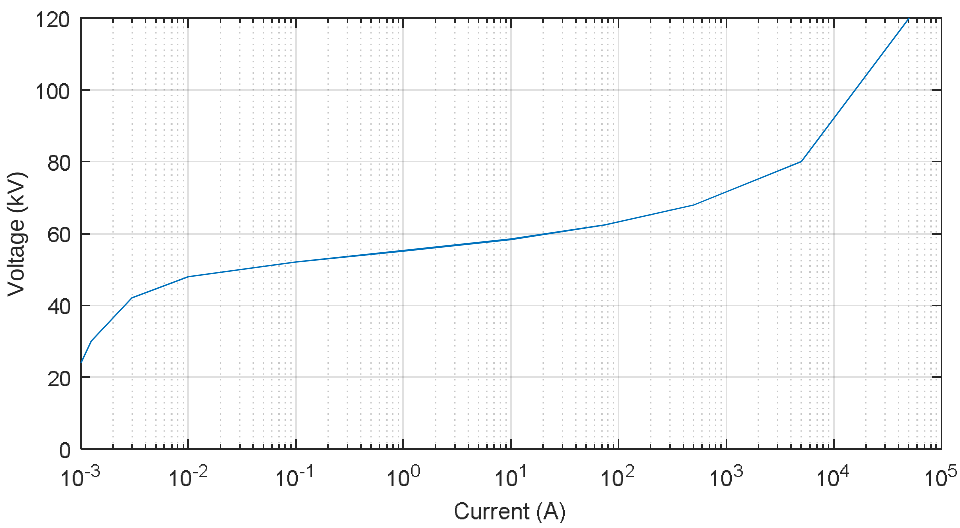


Figure 15. Voltage-current characteristic of the modelled surge arrester.

3.3 Simulated cases

The simulated cases are introduced in the following tables.

Table 1. Cases 1-34

Case	Reactor size [MVAr]	Connection cable [m]	CCL [A]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)
1	1	15	1	25	yes	no
2	1	15	2	25	yes	no
3	1	15	3	25	yes	no
4	1	15	4	25	yes	no
5	1	15	5	25	yes	no
6	1	15	6	25	yes	no
7	1	15	7	25	yes	no
8	1	15	8	25	yes	no
9	1	15	9	25	yes	no
10	1	15	10	25	yes	no
11	1	50	1	25	yes	no
12	1	50	2	25	yes	no
13	1	50	3	25	yes	no
14	1	50	4	25	yes	no
15	1	50	5	25	yes	no
16	1	50	6	25	yes	no
17	1	50	7	25	yes	no
18	1	50	8	25	yes	no
19	1	50	9	25	yes	no
20	1	50	10	25	yes	no
21	1	15	10	10	yes	no
22	1	15	10	10	yes	yes
23	1	15	10	10	no	yes
24	1	15	10	10	no	no
25	1	15	10	25	yes	yes
26	1	15	10	25	no	yes
27	1	15	10	25	no	no
28	1	50	10	10	yes	no
29	1	50	10	10	yes	yes
30	1	50	10	10	no	yes
31	1	50	10	10	no	no
32	1	50	10	25	yes	yes
33	1	50	10	25	no	yes
34	1	50	10	25	no	no

Table 2. Cases 35-68

Case	Reactor size [MVAr]	Connection cable [m]	CCL [A]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)
35	3	15	1	25	yes	no
36	3	15	2	25	yes	no
37	3	15	3	25	yes	no
38	3	15	4	25	yes	no
39	3	15	5	25	yes	no
40	3	15	6	25	yes	no
41	3	15	7	25	yes	no
42	3	15	8	25	yes	no
43	3	15	9	25	yes	no
44	3	15	10	25	yes	no
45	3	50	1	25	yes	no
46	3	50	2	25	yes	no
47	3	50	3	25	yes	no
48	3	50	4	25	yes	no
49	3	50	5	25	yes	no
50	3	50	6	25	yes	no
51	3	50	7	25	yes	no
52	3	50	8	25	yes	no
53	3	50	9	25	yes	no
54	3	50	10	25	yes	no
55	3	15	10	10	yes	no
56	3	15	10	10	yes	yes
57	3	15	10	10	no	yes
58	3	15	10	10	no	no
59	3	15	10	25	yes	yes
60	3	15	10	25	no	yes
61	3	15	10	25	no	no
62	3	50	10	10	yes	no
63	3	50	10	10	yes	yes
64	3	50	10	10	no	yes
65	3	50	10	10	no	no
66	3	50	10	25	yes	yes
67	3	50	10	25	no	yes
68	3	50	10	25	no	no

Table 3. Cases 69-102

Case	Reactor size [MVAr]	Connection cable [m]	CCL [A]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)
69	6	15	1	25	yes	no
70	6	15	2	25	yes	no
71	6	15	3	25	yes	no
72	6	15	4	25	yes	no
73	6	15	5	25	yes	no
74	6	15	6	25	yes	no
75	6	15	7	25	yes	no
76	6	15	8	25	yes	no
77	6	15	9	25	yes	no
78	6	15	10	25	yes	no
79	6	50	1	25	yes	no
80	6	50	2	25	yes	no
81	6	50	3	25	yes	no
82	6	50	4	25	yes	no
83	6	50	5	25	yes	no
84	6	50	6	25	yes	no
85	6	50	7	25	yes	no
86	6	50	8	25	yes	no
87	6	50	9	25	yes	no
88	6	50	10	25	yes	no
89	6	15	10	10	yes	no
90	6	15	10	10	yes	yes
91	6	15	10	10	no	yes
92	6	15	10	10	no	no
93	6	15	10	25	yes	yes
94	6	15	10	25	no	yes
95	6	15	10	25	no	no
96	6	50	10	10	yes	no
97	6	50	10	10	yes	yes
98	6	50	10	10	no	yes
99	6	50	10	10	no	no
100	6	50	10	25	yes	yes
101	6	50	10	25	no	yes
102	6	50	10	25	no	no

Table 4. Cases 103-144

Case	Reactor size [MVAr]	Connection cable [m]	CCL [A]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)
103	1	15	5	10	yes	no
104	1	15	5	10	yes	yes
105	1	15	5	10	no	yes
106	1	15	5	10	no	no
107	1	15	5	25	yes	yes
108	1	15	5	25	no	yes
109	1	15	5	25	no	no
110	1	50	5	10	yes	no
111	1	50	5	10	yes	yes
112	1	50	5	10	no	yes
113	1	50	5	10	no	no
114	1	50	5	25	yes	yes
115	1	50	5	25	no	yes
116	1	50	5	25	no	no
117	3	15	5	10	yes	no
118	3	15	5	10	yes	yes
119	3	15	5	10	no	yes
120	3	15	5	10	no	no
121	3	15	5	25	yes	yes
122	3	15	5	25	no	yes
123	3	15	5	25	no	no
124	3	50	5	10	yes	no
125	3	50	5	10	yes	yes
126	3	50	5	10	no	yes
127	3	50	5	10	no	no
128	3	50	5	25	yes	yes
129	3	50	5	25	no	yes
130	3	50	5	25	no	no
131	6	15	5	10	yes	no
132	6	15	5	10	yes	yes
133	6	15	5	10	no	yes
134	6	15	5	10	no	no
135	6	15	5	25	yes	yes
136	6	15	5	25	no	yes
137	6	15	5	25	no	no
138	6	50	5	10	yes	no
139	6	50	5	10	yes	yes
140	6	50	5	10	no	yes
141	6	50	5	10	no	no
142	6	50	5	25	yes	yes
143	6	50	5	25	no	yes
144	6	50	5	25	no	no

4 Results from the simulations

In the following sections the main results of simulations are presented in tables and figures. In the tables the measured highest peak overvoltages are given for basic cases (= 25 MVA transformer, background load included and no surge arrester) and the special variants considering only the CLL values of 10 A and 5 A. The figures show the overvoltage behaviour as the function of CLL over the whole range from 1 A to 10 A. In this chapter the results are no further discussed. In the next chapter brief summary is given about the main findings along with some further analysis.

4.1 Simulations with 1 MVAr reactor

4.1.1 Chopping Current Limit (CCL) 10 A

Table 5. Peak values of breaker voltages (before cable and reactor) and reactor star point voltage, CCL 10 A, 1 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection	Main transformer	Background load	Surge arrester	Measurements [kV]			
	cable [m]	[MVA]	included (yes/no)	included (yes/no)	UbrkA	UbrkB	UbrkC	Un
32	50	25	yes	yes	50,6	71,2	72,3	24,1
20	50	25	yes	no	114,6	205,9	180,6	60,3
33	50	25	no	yes	50,5	71,1	72,2	24,1
34	50	25	no	no	114,4	205,6	180,4	60,2
29	50	10	yes	yes	49,9	71,1	72,2	24,1
28	50	10	yes	no	115,5	206,5	180,3	60,1
30	50	10	no	yes	49,9	71,2	72,3	24,1
31	50	10	no	no	113,8	203,8	180,5	60,2
25	15	25	yes	yes	60,3	67,3	71,5	23,9
10	15	25	yes	no	239,0	310,9	297,6	99,2
26	15	25	no	yes	60,4	67,0	71,4	23,8
27	15	25	no	no	239,1	308,8	297,3	99,1
22	15	10	yes	yes	59,5	67,7	71,4	23,8
21	15	10	yes	no	240,8	312,3	297,3	99,1
23	15	10	no	yes	59,3	67,9	71,5	23,8
24	15	10	no	no	241,2	312,9	297,5	99,2
				Max, 50 m	115,5	206,5	180,6	60,3
				Max, 15 m	241,2	312,9	297,6	99,2
				Min, 50 m	49,9	71,1	72,2	24,1
				Min, 15 m	59,3	67,0	71,4	23,8

Table 6. Peak values of reactor bus phase and phase to phase voltages, CCL 10 A, 1 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection cable [m]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)	Measurements [kV] Ua	Ub	Uc	Uab	Ubc	Uca
32	50	25	yes	yes	57,7	58,3	58,0	116,0	81,7	85,8
20	50	25	yes	no	125,9	190,2	163,9	238,6	274,8	162,1
33	50	25	no	yes	57,7	58,3	58,0	116,0	81,6	85,9
34	50	25	no	no	125,6	189,9	163,8	238,3	274,6	162,1
29	50	10	yes	yes	57,7	58,3	58,0	116,0	82,1	85,3
28	50	10	yes	no	126,6	191,0	163,7	239,8	275,4	162,1
30	50	10	no	yes	57,7	58,3	58,0	116,0	82,2	85,0
31	50	10	no	no	125,1	188,1	163,8	252,9	276,0	162,2
25	15	25	yes	yes	58,4	58,2	58,3	116,6	63,2	73,2
10	15	25	yes	no	250,4	294,8	281,0	423,9	356,2	288,4
26	15	25	no	yes	58,4	58,2	58,3	116,6	63,2	73,1
27	15	25	no	no	250,5	292,9	280,8	427,5	355,2	288,2
22	15	10	yes	yes	58,4	58,2	58,3	116,6	63,1	73,4
21	15	10	yes	no	252,1	296,4	280,8	426,3	357,5	288,3
23	15	10	no	yes	58,4	58,2	58,3	116,6	63,2	73,5
24	15	10	no	no	252,6	296,9	281,0	427,1	357,9	288,4
				Max, 50 m	126,6	191,0	163,9	252,9	276,0	162,2
				Max, 15 m	252,6	296,9	281,0	427,5	357,9	288,4
				Min, 50 m	57,7	58,3	58,0	116,0	81,6	85,0
				Min, 15 m	58,4	58,2	58,3	116,6	63,1	73,1

4.1.2 Chopping Current Limit (CCL) 5 A

Table 7. Peak values of breaker voltages (before cable and reactor) and reactor star point voltage, CCL 5 A, 1 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection cable [m]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)	Measurements [kV] UbrkA	UbrkB	UbrkC	Un
114	50	25	yes	yes	43,0	70,9	72,2	24,1
15	50	25	yes	no	63,5	133,1	105,9	35,3
115	50	25	no	yes	43,0	70,9	72,2	24,1
116	50	25	no	no	63,3	132,7	105,6	35,2
111	50	10	yes	yes	43,0	70,9	72,2	24,1
110	50	10	yes	no	64,2	133,7	105,7	35,3
112	50	10	no	yes	42,9	71,0	72,3	24,1
113	50	10	no	no	64,4	134,0	105,8	35,3
107	15	25	yes	yes	49,4	70,3	71,7	23,9
5	15	25	yes	no	129,9	187,5	163,3	54,5
108	15	25	no	yes	49,3	70,2	71,5	23,8
109	15	25	no	no	129,9	187,3	163,2	54,4
104	15	10	yes	yes	49,5	70,1	71,5	23,8
103	15	10	yes	no	131,7	188,4	163,1	54,4
105	15	10	no	yes	49,7	70,2	71,6	23,9
106	15	10	no	no	132,0	188,8	163,3	54,5
				Max. 50 m	64,4	134,0	105,9	35,3
				Max. 15 m	132,0	188,8	163,3	54,5
				Min. 50 m	42,9	70,9	72,2	24,1
				Min. 15 m	49,3	70,1	71,5	23,8

Table 8. Peak values of reactor bus phase and phase to phase voltages, CCL 5 A, 1 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection cable [m]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)	Measurements [kV] Ua	Ub	Uc	Uab	Ubc	Uca
114	50	25	yes	yes	56,0	56,1	55,9	107,7	98,3	65,4
15	50	25	yes	no	76,6	118,2	89,1	135,3	143,3	83,6
115	50	25	no	yes	56,0	56,2	55,9	107,1	98,7	65,4
116	50	25	no	no	76,3	117,9	89,0	134,9	143,1	83,5
111	50	10	yes	yes	56,0	56,1	55,9	107,7	98,3	65,4
110	50	10	yes	no	77,2	119,0	89,0	135,7	142,9	83,6
112	50	10	no	yes	56,0	56,1	55,9	107,8	98,2	65,5
113	50	10	no	no	77,5	119,2	89,1	136,0	143,0	83,6
107	15	25	yes	yes	56,4	56,3	56,4	112,4	79,1	66,2
5	15	25	yes	no	143,1	172,3	146,5	229,1	179,7	145,7
108	15	25	no	yes	56,4	56,3	56,4	112,4	79,1	66,1
109	15	25	no	no	142,9	172,2	146,5	228,9	179,7	145,7
104	15	10	yes	yes	56,4	56,3	56,4	112,4	79,2	66,1
103	15	10	yes	no	144,8	173,3	146,4	229,9	178,1	145,7
105	15	10	no	yes	56,4	56,3	56,4	112,4	79,2	66,2
106	15	10	no	no	145,2	173,7	146,6	230,4	178,3	145,7
				Max. 50 m	77,5	119,2	89,1	136,0	143,3	83,6
				Max. 15 m	145,2	173,7	146,6	230,4	179,7	145,7
				Min. 50 m	56,0	56,1	55,9	107,1	98,2	65,4
				Min. 15 m	56,4	56,3	56,4	112,4	79,1	66,1

4.1.3 System operation with respect to Current Chopping Level

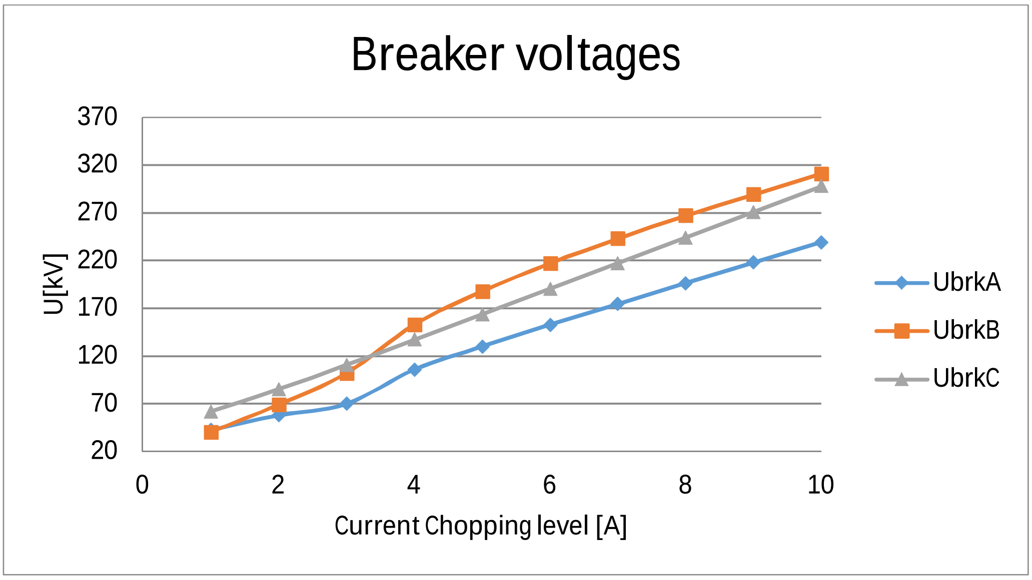


Figure 16. Peak values of breaker voltages on cases 1-10 (Reactor 1 MVAr, connection cable 15 m, main transformer 25 MVA)

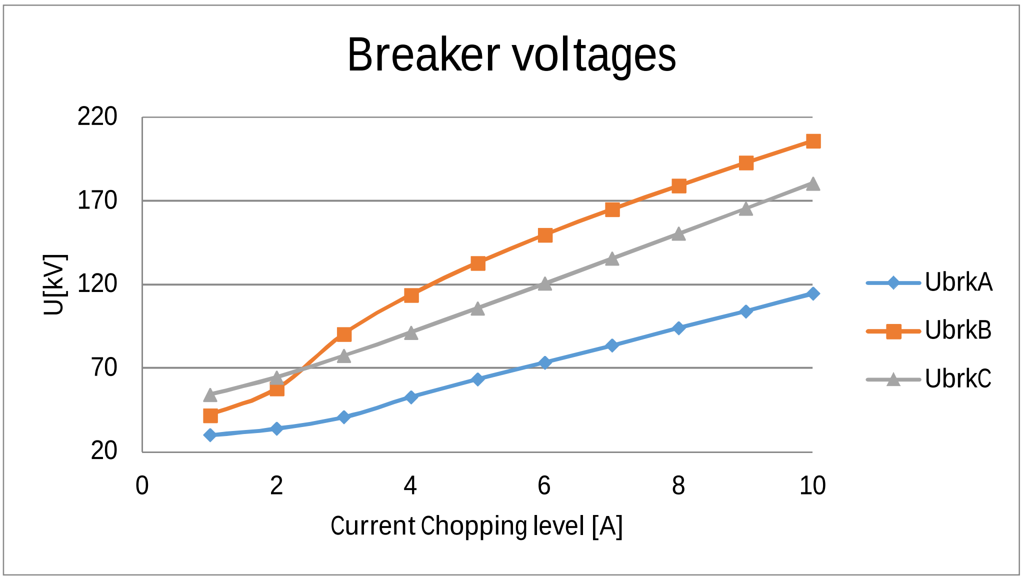


Figure 17. Peak values of breaker voltages on cases 11-20 (Reactor 1 MVAr, connection cable 50 m, main transformer 25 MVA)

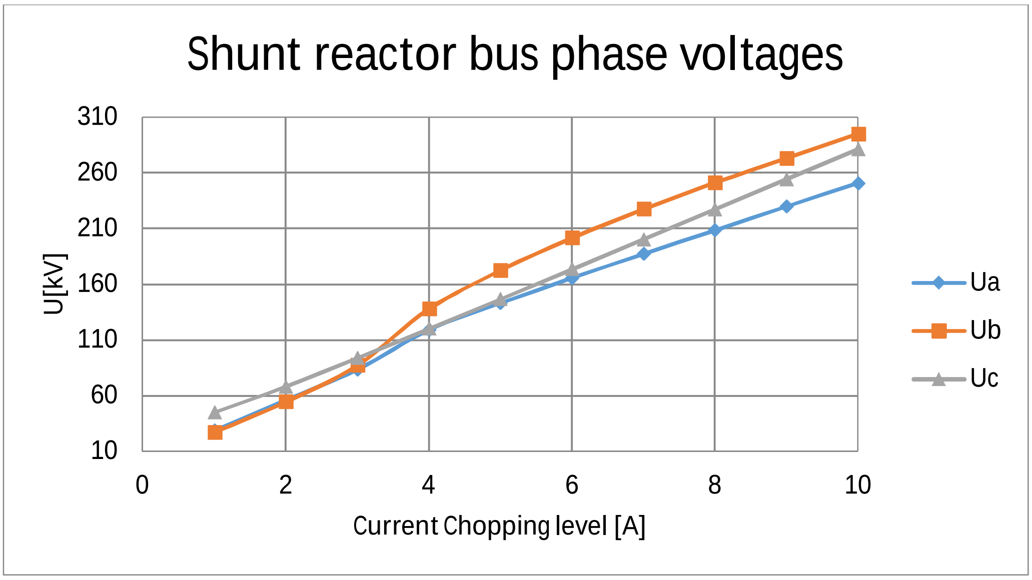


Figure 18. Peak values of shunt reactor bus phase voltages on cases 1-10 (Reactor 1 MVAr, connection cable 15 m, main transformer 25 MVA)

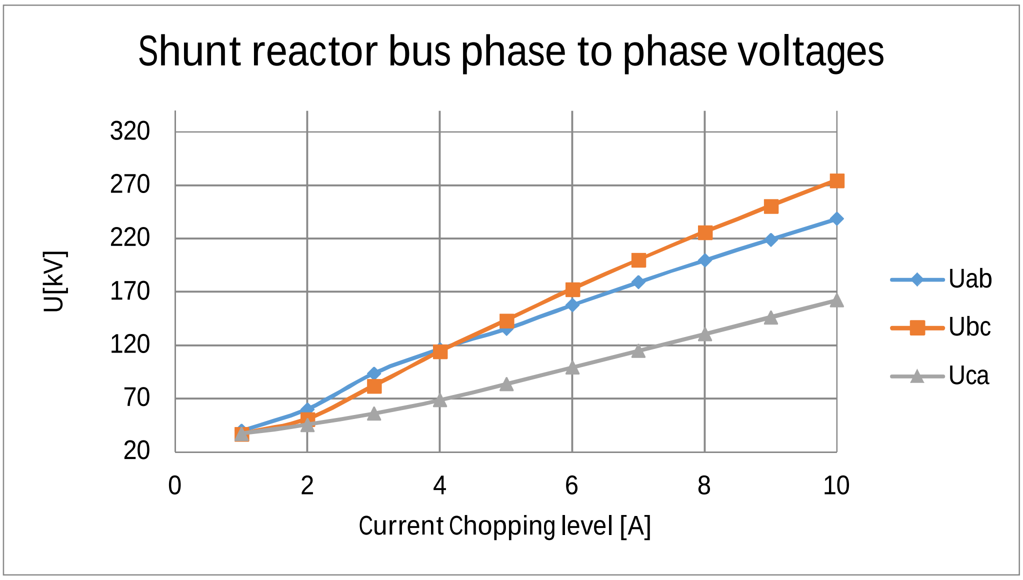


Figure 19. Peak values of shunt reactor bus phase voltages on cases 11-20 (Reactor 1 MVAr, connection cable 50 m, main transformer 25 MVA)

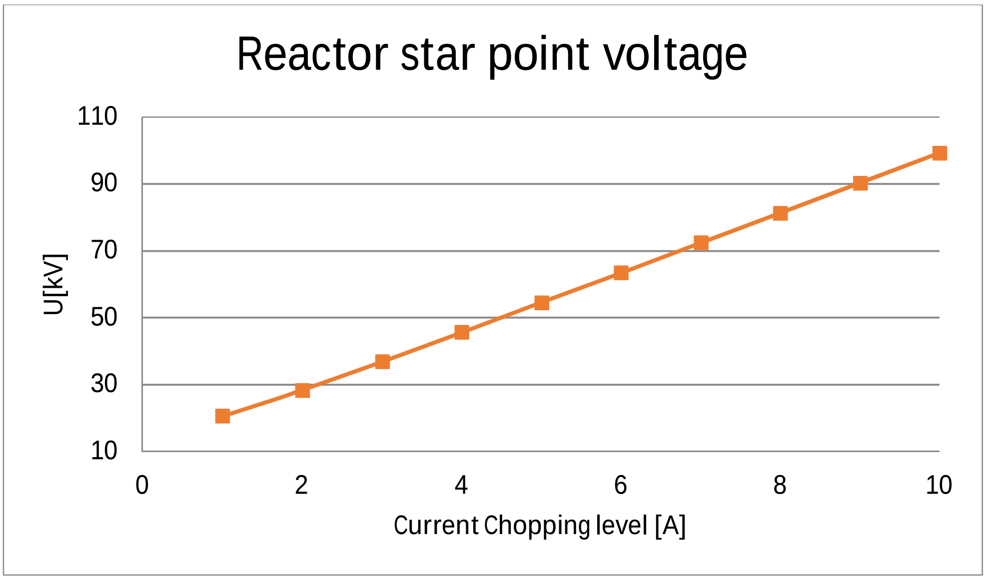


Figure 20. Peak values of shunt reactor star point voltage on cases 1-10 (Reactor 1 MVAr, connection cable 15 m, main transformer 25 MVA)

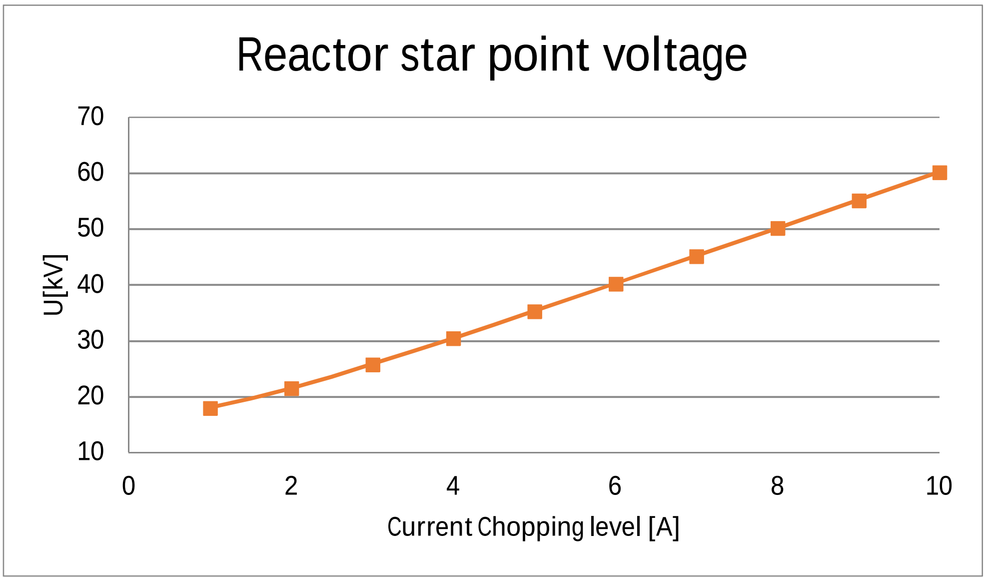


Figure 21. Peak values of shunt reactor star point voltage on cases 11-20 (Reactor 1 MVAr, connection cable 50 m, main transformer 25 MVA)

4.2 Simulations with 3 MVAr reactor

4.2.1 Chopping Current Limit (CCL) 10 A

Table 9. Peak values of breaker voltages (before cable and reactor) and reactor star point voltage, CCL 10 A, 3 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection cable [m]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)	Measurements			
					UbrkA	UbrkB	UbrkC	Un
66	50	25	yes	yes	71,2	42,2	72,7	24,3
54	50	25	yes	no	154,6	76,4	118,2	39,8
67	50	25	no	yes	71,3	42,0	72,9	24,3
68	50	25	no	no	155,3	76,8	118,6	40,1
63	50	10	yes	yes	71,3	42,5	72,9	24,3
62	50	10	yes	no	158,4	80,7	118,6	42,9
64	50	10	no	yes	71,2	42,3	72,8	24,3
65	50	10	no	no	157,8	80,4	118,2	42,7
59	15	25	yes	yes	66,5	65,1	72,4	24,1
44	15	25	yes	no	184,6	130,7	187,8	62,6
60	15	25	no	yes	66,5	64,9	72,3	24,1
61	15	25	no	no	185,4	131,2	188,2	62,8
56	15	10	yes	yes	68,7	60,2	72,3	24,1
55	15	10	yes	no	194,8	133,8	188,3	62,8
57	15	10	no	yes	68,5	60,2	72,1	24,1
58	15	10	no	no	194,0	134,7	187,9	62,7
				Max, 50 m	158,4	80,7	118,6	42,9
				Max, 15 m	194,8	134,7	188,3	62,8
				Min, 50 m	71,2	42,0	72,7	24,3
				Min, 15 m	66,5	60,2	72,1	24,1

Table 10. Peak values of reactor bus phase and phase to phase voltages, CCL 10 A, 3 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection cable [m]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)	Measurements [kV] Ua	Ub	Uc	Uab	Ubc	Uca
66	50	25	yes	yes	57,1	57,4	57,3	112,1	64,9	100,4
54	50	25	yes	no	140,5	91,6	101,5	151,8	94,2	161,1
67	50	25	no	yes	57,1	57,4	57,3	112,1	65,0	100,3
68	50	25	no	no	141,0	92,2	101,7	152,3	94,4	161,2
63	50	10	yes	yes	57,0	57,5	57,3	112,2	64,9	98,7
62	50	10	yes	no	144,2	96,0	101,7	155,0	94,2	159,1
64	50	10	no	yes	57,0	57,5	57,3	112,3	64,8	98,9
65	50	10	no	no	143,8	95,5	101,5	154,4	94,1	158,9
59	15	25	yes	yes	58,0	58,0	58,0	115,9	72,8	67,3
44	15	25	yes	no	170,7	145,8	171,2	252,9	166,6	200,5
60	15	25	no	yes	58,0	57,9	58,0	115,9	72,8	67,3
61	15	25	no	no	171,3	146,5	171,4	253,8	166,8	201,0
56	15	10	yes	yes	58,0	57,9	58,0	115,8	70,7	67,3
55	15	10	yes	no	180,7	149,1	171,4	255,1	166,7	207,1
57	15	10	no	yes	58,0	57,9	58,0	115,8	70,8	67,3
58	15	10	no	no	180,1	149,9	171,3	256,1	166,7	207,1
				Max, 50 m	144,2	96,0	101,7	155,0	94,4	161,2
				Max, 15 m	180,7	149,9	171,4	256,1	166,8	207,1
				Min, 50 m	57,0	57,4	57,3	112,1	64,8	98,7
				Min, 15 m	58,0	57,9	58,0	115,8	70,7	67,3

4.2.2 Chopping Current Limit (CCL) 5 A

Table 11. Peak values of breaker voltages (before cable and reactor) and reactor star point voltage, CCL 5 A, 3 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection cable [m]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)	Measurements [kV] UbrkA	UbrkB	UbrkC	Un
128	50	25	yes	yes	68,5	42,3	72,0	24,0
49	50	25	yes	no	73,2	45,1	76,2	25,4
129	50	25	no	yes	68,6	42,5	72,2	24,1
130	50	25	no	no	73,6	45,4	76,5	25,5
125	50	10	yes	yes	68,4	44,4	72,3	24,1
124	50	10	yes	no	73,2	47,7	76,7	25,6
126	50	10	no	yes	68,3	44,2	72,1	24,0
127	50	10	no	no	72,9	47,4	76,3	25,5
121	15	25	yes	yes	70,1	53,1	72,5	24,2
39	15	25	yes	no	110,5	63,7	109,2	36,4
115	15	25	no	yes	73,2	45,1	76,2	25,4
116	15	25	no	no	73,2	45,1	76,2	25,4
118	15	10	yes	yes	70,1	52,0	72,4	24,1
117	15	10	yes	no	114,4	66,8	109,4	36,5
119	15	10	no	yes	70,0	51,8	72,2	24,1
120	15	10	no	no	114,2	66,9	109,3	36,4
				Max, 50 m	73,6	47,7	76,7	25,6
				Max, 15 m	114,4	66,9	109,4	36,5
				Min, 50 m	68,3	42,3	72,0	24,0
				Min, 15 m	70,0	45,1	72,2	24,1

Table 12. Peak values of reactor bus phase and phase to phase voltages, CCL 5 A, 3 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection cable [m]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)	Measurements [kV] Ua	Ub	Uc	Uab	Ubc	Uca
128	50	25	yes	yes	53,9	48,8	55,4	80,3	52,0	59,6
49	50	25	yes	no	58,6	51,2	59,5	81,2	54,6	64,6
129	50	25	no	yes	53,8	48,9	55,4	80,4	52,1	59,5
130	50	25	no	no	58,8	51,4	59,7	81,6	54,8	64,7
125	50	10	yes	yes	53,6	51,6	55,4	83,1	52,2	57,4
124	50	10	yes	no	58,4	54,5	59,9	84,3	54,9	62,4
126	50	10	no	yes	53,6	51,5	55,4	83,0	52,0	57,6
127	50	10	no	no	58,2	54,3	59,6	84,1	54,6	62,2
121	15	25	yes	yes	55,5	56,0	56,0	110,7	64,3	75,6
39	15	25	yes	no	96,2	78,5	92,6	132,4	86,5	103,9
115	15	25	no	yes	58,6	51,2	59,5	81,2	54,6	64,6
116	15	25	no	no	58,6	51,2	59,5	81,2	54,6	64,6
118	15	10	yes	yes	55,6	56,0	56,0	110,7	64,2	77,0
117	15	10	yes	no	99,8	81,7	92,6	136,9	86,3	103,4
119	15	10	no	yes	55,6	56,0	56,0	110,7	64,1	77,0
120	15	10	no	no	99,8	81,6	92,6	136,9	86,4	103,5
				Max, 50 m	58,8	54,5	59,9	84,3	54,9	64,7
				Max, 15 m	99,8	81,7	92,6	136,9	86,5	103,9
				Min, 50 m	53,6	48,8	55,4	80,3	52,0	57,4
				Min, 15 m	55,5	51,2	56,0	81,2	54,6	64,6

4.2.3 System operation with respect to Current Chopping Level

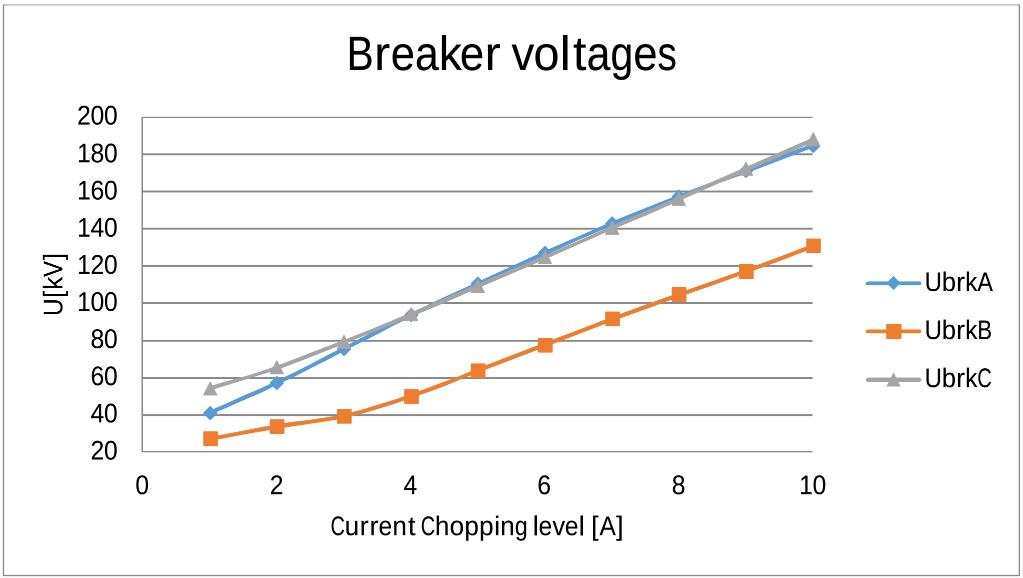


Figure 22. Peak values of breaker voltages on cases 35-44 (Reactor 3 MVAr, connection cable 15 m, main transformer 25 MVA)

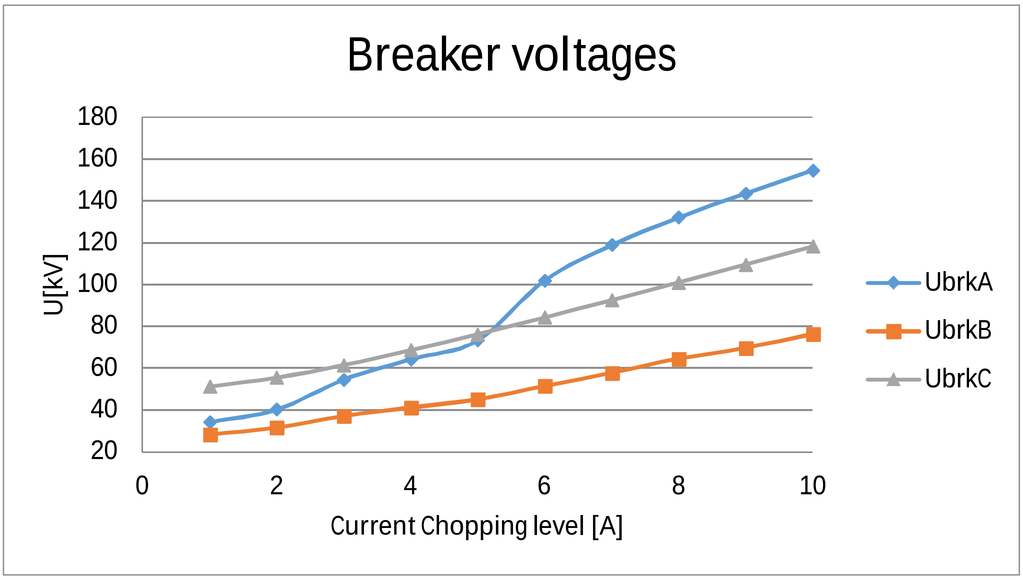


Figure 23. Peak values of breaker voltages on cases 45-54 (Reactor 3 MVAr, connection cable 50 m, main transformer 25 MVA)

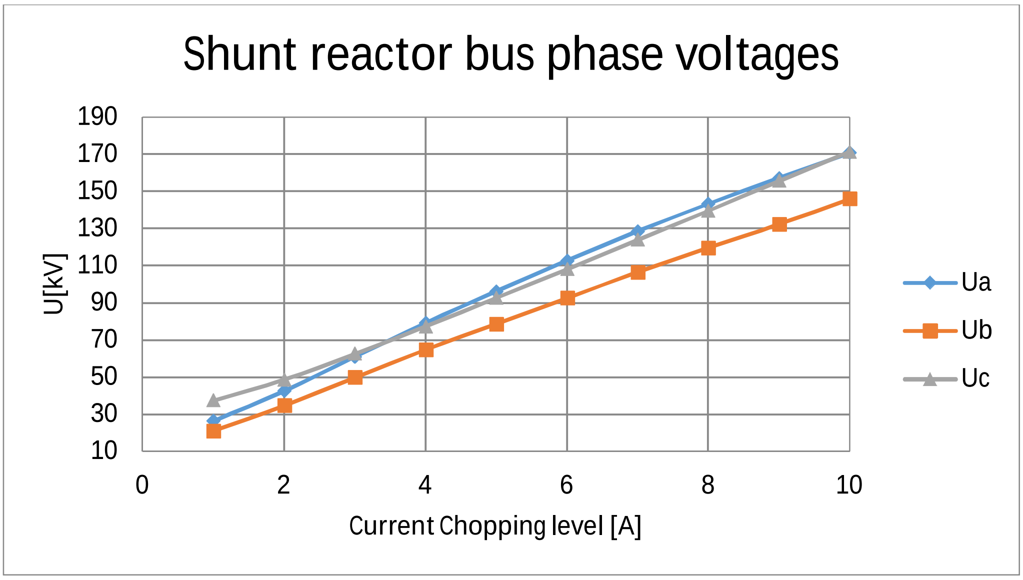


Figure 24. Peak values of shunt reactor bus phase voltages on cases 35-44 (Reactor 3 MVAr, connection cable 15 m, main transformer 25 MVA)

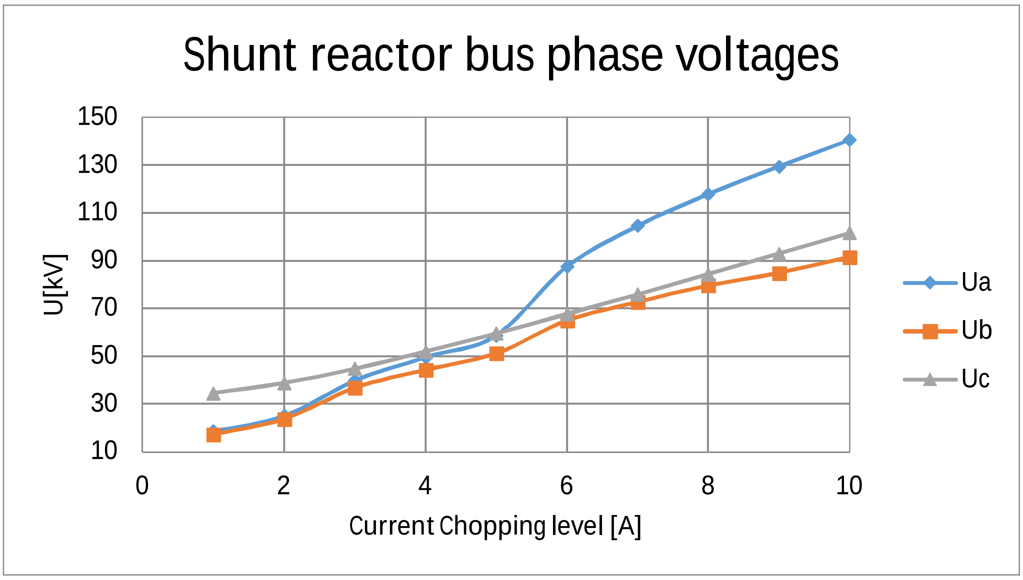


Figure 25. Peak values of shunt reactor bus phase voltages on cases 45-54 (Reactor 3 MVAr, connection cable 50 m, main transformer 25 MVA)

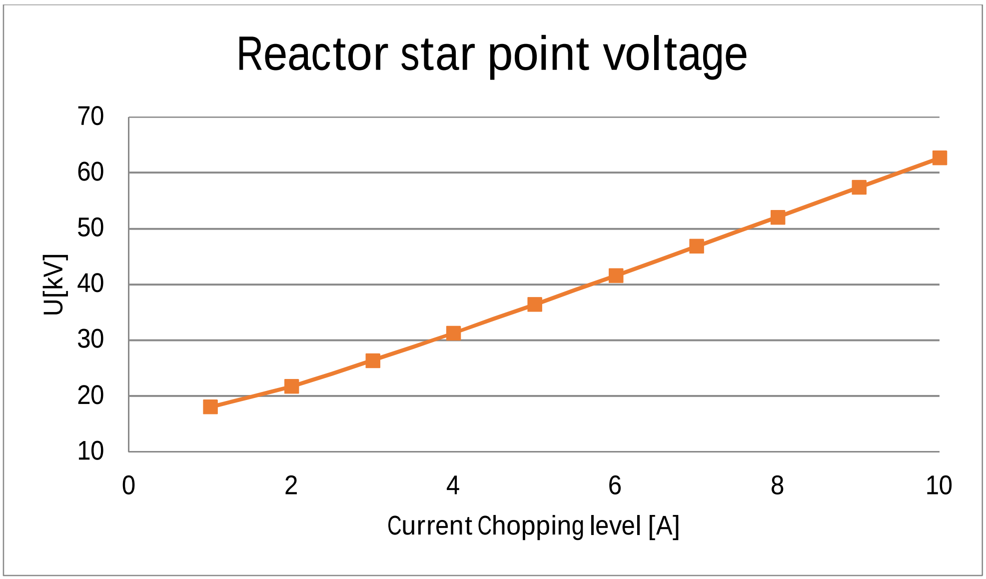


Figure 26. Peak values of shunt reactor star point voltages on cases 35-44 (Reactor 3 MVAr, connection cable 15 m, main transformer 25 MVA)

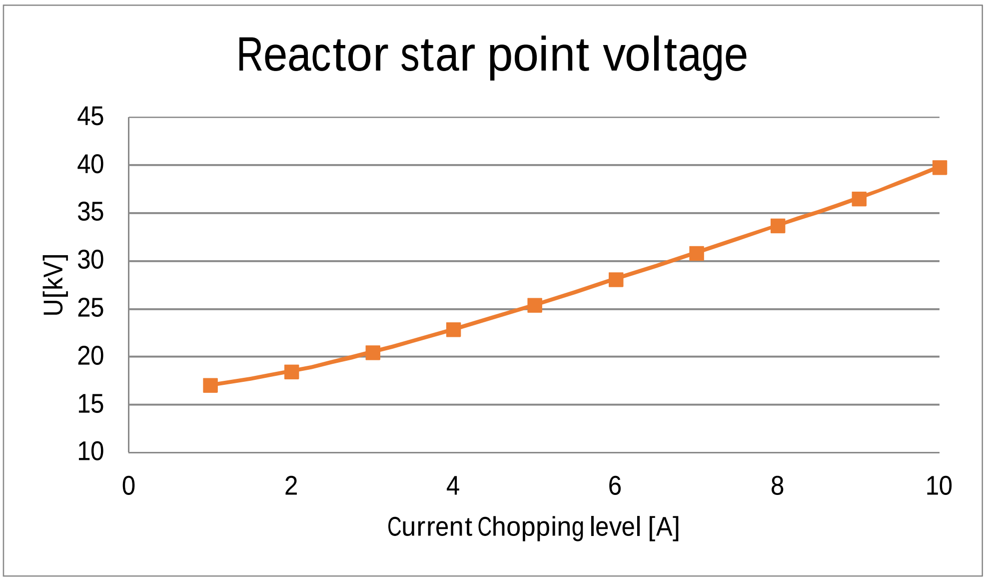


Figure 27. Peak values of shunt reactor star point voltage on cases 45-54 (Reactor 3 MVAr, connection cable 50 m, main transformer 25 MVA)

4.3 Simulations with 6 MVAr reactor

4.3.1 Chopping Current Limit (CCL) 10 A

Table 13. Peak values of breaker voltages (before cable and reactor) and reactor star point voltage, CCL 10 A, 6 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection	Main transformer	Background load	Surge arrester	Measurements [kV]			
	cable [m]	[MVA]	included (yes/no)	included (yes/no)	UbrkA	UbrkB	UbrkC	Un
100	50	25	yes	yes	42,1	72,1	73,4	24,5
88	50	25	yes	no	49,0	108,9	85,9	28,7
101	50	25	no	yes	42,0	72,2	73,6	24,5
102	50	25	no	no	49,3	109,5	86,2	28,8
97	50	10	yes	yes	50,4	71,3	73,9	24,6
96	50	10	yes	no	55,3	106,3	86,2	28,8
98	50	10	no	yes	51,5	71,4	74,3	24,8
99	50	10	no	no	54,9	104,9	87,0	29,1
93	15	25	yes	yes	51,2	70,8	72,7	24,2
78	15	25	yes	no	77,8	134,4	128,1	42,7
94	15	25	no	yes	51,3	70,9	72,8	24,3
95	15	25	no	no	78,6	135,5	128,7	42,9
90	15	10	yes	yes	48,4	71,2	73,1	24,4
89	15	10	yes	no	87,0	147,2	128,4	42,8
91	15	10	no	yes	49,1	71,6	73,5	24,5
92	15	10	no	no	87,0	147,4	128,7	42,9
				Max, 50 m	55,3	109,5	87,0	29,1
				Max, 15 m	87,0	147,4	128,7	42,9
				Min, 50 m	42,0	71,3	73,4	24,5
				Min, 15 m	48,4	70,8	72,7	24,2

Table 14. Peak values of reactor bus phase and phase to phase voltages, CCL 10 A, 6 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection	Main transformer	Background load	Surge arrester	Measurements					
	cable [m]	[MVA]	included (yes/no)	included (yes/no)	Ua	Ub	Uc	Uab	Ubc	Uca
100	50	25	yes	yes	56,0	57,6	56,7	92,6	80,2	61,1
88	50	25	yes	no	63,0	94,5	69,3	103,2	101,3	64,9
101	50	25	no	yes	56,1	57,6	56,8	92,2	79,4	61,2
102	50	25	no	no	63,4	94,9	69,4	103,8	101,5	65,0
97	50	10	yes	yes	55,6	56,6	56,8	99,3	71,9	61,4
96	50	10	yes	no	69,6	91,9	69,4	110,5	91,6	65,0
98	50	10	no	yes	55,5	56,4	56,8	97,7	69,5	61,6
99	50	10	no	no	69,5	90,1	69,8	111,6	91,0	65,5
93	15	25	yes	yes	57,4	57,0	57,5	113,2	80,7	66,1
78	15	25	yes	no	91,8	119,8	111,4	152,6	140,7	104,9
94	15	25	no	yes	57,4	57,0	57,5	113,2	80,8	66,1
95	15	25	no	no	92,7	120,7	111,8	150,6	140,4	105,3
90	15	10	yes	yes	57,5	56,9	57,5	113,1	85,1	66,4
89	15	10	yes	no	101,2	132,6	111,6	158,8	139,7	105,1
91	15	10	no	yes	57,5	56,9	57,5	113,2	84,6	66,5
92	15	10	no	no	101,3	132,7	111,8	158,5	138,9	105,3
				Max, 50 m	69,6	94,9	69,8	111,6	101,5	65,5
				Max, 15 m	101,3	132,7	111,8	158,8	140,7	105,3
				Min, 50 m	55,5	56,4	56,7	92,2	69,5	61,1
				Min, 15 m	57,4	56,9	57,5	113,1	80,7	66,1

4.3.2 Chopping Current Limit (CCL) 5 A

Table 15. Peak values of breaker voltages (before cable and reactor) and reactor star point voltage, CCL 5 A, 6 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection	Main transformer	Background load	Surge arrester	Measurements [kV]			
	cable [m]	[MVA]	included (yes/no)	included (yes/no)	UbrkA	UbrkB	UbrkC	Un
142	50	25	yes	yes	34,3	55,5	62,2	20,7
83	50	25	yes	no	35,2	56,5	62,2	20,8
143	50	25	no	yes	34,6	55,8	62,7	20,9
144	50	25	no	no	35,2	55,7	62,7	20,9
139	50	10	yes	yes	41,6	44,8	62,5	20,8
138	50	10	yes	no	41,4	48,7	62,6	20,9
140	50	10	no	yes	41,8	44,9	62,7	20,9
141	50	10	no	no	41,6	48,9	62,8	20,9
135	15	25	yes	yes	38,6	70,1	72,4	24,1
73	15	25	yes	no	37,4	81,5	80,8	26,9
136	15	25	no	yes	39,1	70,2	72,5	24,2
137	15	25	no	no	36,9	81,4	81,0	27,0
132	15	10	yes	yes	43,3	69,8	72,5	24,2
131	15	10	yes	no	40,8	79,9	81,1	27,0
133	15	10	no	yes	43,7	69,9	72,6	24,2
134	15	10	no	no	41,0	80,1	81,2	27,1
				Max, 50 m	41,8	56,5	62,8	20,9
				Max, 15 m	43,7	81,5	81,2	27,1
				Min, 50 m	34,3	44,8	62,2	20,7
				Min, 15 m	36,9	69,8	72,4	24,1

Table 16. Peak values of reactor bus phase and phase to phase voltages, CCL 5 A, 6 MVAr reactor. Basic cases are highlighted in grey.

Case	Connection cable [m]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)	Measurements [kV] Ua	Ub	Uc	Uab	Ubc	Uca
142	50	25	yes	yes	34,4	41,3	45,5	55,3	47,9	44,3
83	50	25	yes	no	35,1	42,2	45,5	55,9	48,3	44,7
143	50	25	no	yes	34,7	41,4	45,8	55,6	48,0	44,7
144	50	25	no	no	34,8	41,4	45,9	55,1	47,9	45,1
139	50	10	yes	yes	31,0	30,6	45,7	49,9	44,5	44,7
138	50	10	yes	no	34,5	34,5	45,7	54,1	45,0	44,9
140	50	10	no	yes	31,1	30,6	45,8	50,1	44,6	44,8
141	50	10	no	no	34,6	34,5	45,8	54,3	45,1	45,0
135	15	25	yes	yes	50,4	55,6	55,7	86,1	63,6	56,5
73	15	25	yes	no	51,6	67,0	64,1	85,6	70,9	56,5
136	15	25	no	yes	50,4	55,6	55,7	86,6	63,7	56,4
137	15	25	no	no	51,2	66,9	64,1	86,4	70,9	56,5
132	15	10	yes	yes	52,2	55,4	55,7	89,3	57,4	56,6
131	15	10	yes	no	55,3	65,5	64,3	91,4	63,1	56,7
133	15	10	no	yes	52,0	55,4	55,7	89,5	57,5	56,7
134	15	10	no	no	55,4	65,7	64,3	91,7	63,2	56,7
				Max, 50 m	35,1	42,2	45,9	55,9	48,3	45,1
				Max, 15 m	55,4	67,0	64,3	91,7	70,9	56,7
				Min, 50 m	31,0	30,6	45,5	49,9	44,5	44,3
				Min, 15 m	50,4	55,4	55,7	85,6	57,4	56,4

4.3.3 System operation with respect to Current Chopping Level

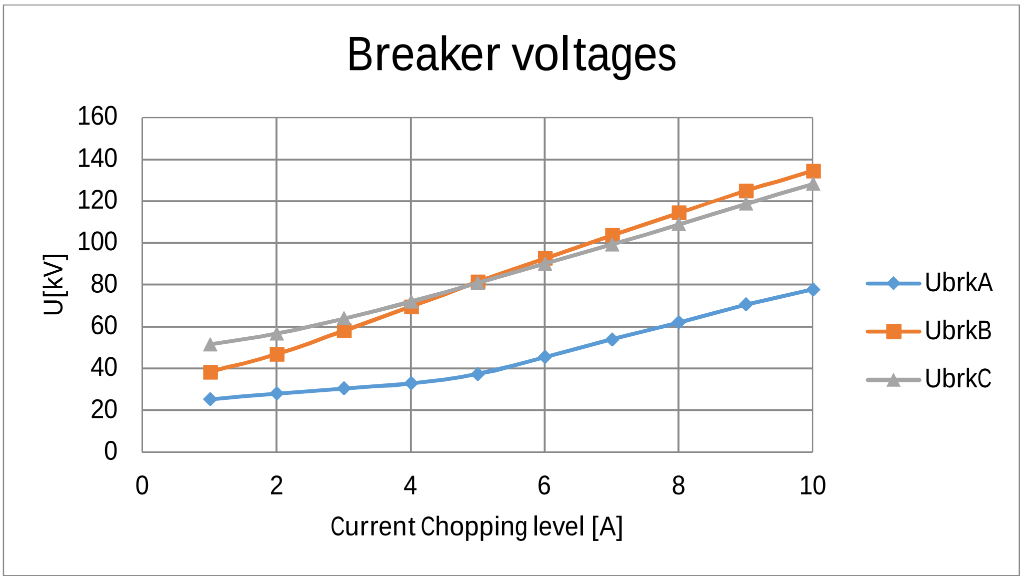


Figure 28. Peak values of breaker voltages on cases 69-78 (Reactor 6 MVAr, connection cable 15 m, main transformer 25 MVA)

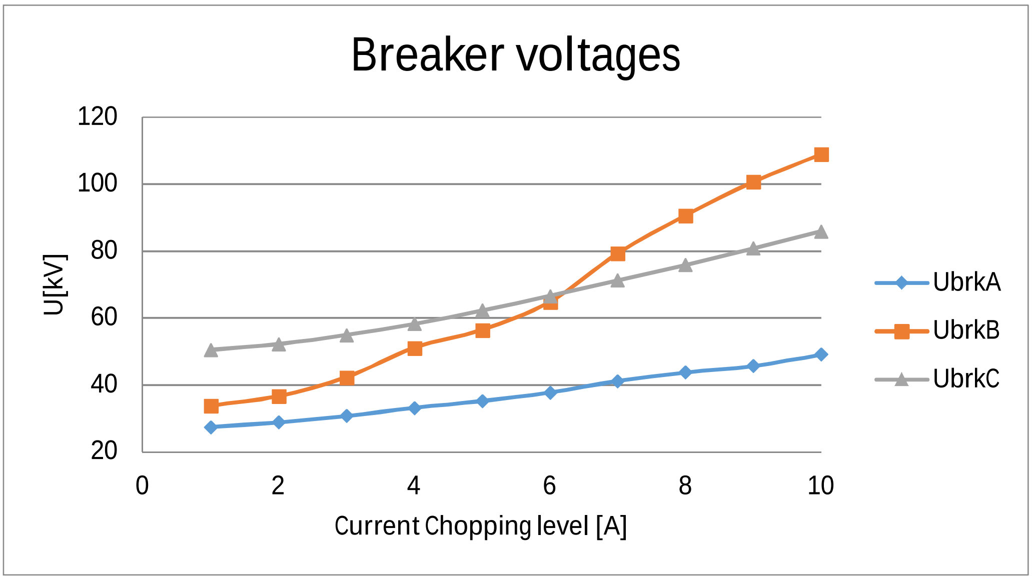


Figure 29. Peak values of breaker voltages on cases 79-88 (Reactor 6 MVAr, connection cable 50 m, main transformer 25 MVA)

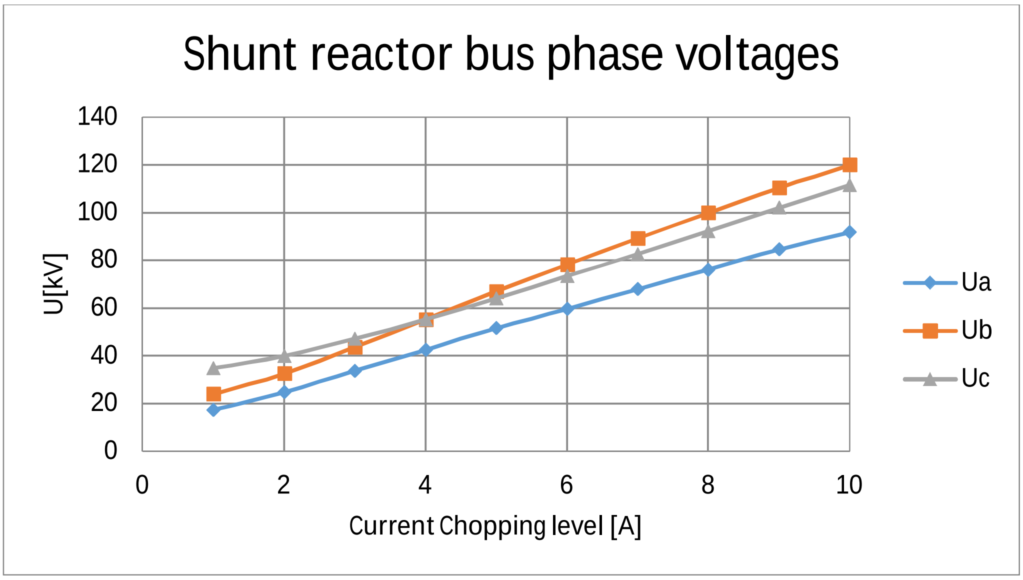


Figure 30. Peak values of shunt reactor bus phase voltages on cases 69-78 (Reactor 6 MVAr, connection cable 15 m, main transformer 25 MVA)

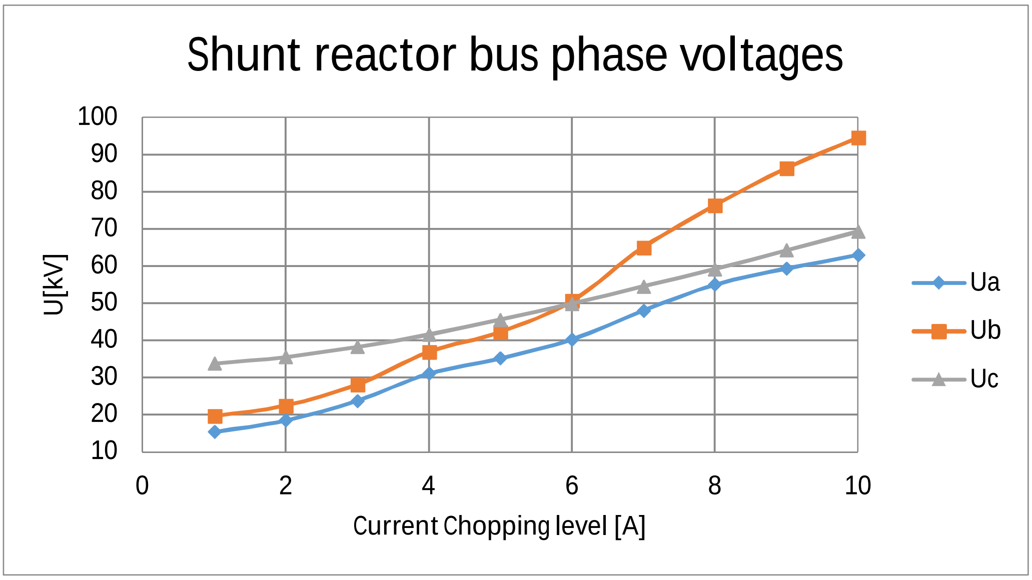


Figure 31. Peak values of shunt reactor bus phase voltages on cases 79-88 (Reactor 6 MVAr, connection cable 50 m, main transformer 25 MVA)

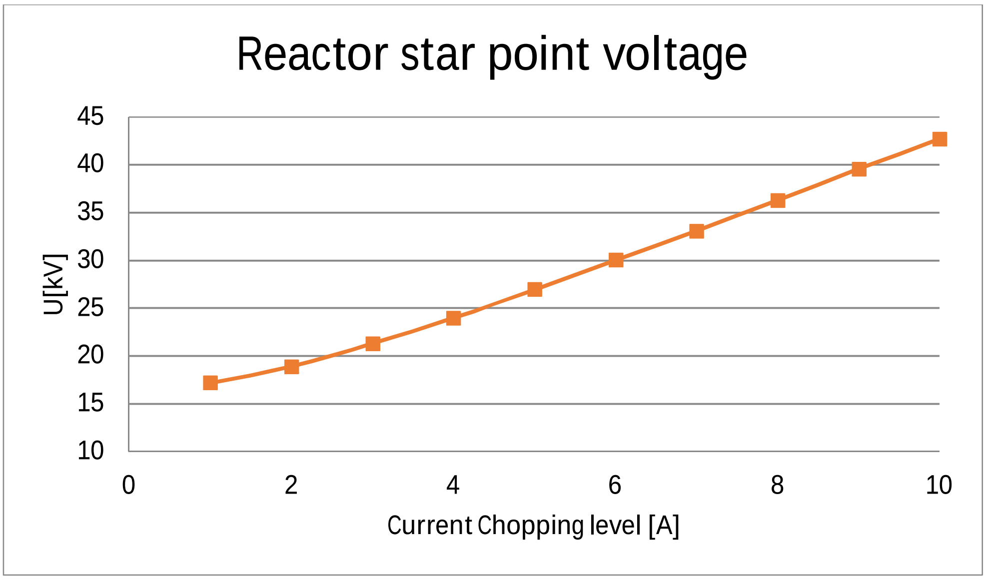


Figure 32. Peak values of shunt reactor star point voltage on cases 69-78 (Reactor 6 MVAr, connection cable 15 m, main transformer 25 MVA)

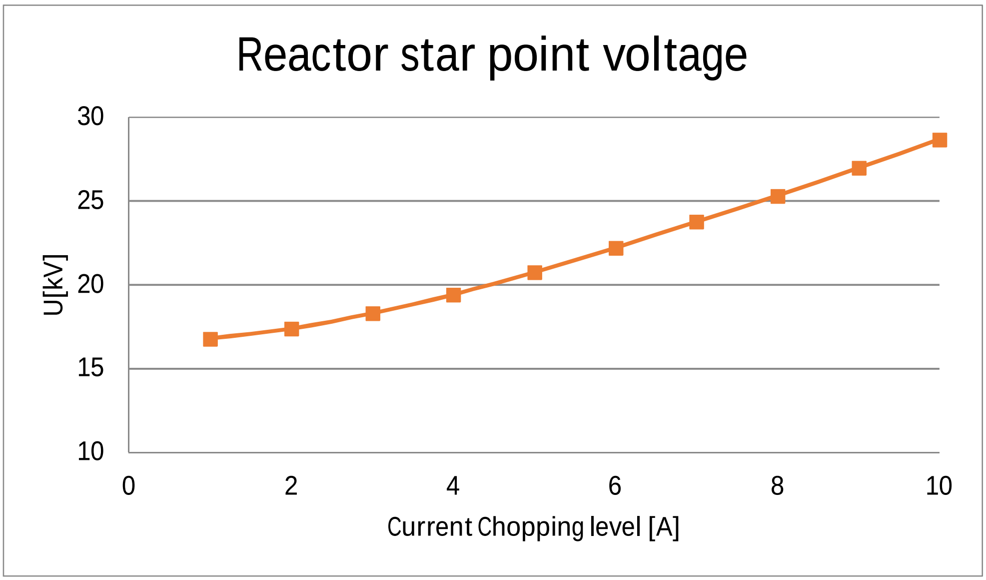


Figure 33. Peak values of shunt reactor star point voltage on cases 79-88 (Reactor 6 MVAr, connection cable 50 m, main transformer 25 MVA)

5 Summary

In the simulations the highest overvoltages occurred with the smallest reactor size and shortest cable. The very highest overvoltage peaks reached 296.9 kV for the phase voltage, 427,5 kV for the phase to phase voltage and 312,9 kV for the breaker voltage (over the poles). The modelled surge arrester was capable to cut these down below 60 kV for phase voltages and below 120 kV for the phase to phase voltages.

The voltage between the star point of the reactor and earth reaches almost the value of 100 kV in the worst case but is limited below 25 kV with the use of surge arrester. The start point voltage starts to oscillate as soon as the current in the first breaking pole is chopped. The oscillation is actually similar as the phase voltage oscillation in the corresponding phase but the magnitude is one third of the phase voltage. The oscillating overvoltage stops as soon as the current is breaked in other two poles. The duration of oscillating overvoltage in the star point is less than 5 ms. When all the phases start oscillate the changing of the oscillation mode causes a decaying DC voltage in the star point. In the simulations the decaying of the DC component to zero takes around 40 ms in the worst case.

The simulation results match well with the theory about the overvoltages. The following table shows the calculated peak values (Vpeak calc) with minimum and maximum (assuming fully symmetrical or unsymmetrical waveform) compared to the simulated ones. It shows that the simulated values are well between the min and max values.

Table 17. Comparison of calculated and simulated phase voltage peak values in cases with CCL of 10 A.

Reactor, [MVAr]	Cable lenght, [m]	C [uF]	L [H]	Vpeak calc min (kV)	Vpeak calc max (kV)	Vpeak sim. (kV)
1	15	0,002343	1,337649	239,5	479,0	294,8
3	15	0,002343	0,445883	138,9	277,8	144,2
6	15	0,00317	0,222942	85,4	170,9	119,8
1	50	0,00781	1,337649	131,9	263,8	190,2
3	50	0,00781	0,445883	77,3	154,6	140,5
6	50	0,010567	0,222942	48,7	97,5	94,5

The results indicate that the overvoltages are clearly increasing as the CCL increases. For the phase c, which was first opened in the simulations, the behaviour is quite linear as a function of CCL. For the behavior of the other phases the asymmetry of evolving overvoltages is affecting.

The frequency of the overvoltage depends on the L and C of the resonating circuit as discussed on Chapter 2. In the simulations the frequency was measured and according to the following table the measured value is close to the calculated one.

Table 18. Comparison of calculated and measured frequency of the overvoltage.

Reactor, [MVAr]	Cable lenght, [m]	C [uF]	L [H]	f calc (Hz)	f sim (Hz)
1	15	0,002343	1,337649	2842,8	2800
3	15	0,002343	0,445883	4923,9	4800
6	15	0,00317	0,222942	5986,7	6000
1	50	0,00781	1,337649	1557,1	1500
3	50	0,00781	0,445883	2696,9	2600
6	50	0,010567	0,222942	3279,0	3300

The duration of the overvoltage was not measured in the simulations, but according to the graphs shown in the Appendix 1 it is usually between 10 and 20 ms.

For the cases including the surge arrester also the energy dissipated at the arrester was recorded in few cases. Since the duration of the overvoltage situation is short, also the energy remained very low as can be seen in the following table.

Table 19. Measured energies at the surge arresters.

Reactor, MVAR	Cable lenght, m	Energy, kJ
1	15	0,088
1	50	0,086
3	15	0,03
3	50	0,028
6	15	0,015
6	50	0,017

The effect of surge arresters is further illustrated in the following figure. The blue curve provides the phase voltage in the first breaking pole at the worst case (Case 10) among the simulations made and the green curve provides the same situation with surge arresters (Case 25). In the same figure there is drawn also the standard lightning impulse test voltage (1,2/50 us, 125 kV). The peak value of the overvoltage with surge arrester remains clearly below the peak value of the impulse. In the figure also the continuous AC test voltage limits are drawn at ±70.7 kV corresponding the peak value of the 50 kV (RMS) test voltage. The peak overvoltage values in case with surge arrester are well below these limits.

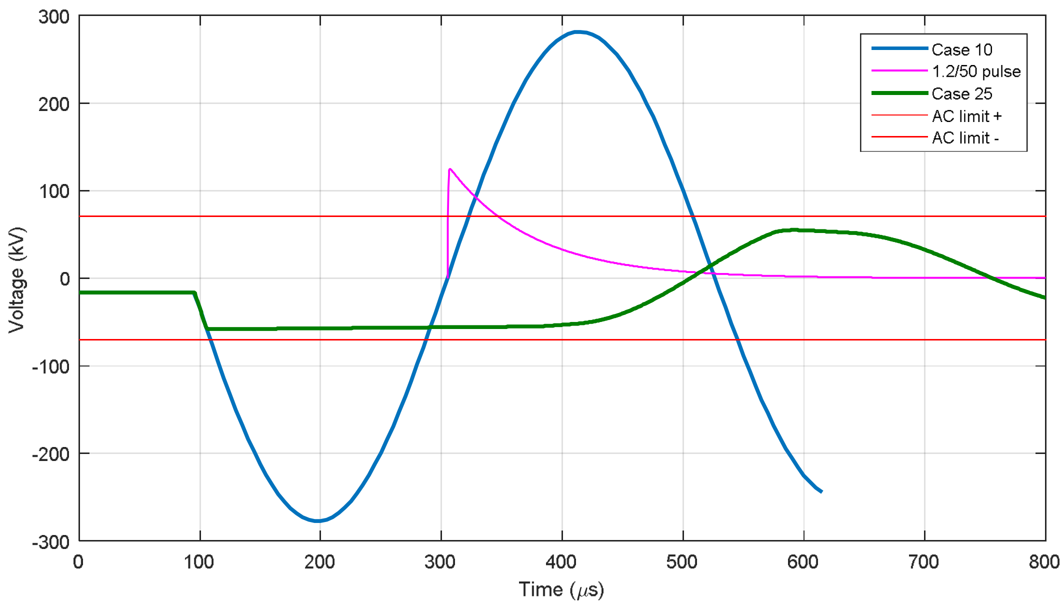


Figure 34. Examples of voltage waveforms in comparison with standard test limits.

According to simulations following conclusions can be drawn:

- The higher the current chopping limit is the higher voltage stress the components must endure.
- Voltage stress level on breaker depends on chopping current and can be highest either in first breaking pole or other poles.
- Longer cabling from substation bus to the reactor results lower voltage stresses to the components.
- The background loads of the network have a small to nonexistant effect on the voltage stresses of the components.
- Changing the main transformer size has a small to nonexistant effect on the voltage stresses of the components.
- Addition of surge arresters causes significant reduction in voltage stresses of the components.

As a final remark it should be noticed that the re-ignitions over breaker contacts were not modelled in the simulation studies made. It can be assumed that the re-ignitions would have limit the level of overvoltages at least in the worst cases.

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Appendix 1. Simulation graphs

In this appendix time series graphs are shown from selected cases are shown. The table below shows the simulations from which the graphs were taken.

Table 20. The simulation cases from which the graphs are included In this Appendix.

Case	Reactor size [MVAr]	Connection cable [m]	CCL [A]	Main transformer [MVA]	Background load included (yes/no)	Surge arrester included (yes/no)
10	1	15	10	25	yes	no
20	1	50	10	25	yes	no
25	1	15	10	25	yes	yes
32	1	50	10	25	yes	yes
44	3	15	10	25	yes	no
54	3	50	10	25	yes	no
59	3	15	10	25	yes	yes
66	3	50	10	25	yes	yes
78	6	15	10	25	yes	no
88	6	50	10	25	yes	no
93	6	15	10	25	yes	yes
100	6	50	10	25	yes	yes
107	1	15	5	25	yes	yes
114	1	50	5	25	yes	yes
121	3	15	5	25	yes	yes
128	3	50	5	25	yes	yes
135	6	15	5	25	yes	yes
142	6	50	5	25	yes	yes

For these cases the following graphs are shown:

- phase to phase voltages at reactor bus
- phase voltages at reactor bus
- voltages over the breaker poles
- reactor start point voltage
- overvoltage frequency measurement.

A1.1 Case 10 Reactor 1 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 10 A

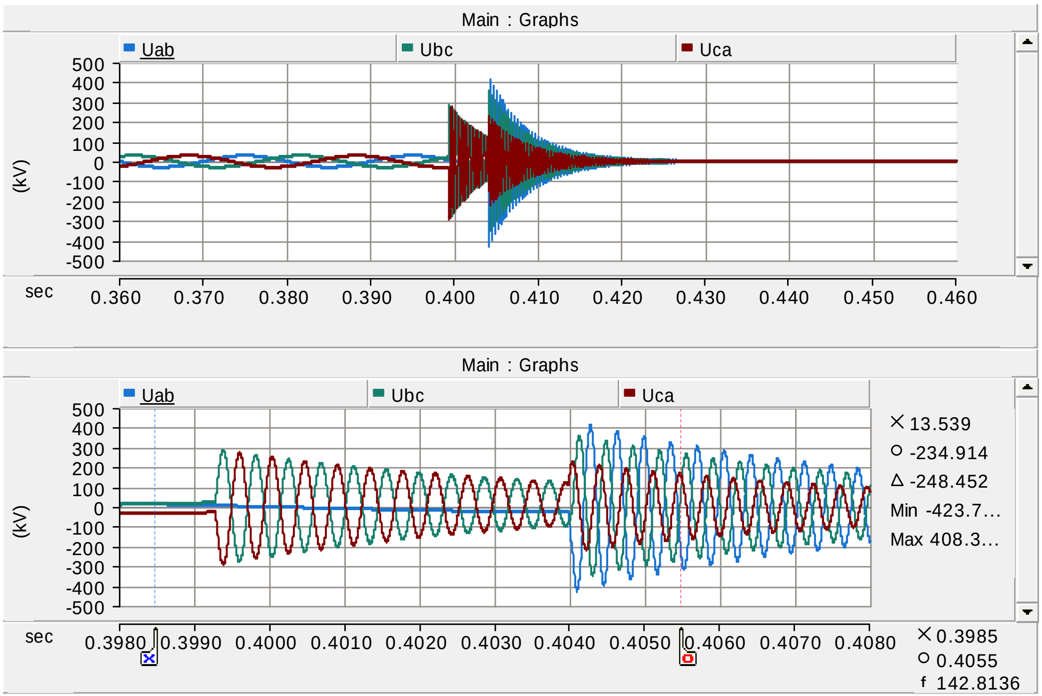

Figure 35. Reactor bus phase to phase voltages on case 10.

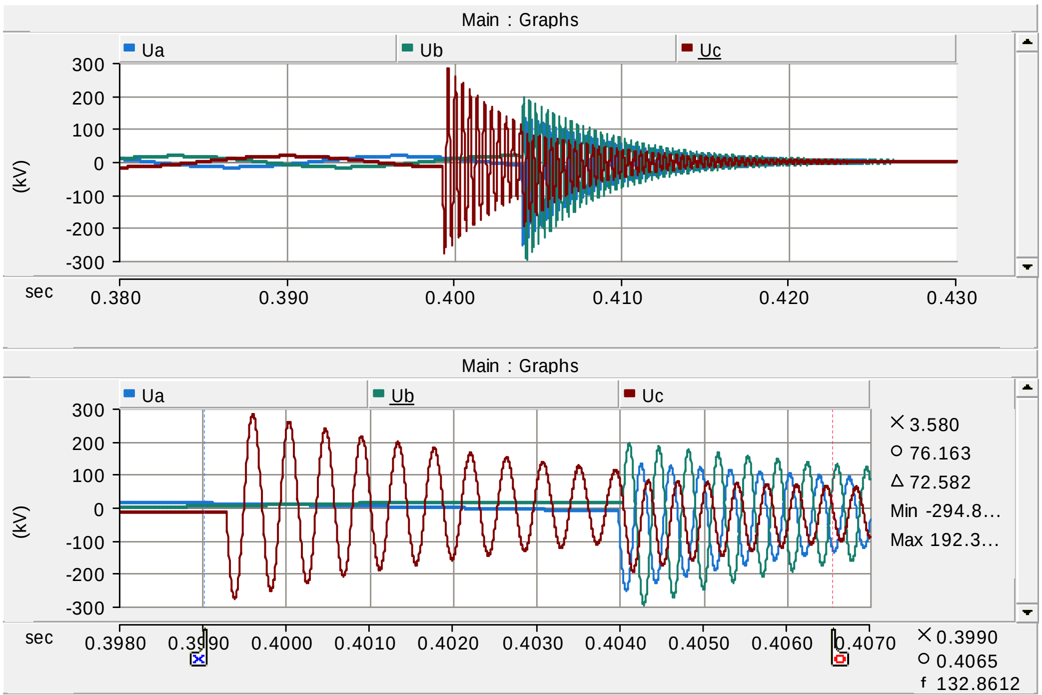

Figure 36. Reactor bus phase voltages on case 10.

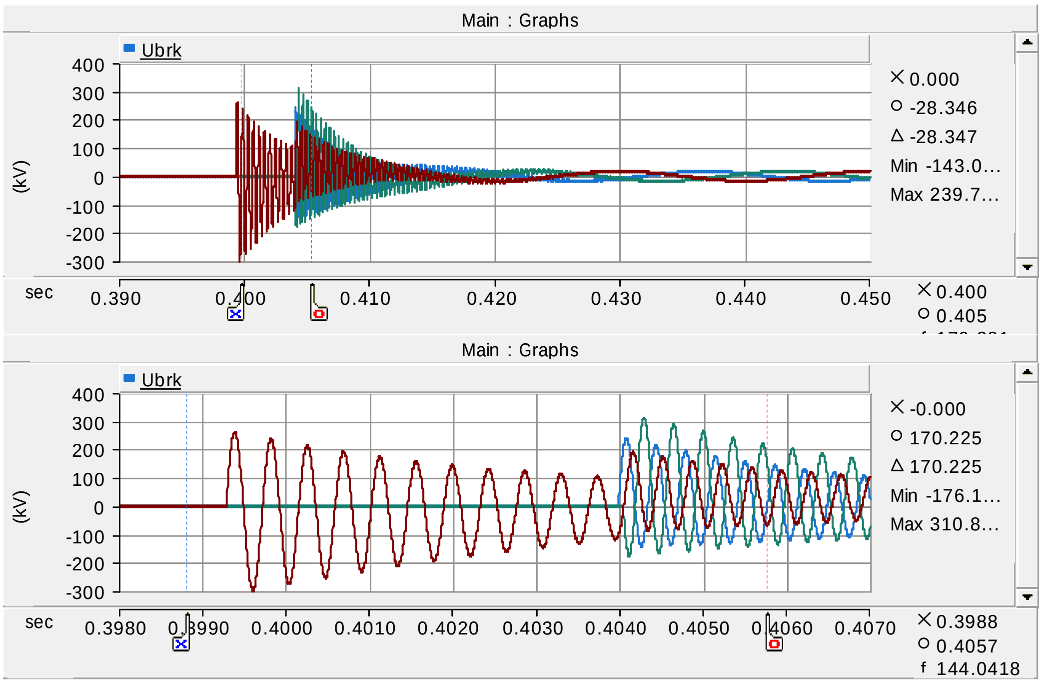

Figure 37. Breaker voltages before cable and reactor on case 10.

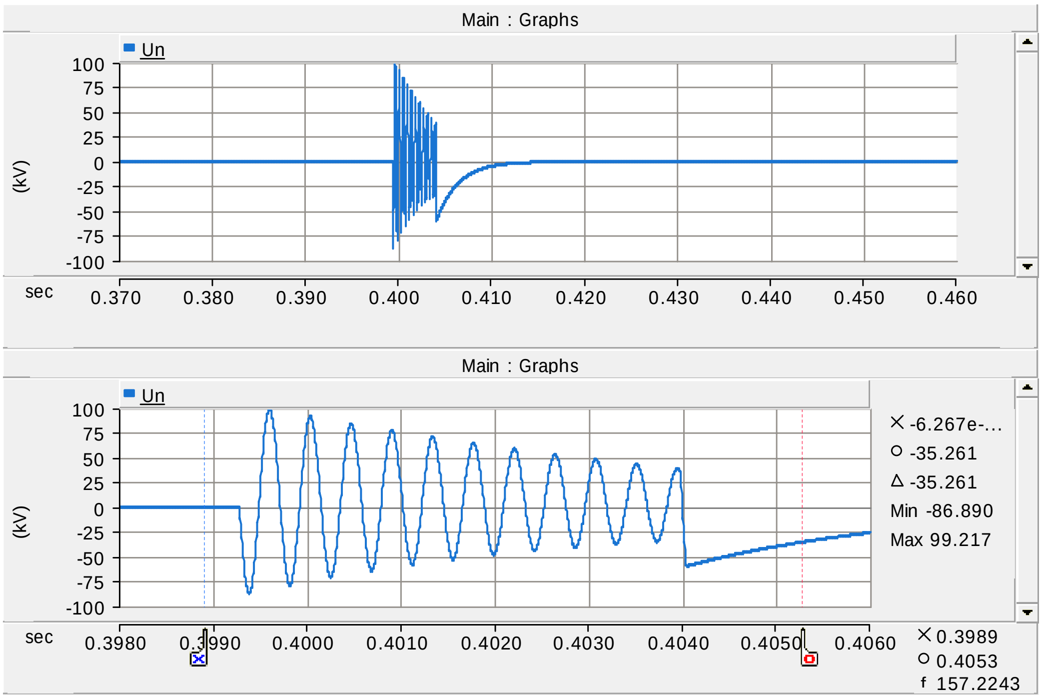

Figure 38. Reactor star point voltage on case 10.

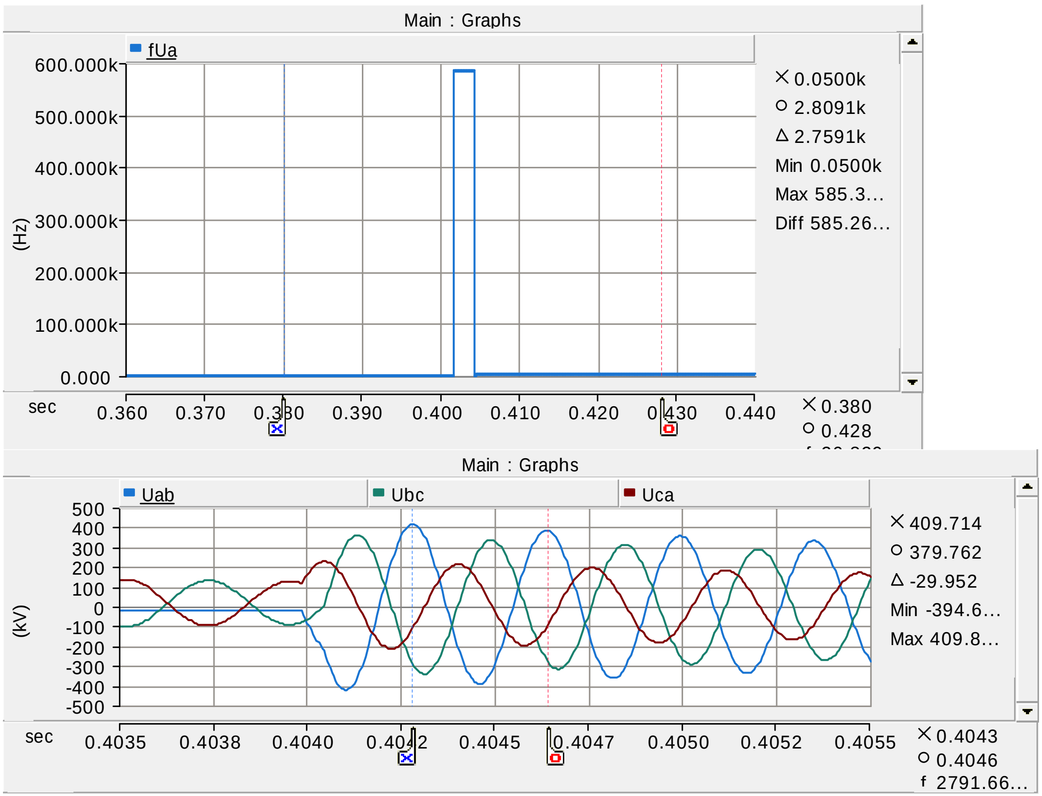

Figure 39. Ua phase Frequency on case 10.

A1.2 Case 20 Reactor 1 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 10 A

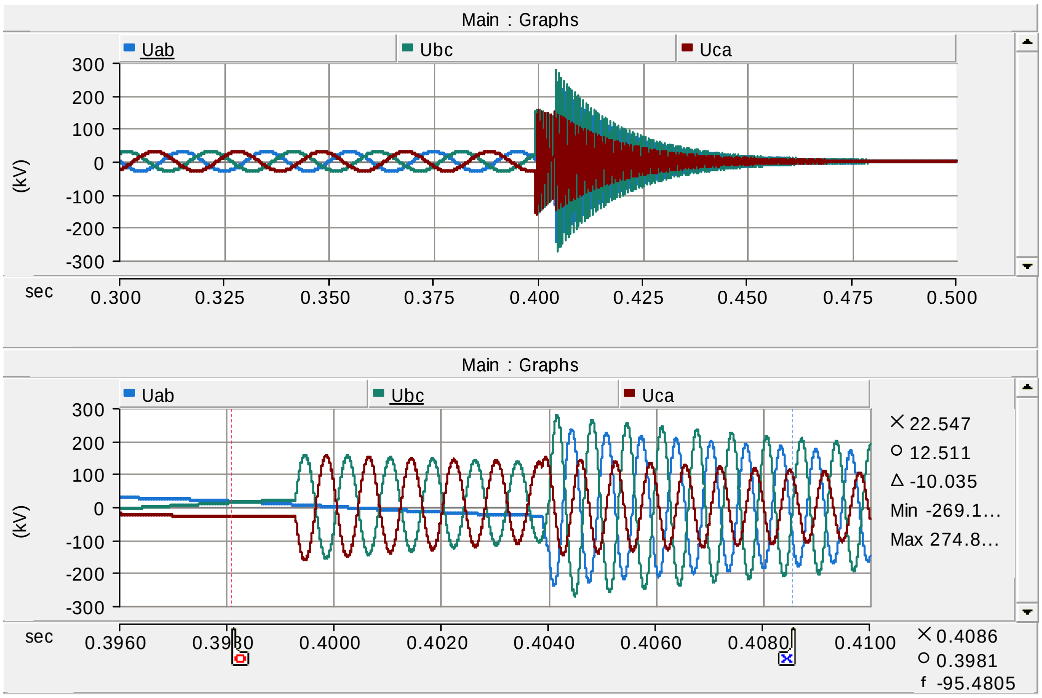

Figure 40. Reactor bus phase to phase voltages on case 20.

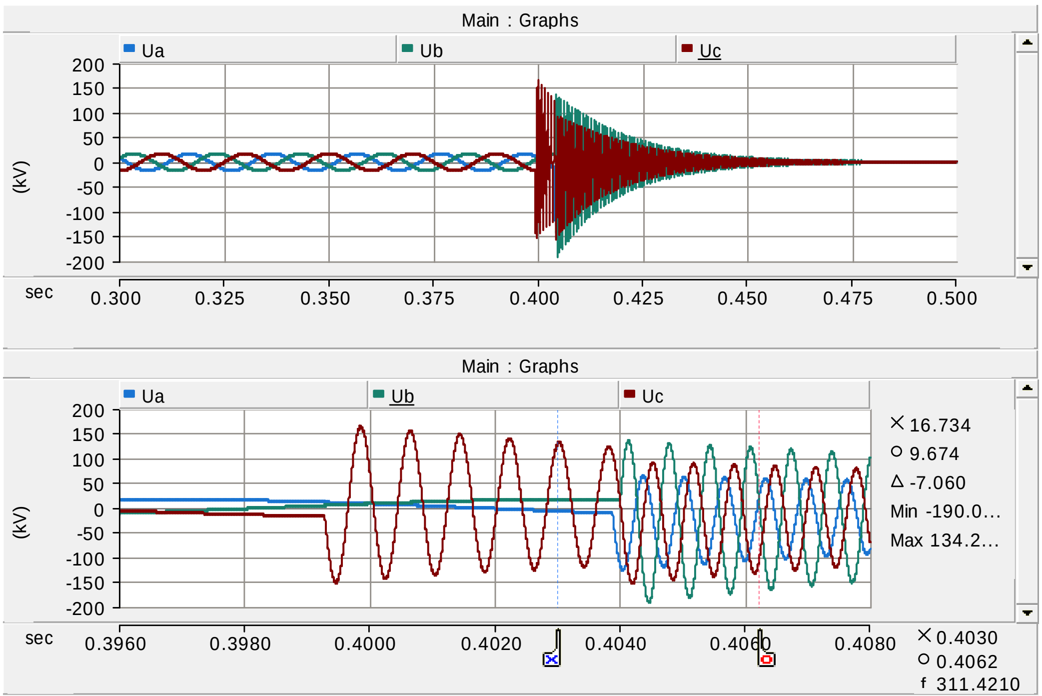

Figure 41. Reactor bus phase voltages on case 20.

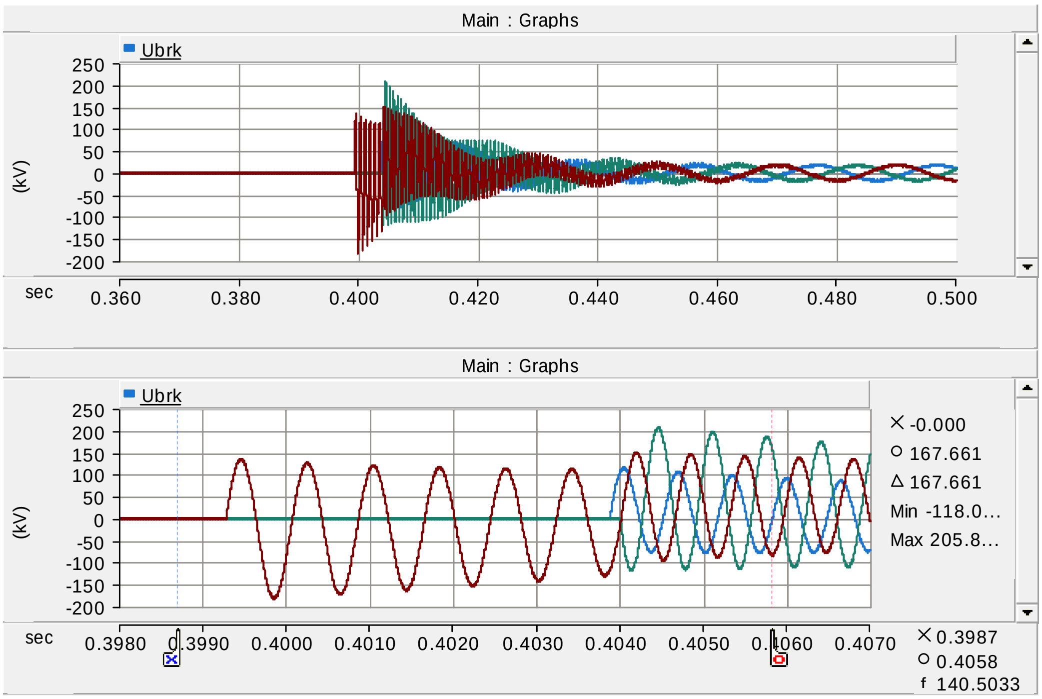

Figure 42. Breaker voltages before cable and reactor on case 20.

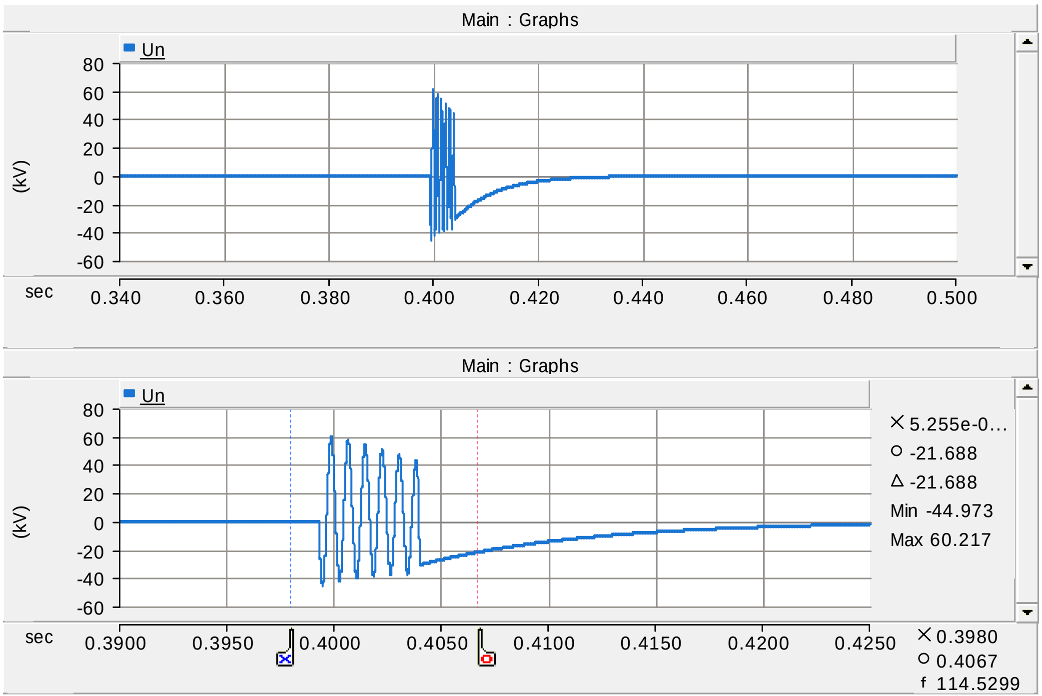

Figure 43. Reactor star point voltage on case 20.

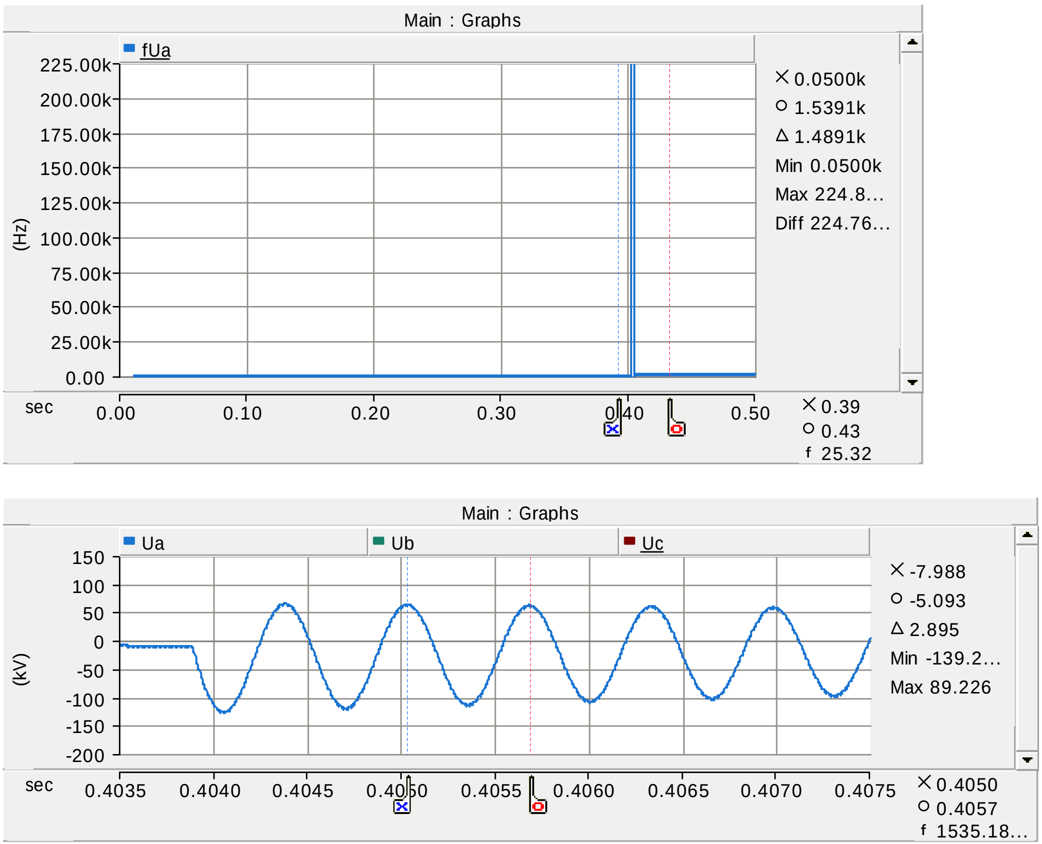

Figure 44. Ua phase Frequency on case 20.

A1.3 Case 25 Reactor 1 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 10 A with surge arrester

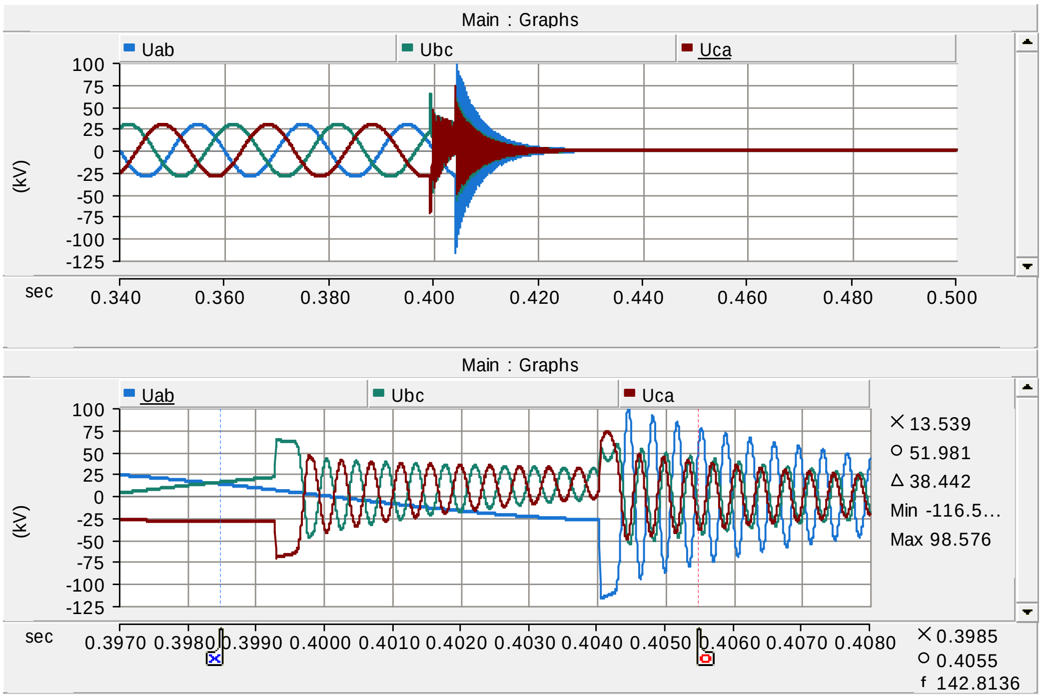

Figure 45. Reactor bus phase to phase voltages on case 25.

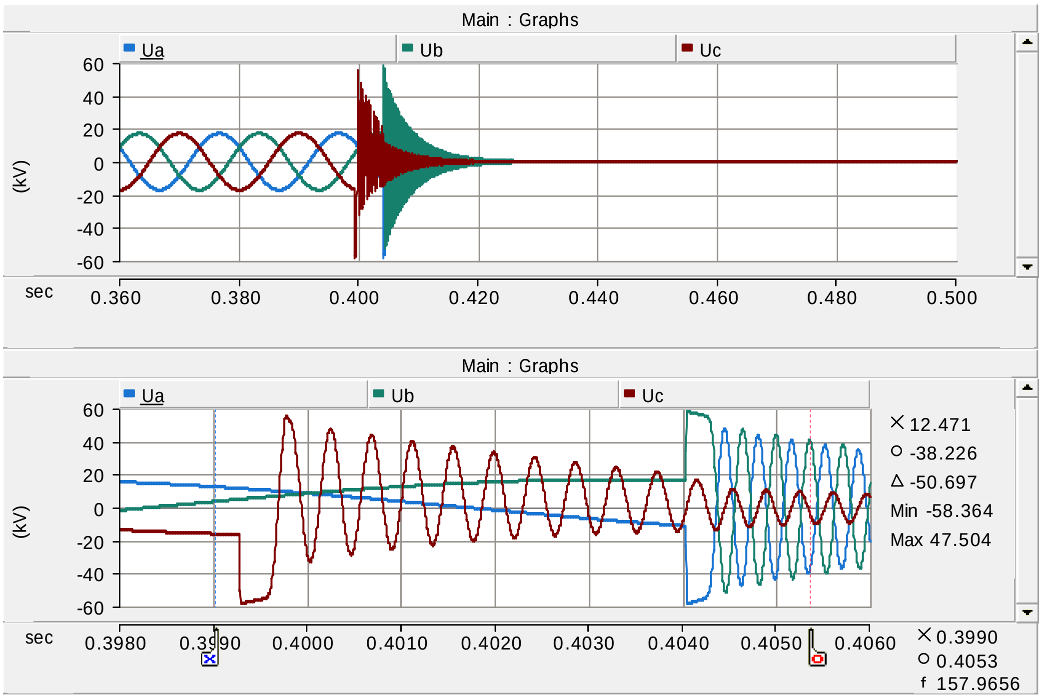

Figure 46. Reactor bus phase voltages on case 25.

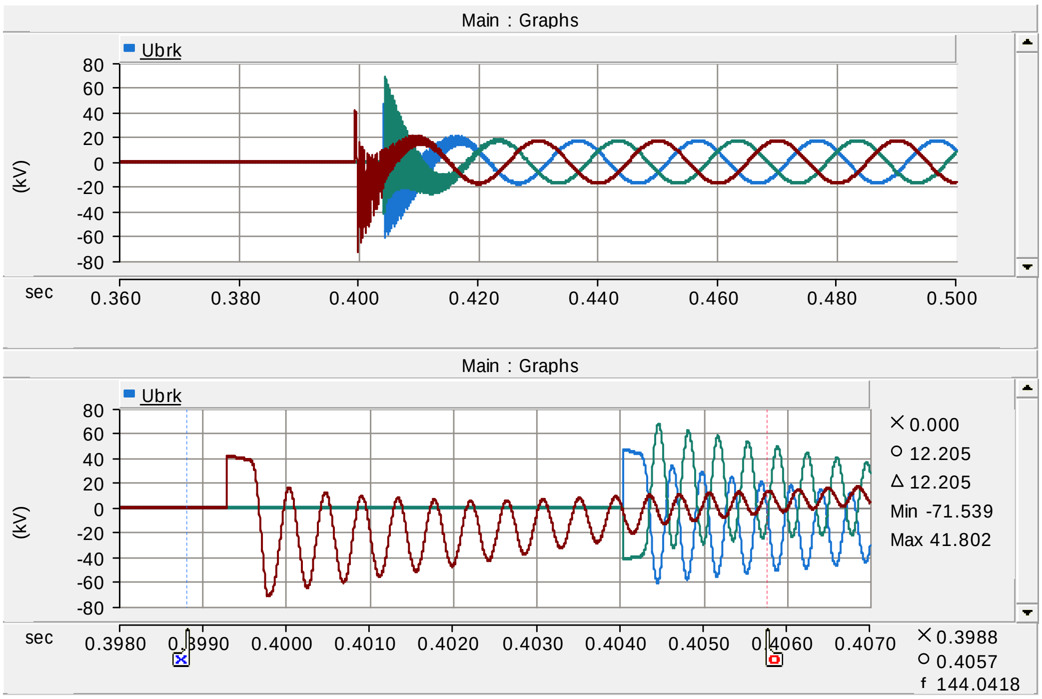

Figure 47. Breaker voltages before cable and reactor on case 25.

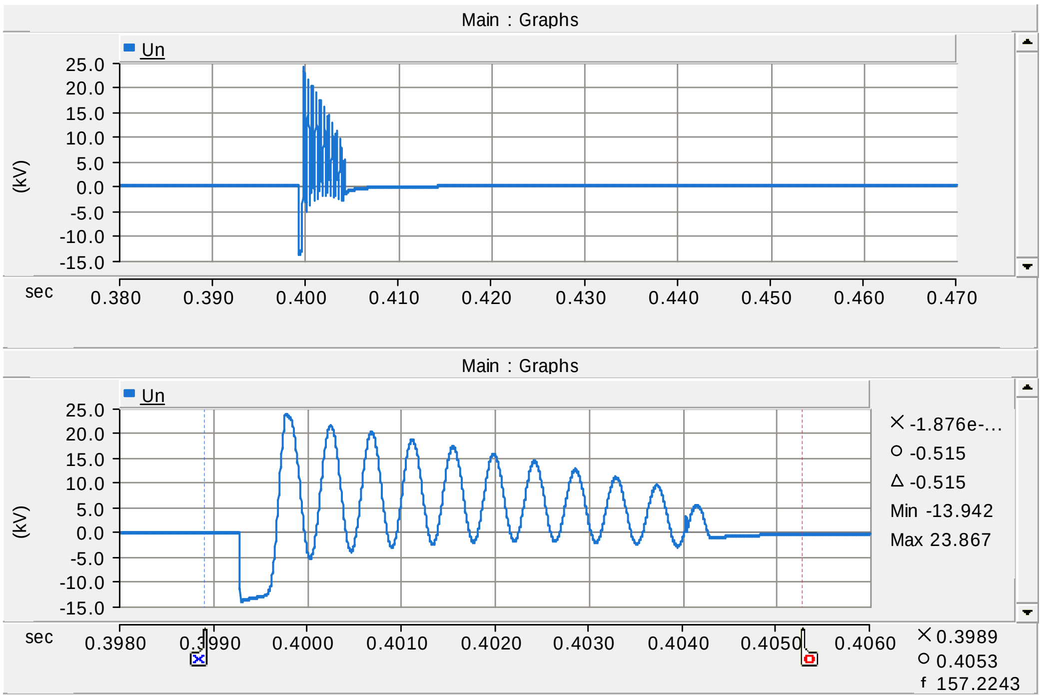

Figure 48. Reactor star point voltage on case 25.

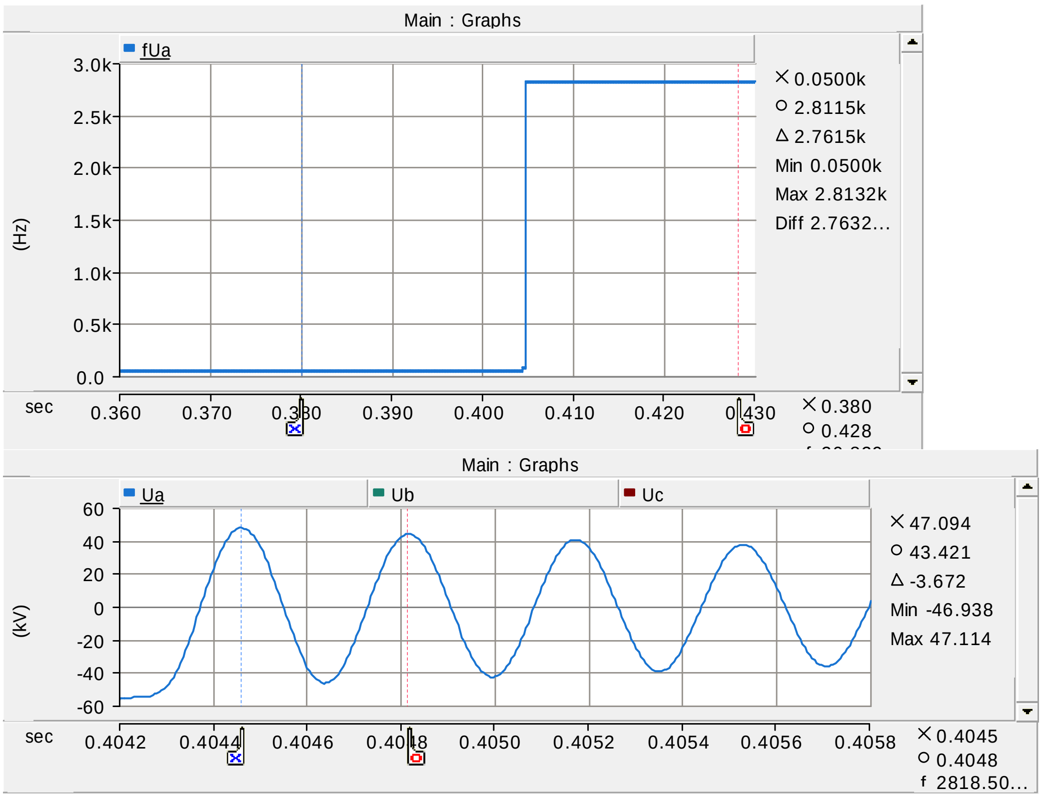

Figure 49. Ua phase Frequency on case 25.

A1.4 Case 32 Reactor 1 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 10 A with surge arrester

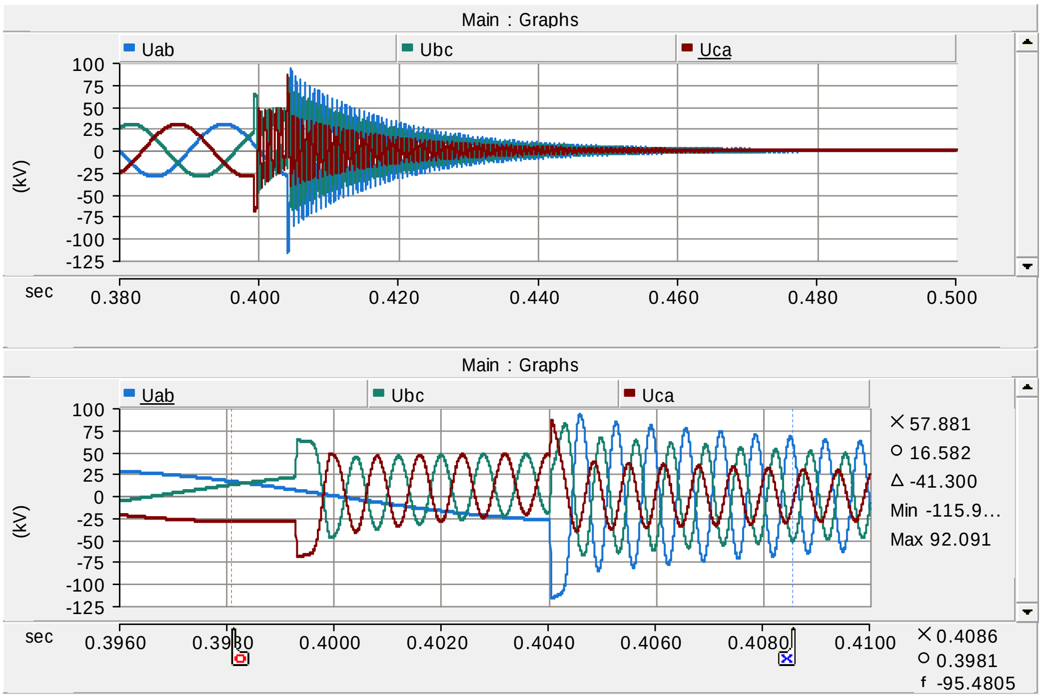

Figure 50. Reactor bus phase to phase voltages on case 32.

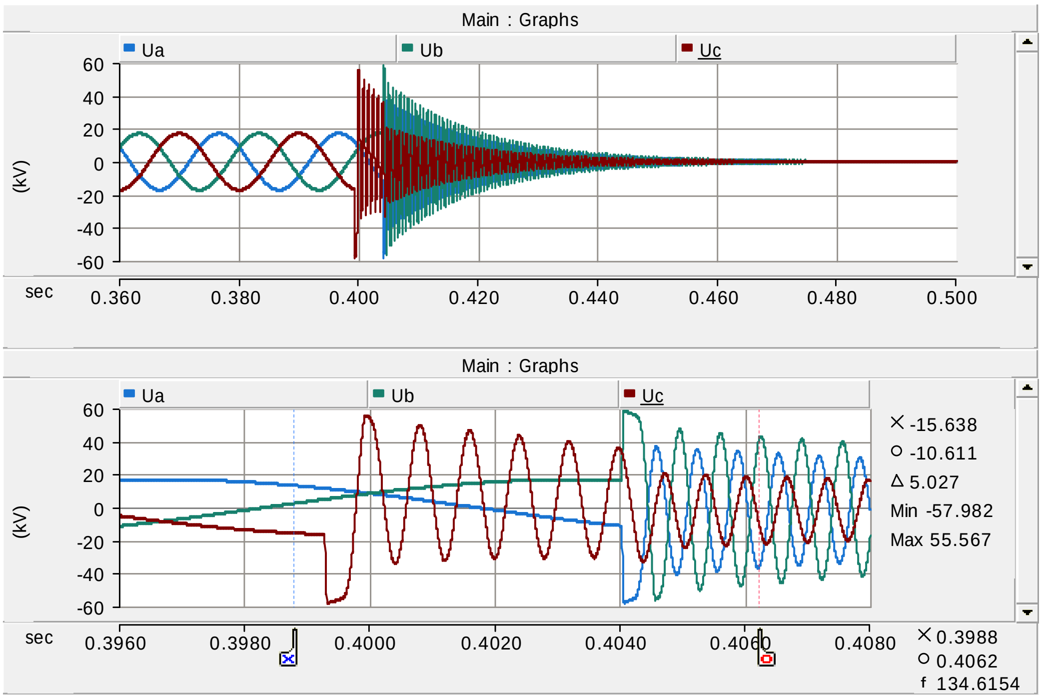

Figure 51. Reactor bus phase voltages on case 32.

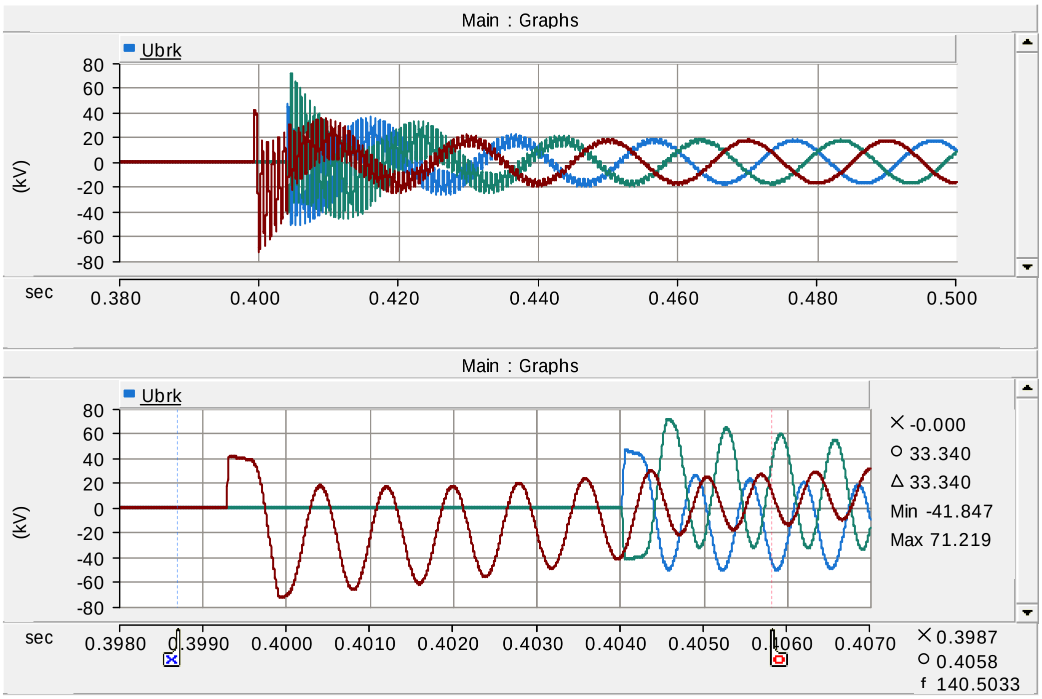

Figure 52. Breaker voltages before cable and reactor on case 32.

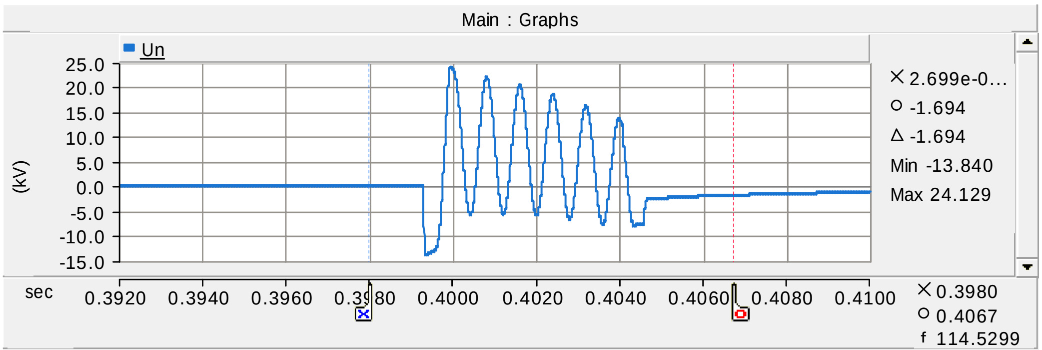

Figure 53. Reactor star point voltage on case 32.

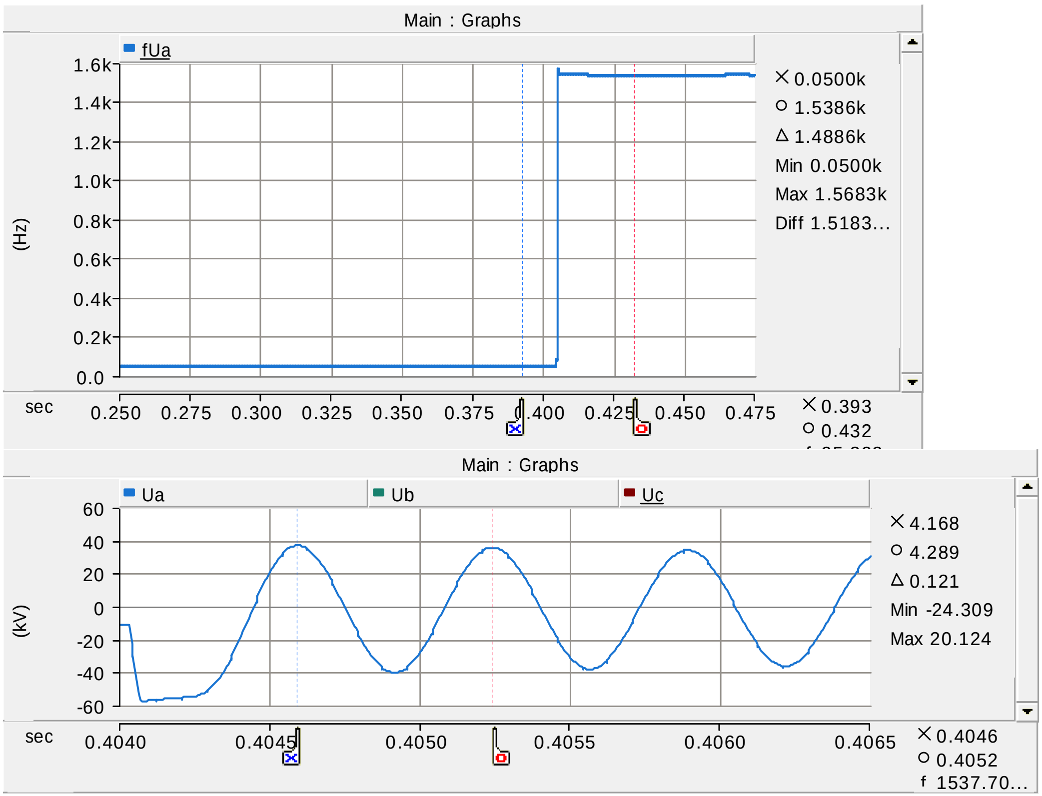

Figure 54. Ua phase Frequency on case 32.

A1.5 Case 44 Reactor 3 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 10 A

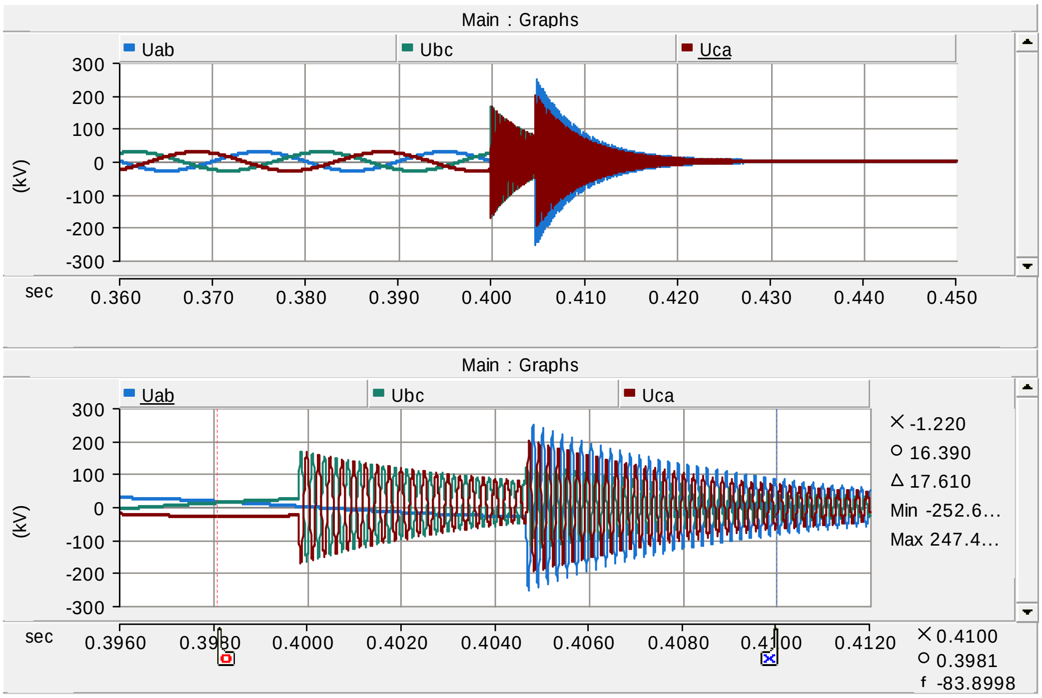

Figure 55. Reactor bus phase to phase voltages on case 44.

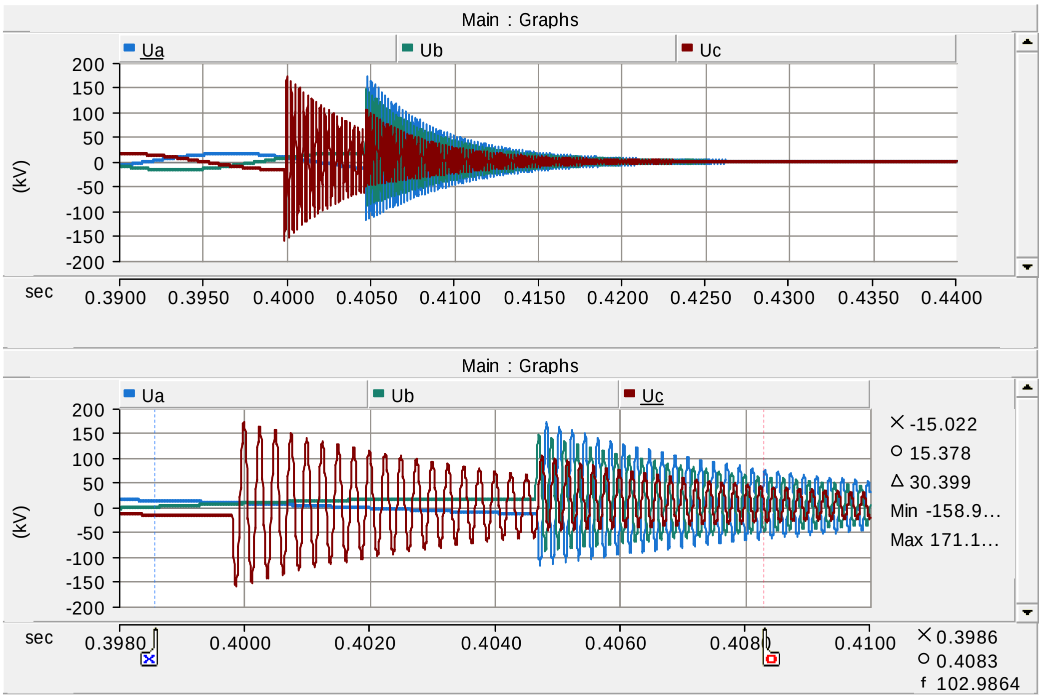

Figure 56. Reactor bus phase voltages on case 44.

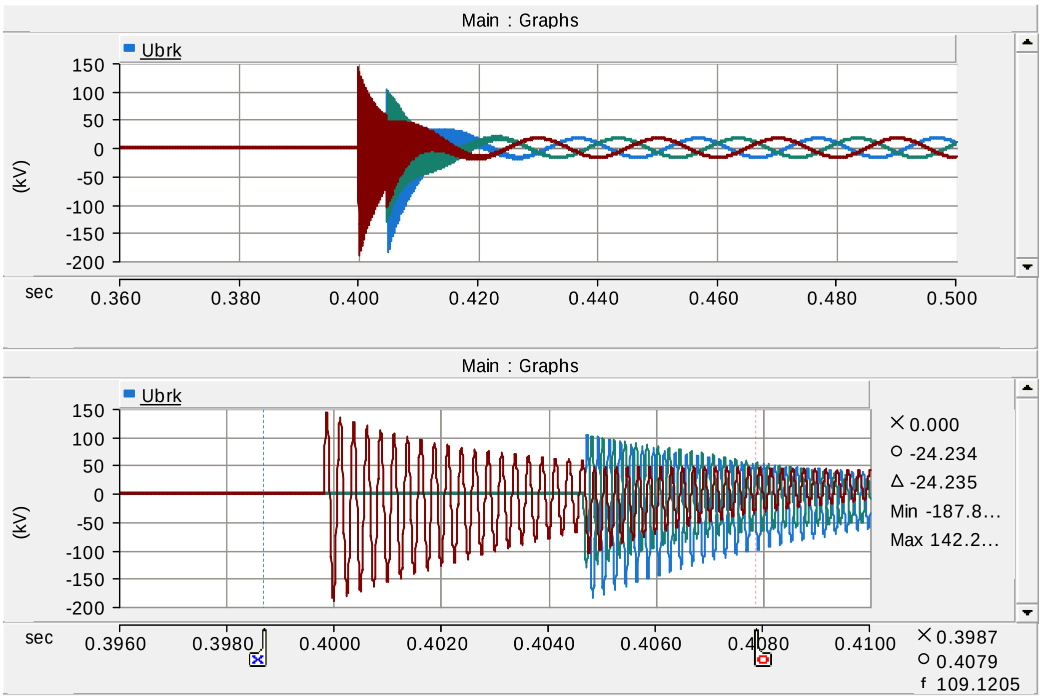

Figure 57. Breaker voltages before cable and reactor on case 44.

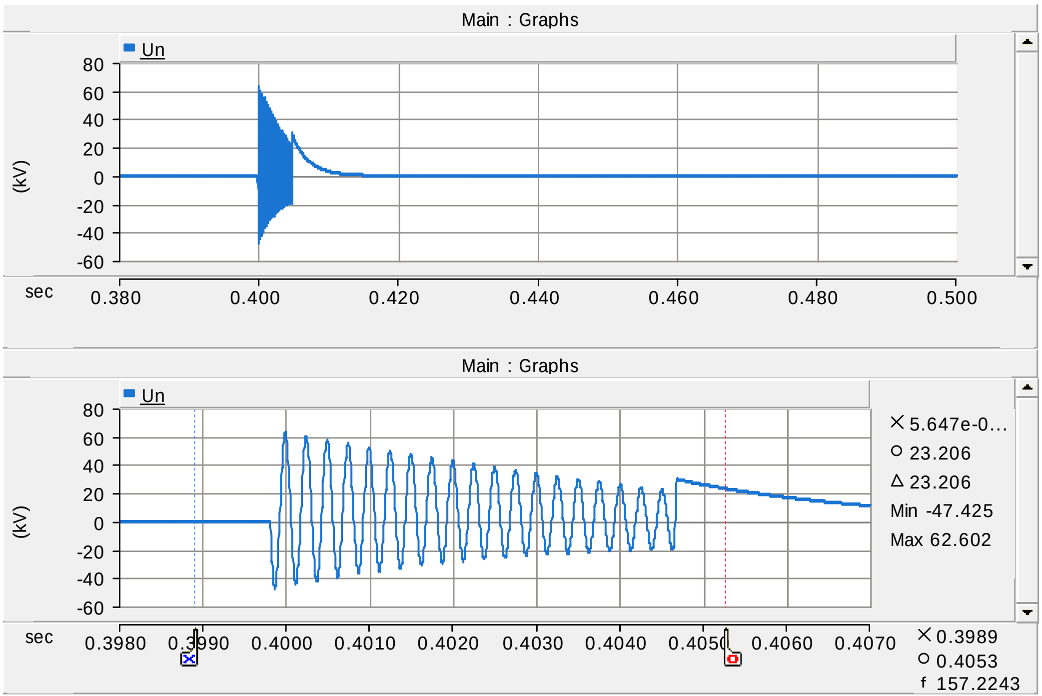

Figure 58. Reactor star point voltage on case 44.

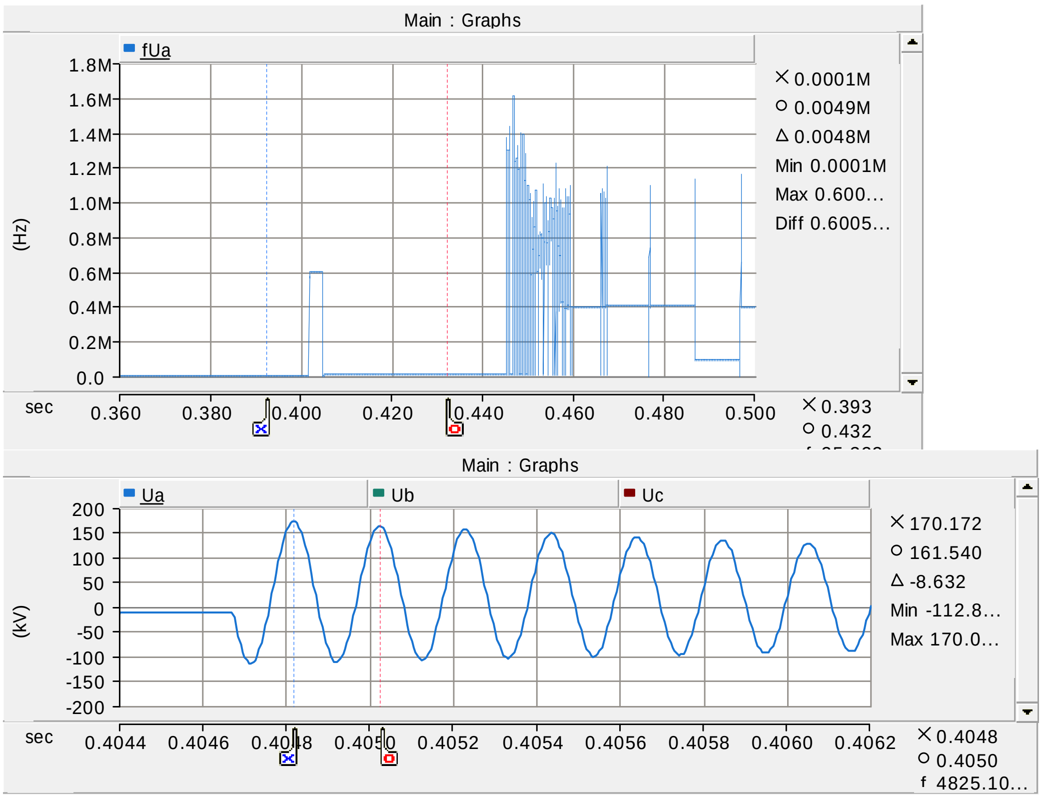

Figure 59. Ua phase Frequency on case 44.

A1.6 Case 54 Reactor 3 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 10 A

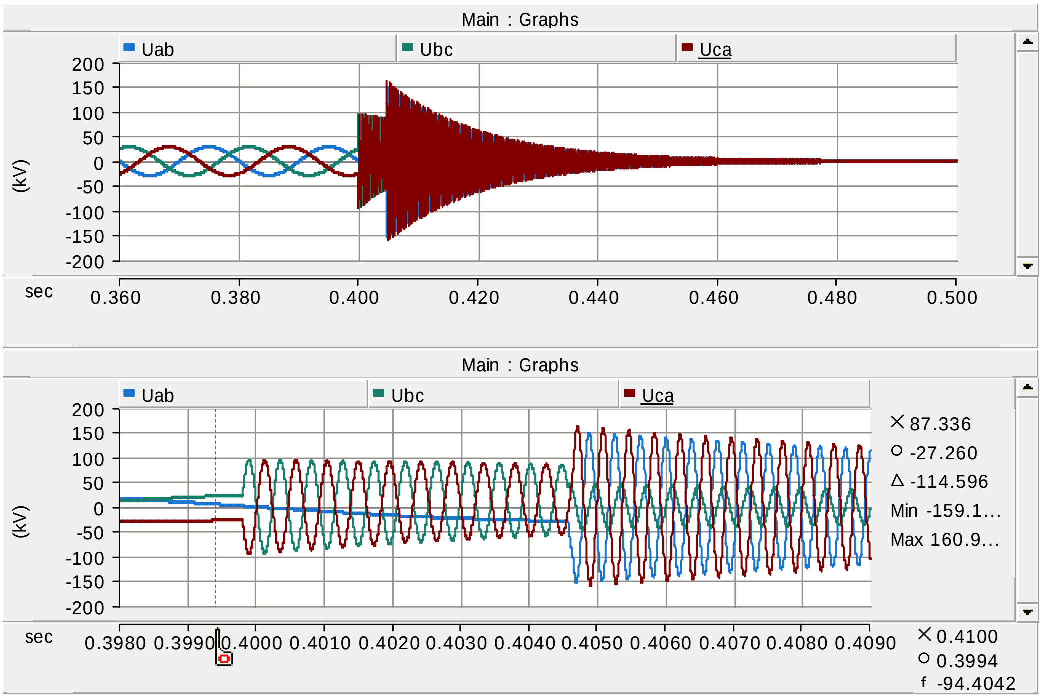

Figure 60. Reactor bus phase to phase voltages on case 54.

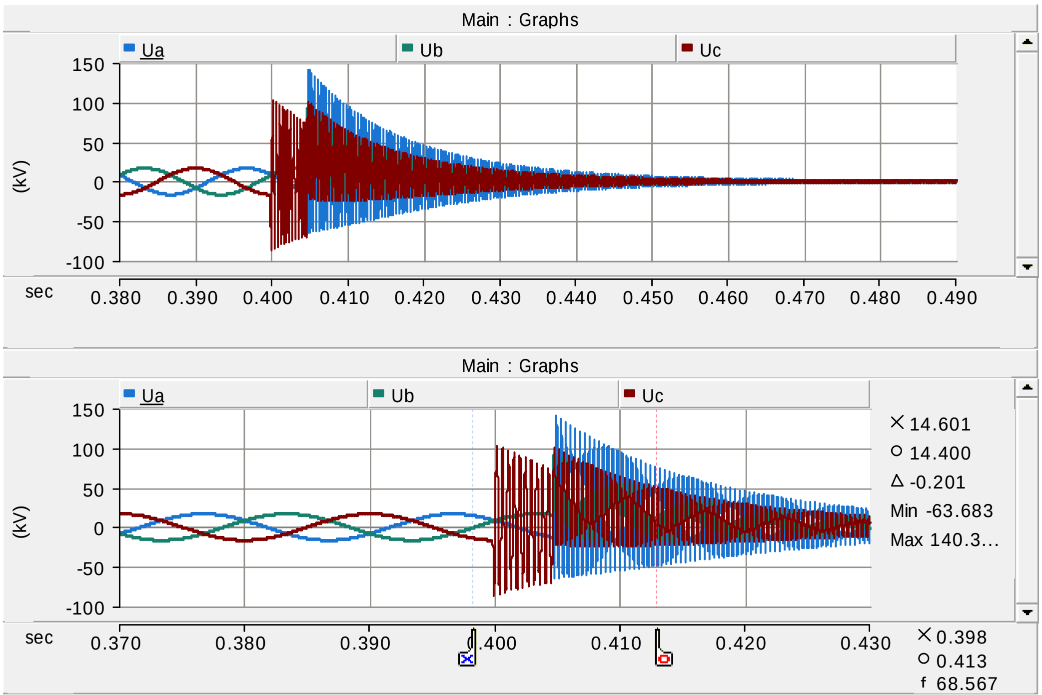

Figure 61. Reactor bus phase voltages on case 54.

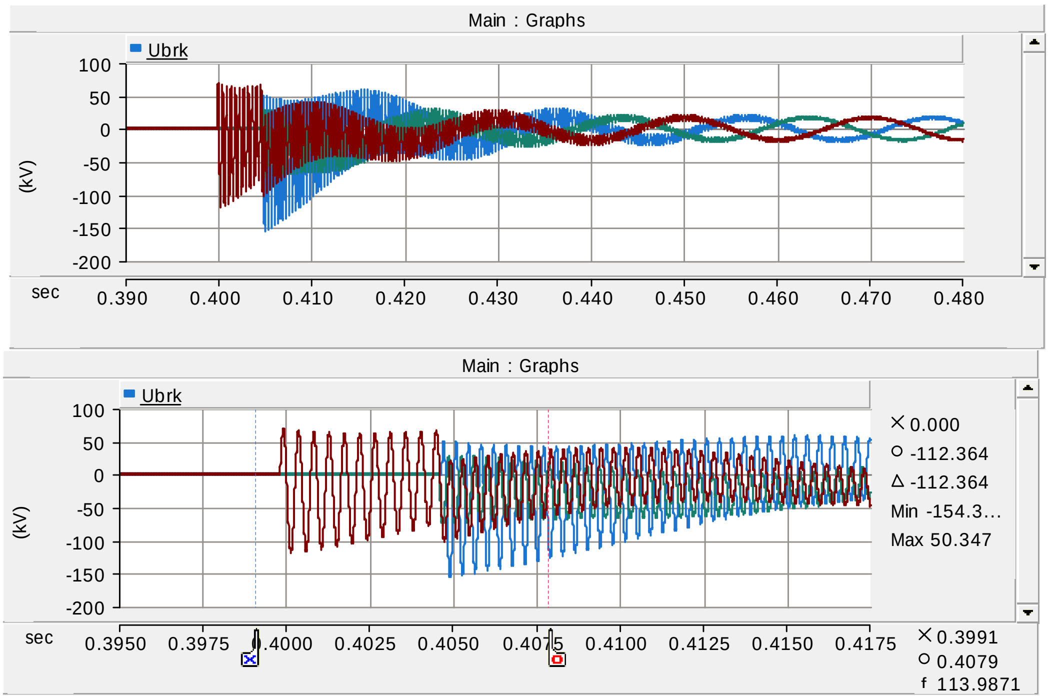

Figure 62. Breaker voltages before cable and reactor on case 54.

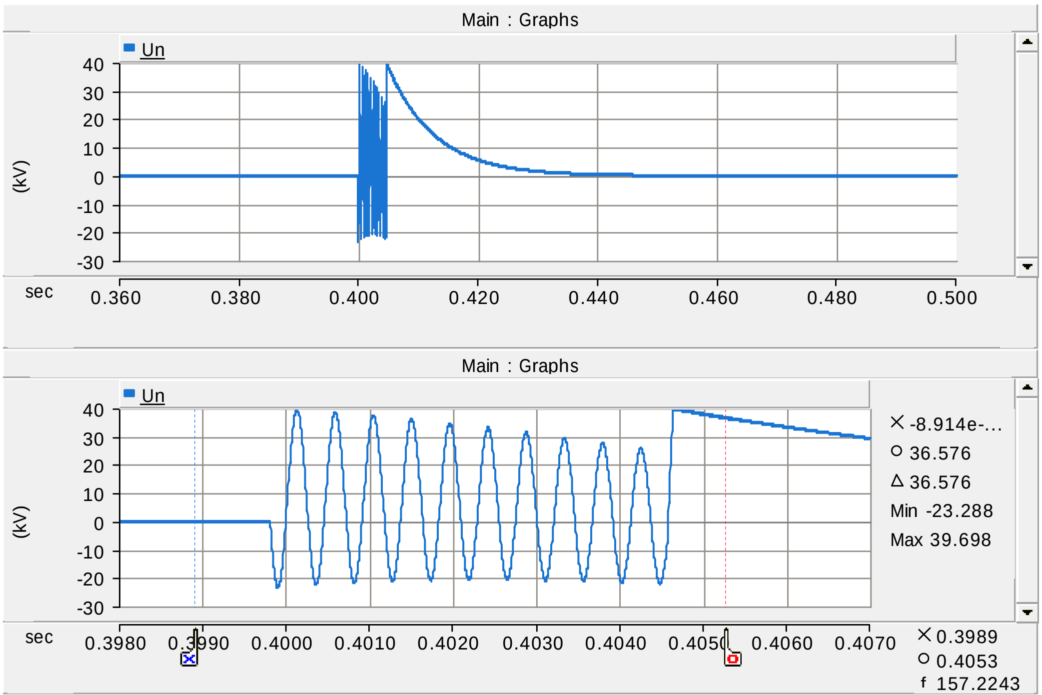

Figure 63. Reactor star point voltage on case 54.

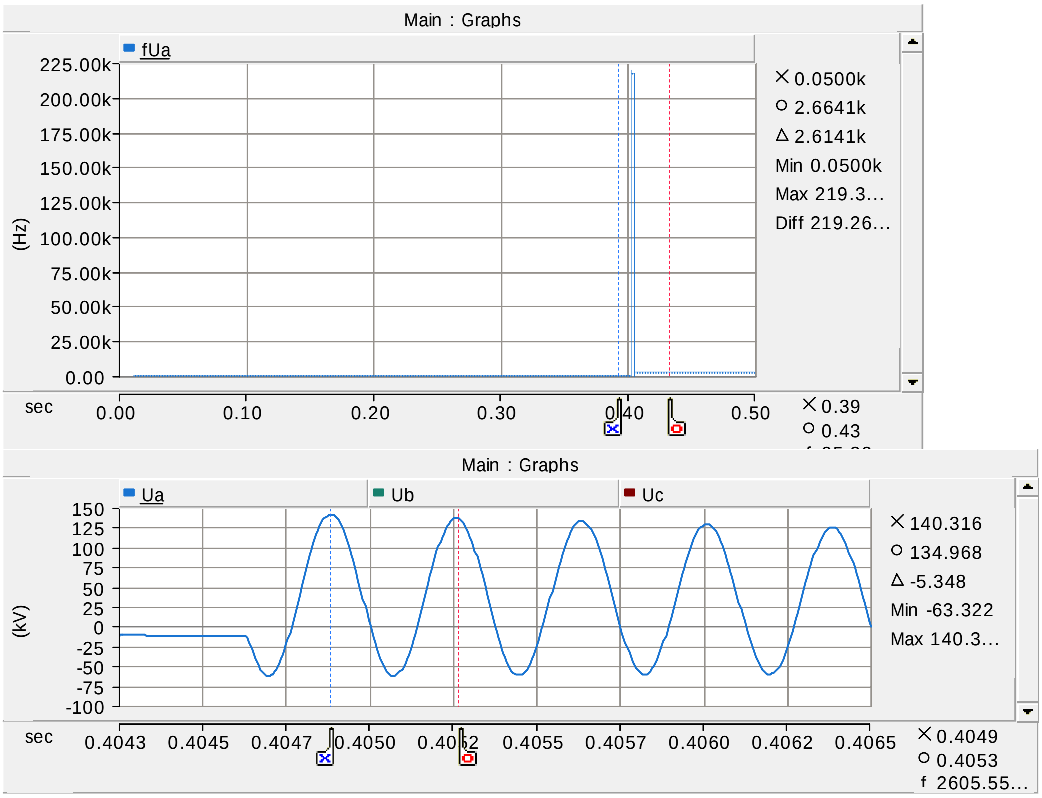

Figure 64. Ua phase Frequency on case 54.

A1.7 Case 59 Reactor 3 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 10 A with surge arrester

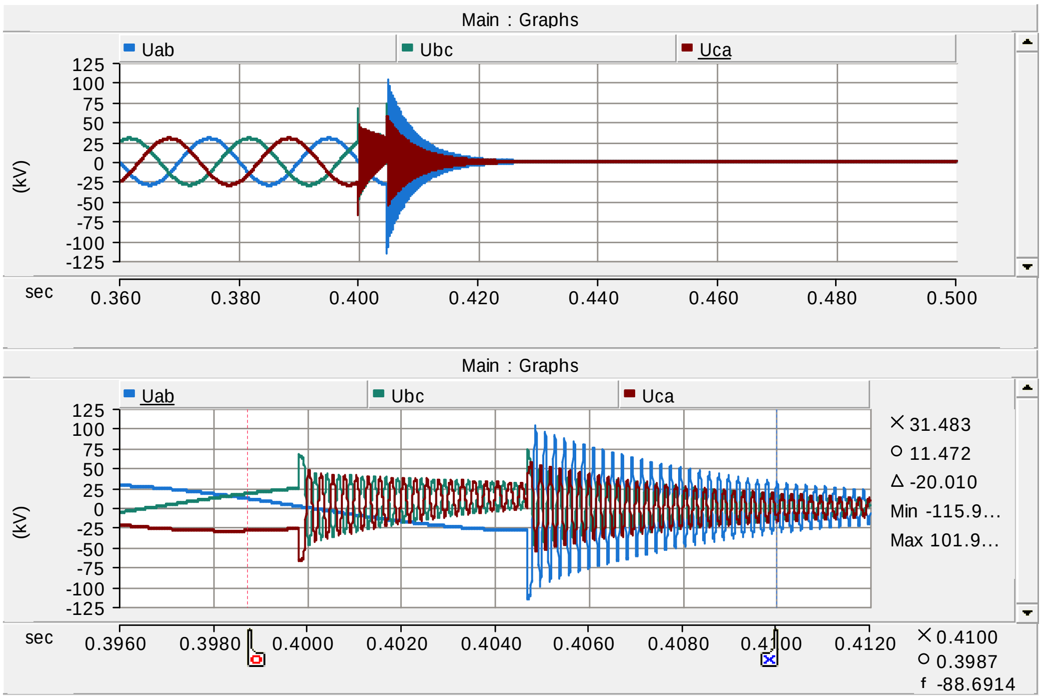

Figure 65. Reactor bus phase to phase voltages on case 59.

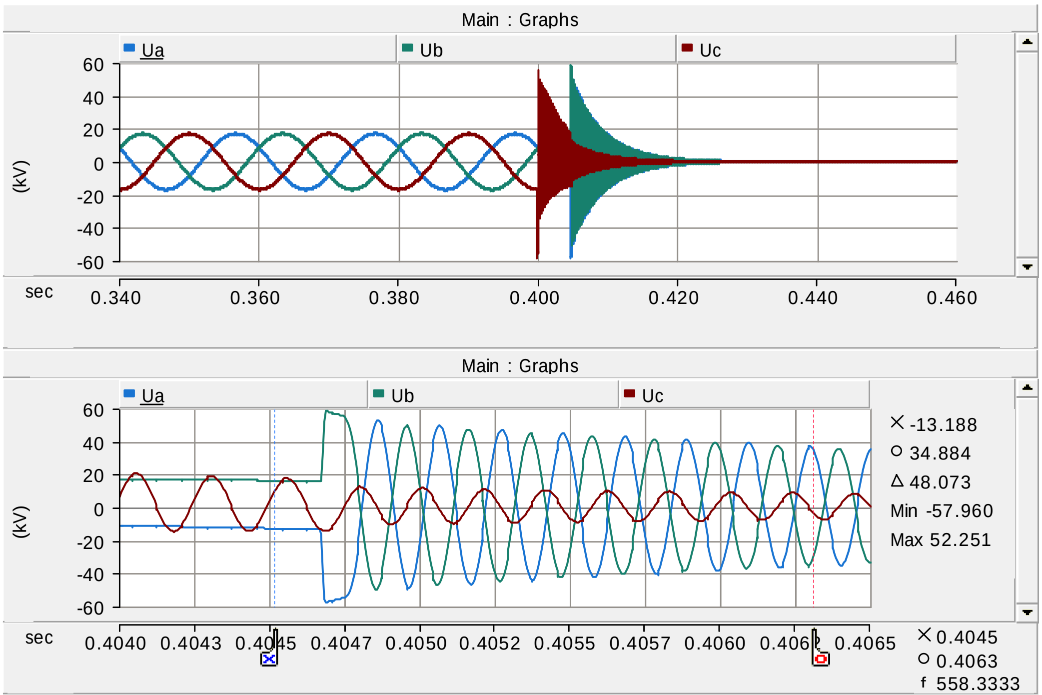

Figure 66. Reactor bus phase voltages on case 59.

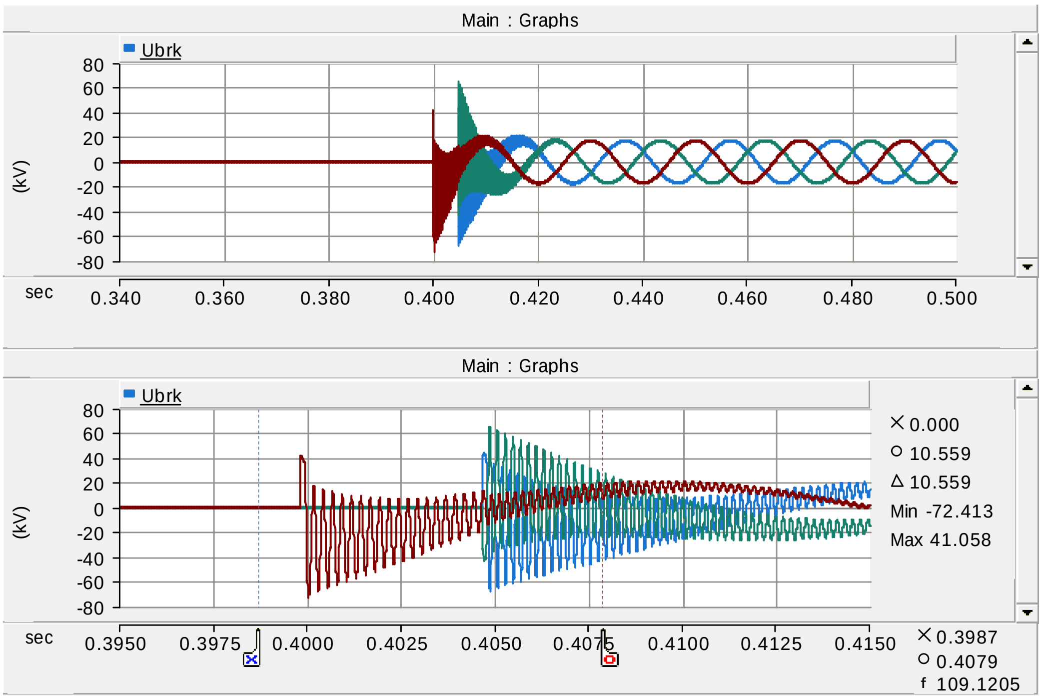

Figure 67. Breaker voltages before cable and reactor on case 59.

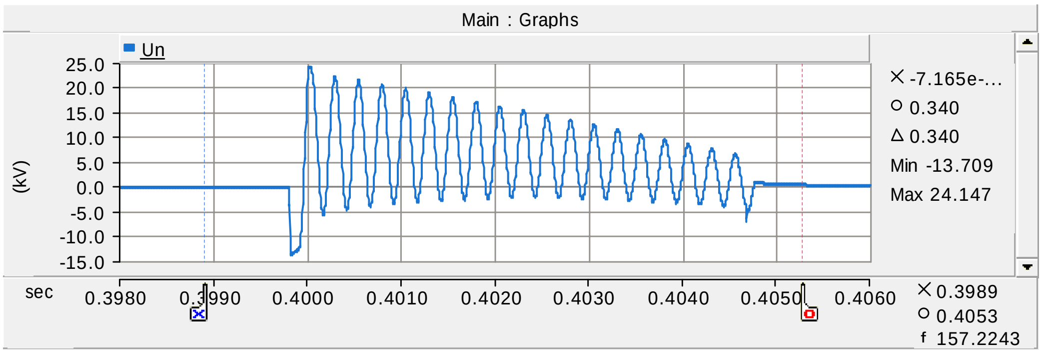

Figure 68. Reactor star point voltage on case 59.

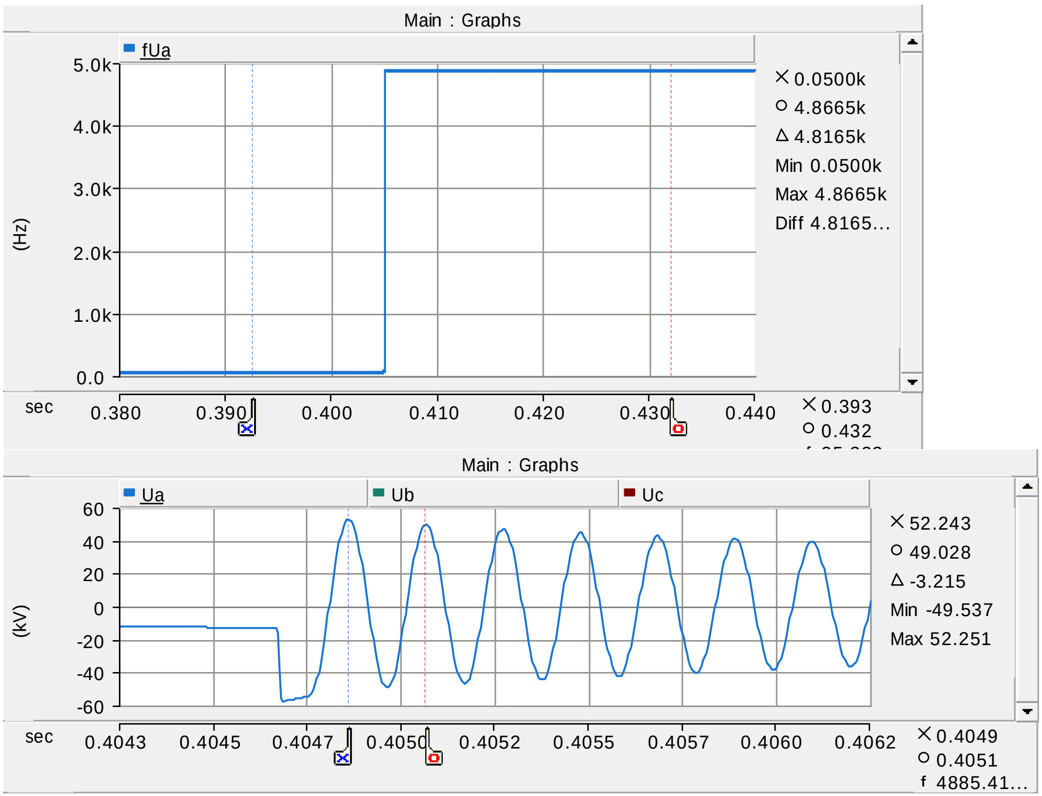

Figure 69. Ua phase Frequency on case 59.

A1.8 Case 66 Reactor 3 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 10 A with surge arrester

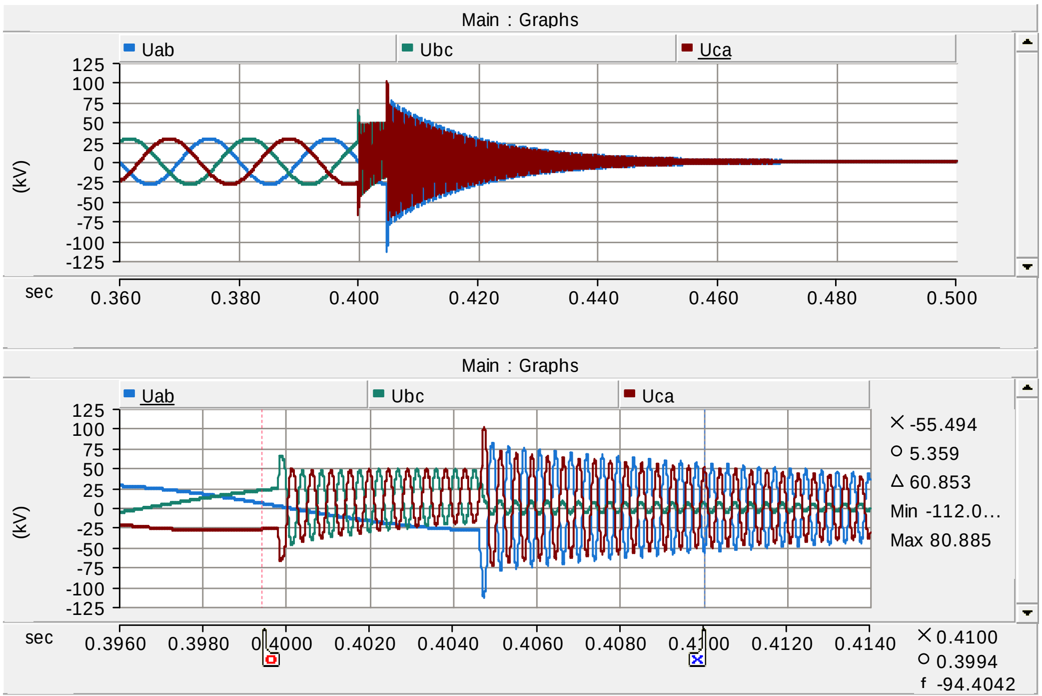

Figure 70. Reactor bus phase to phase voltages on case 66.

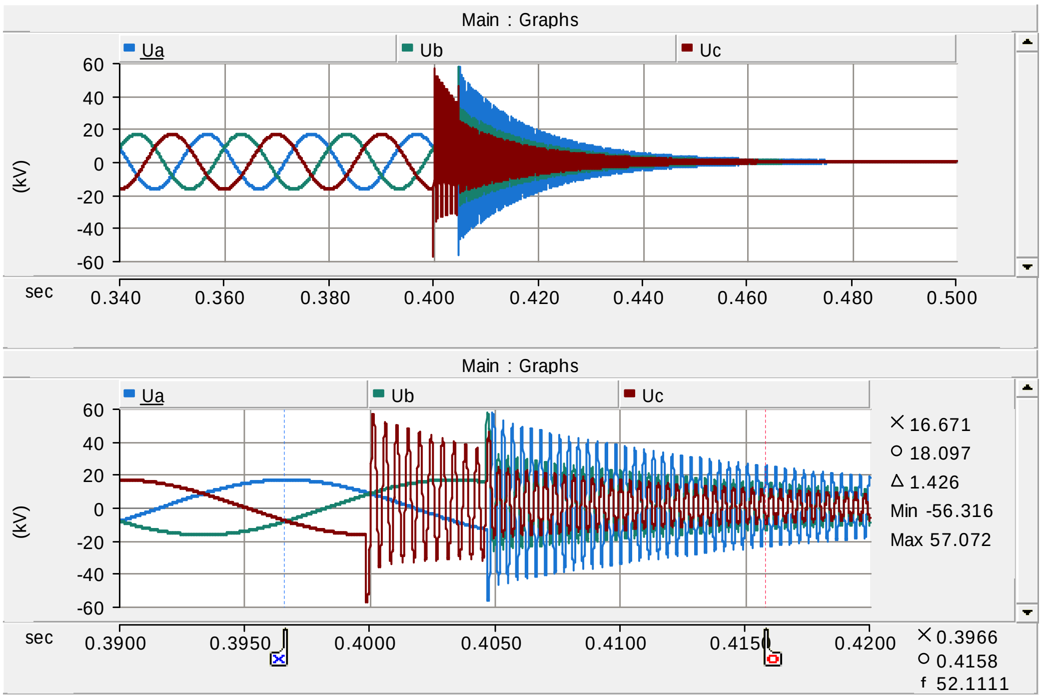

Figure 71. Reactor bus phase voltages on case 66.

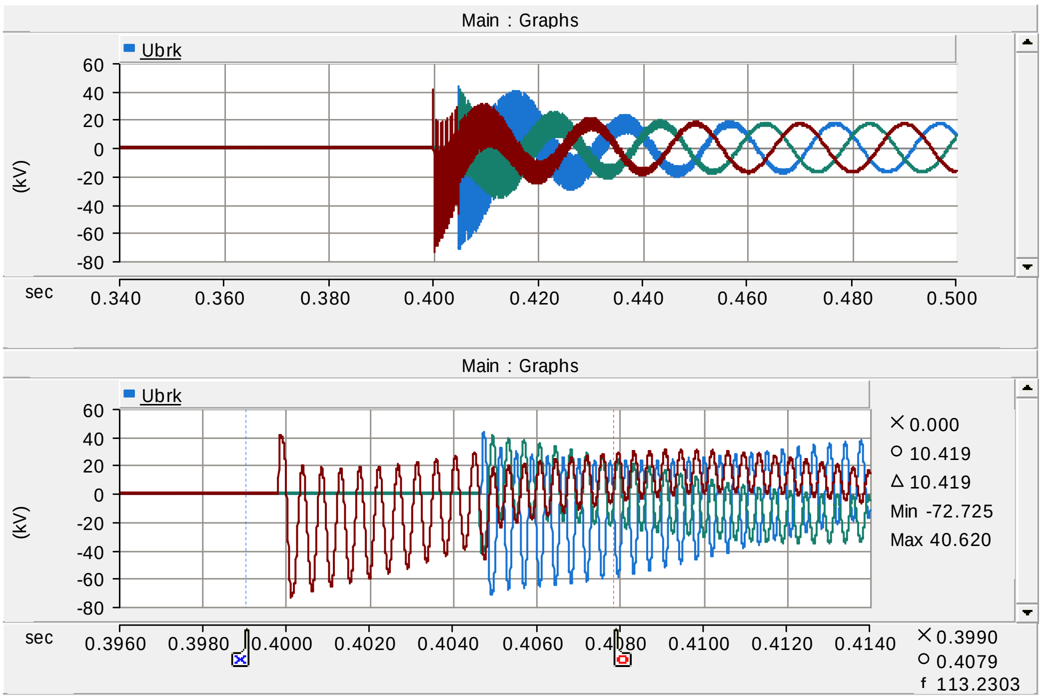

Figure 72. Breaker voltages before cable and reactor on case 66.

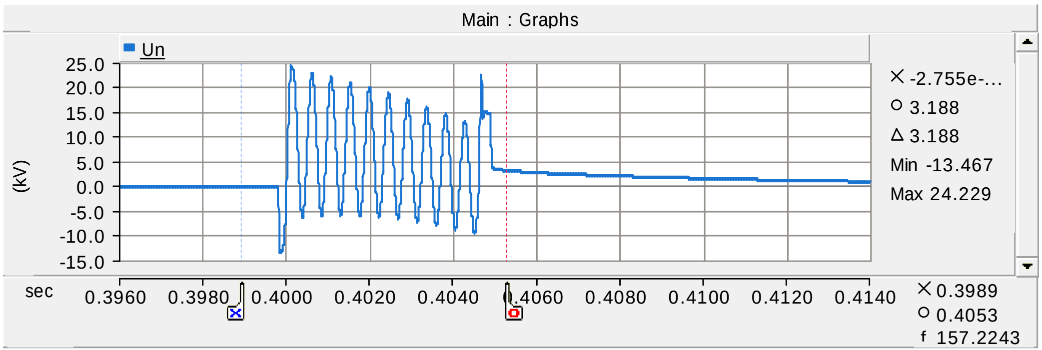

Figure 73. Reactor star point voltage on case 66.

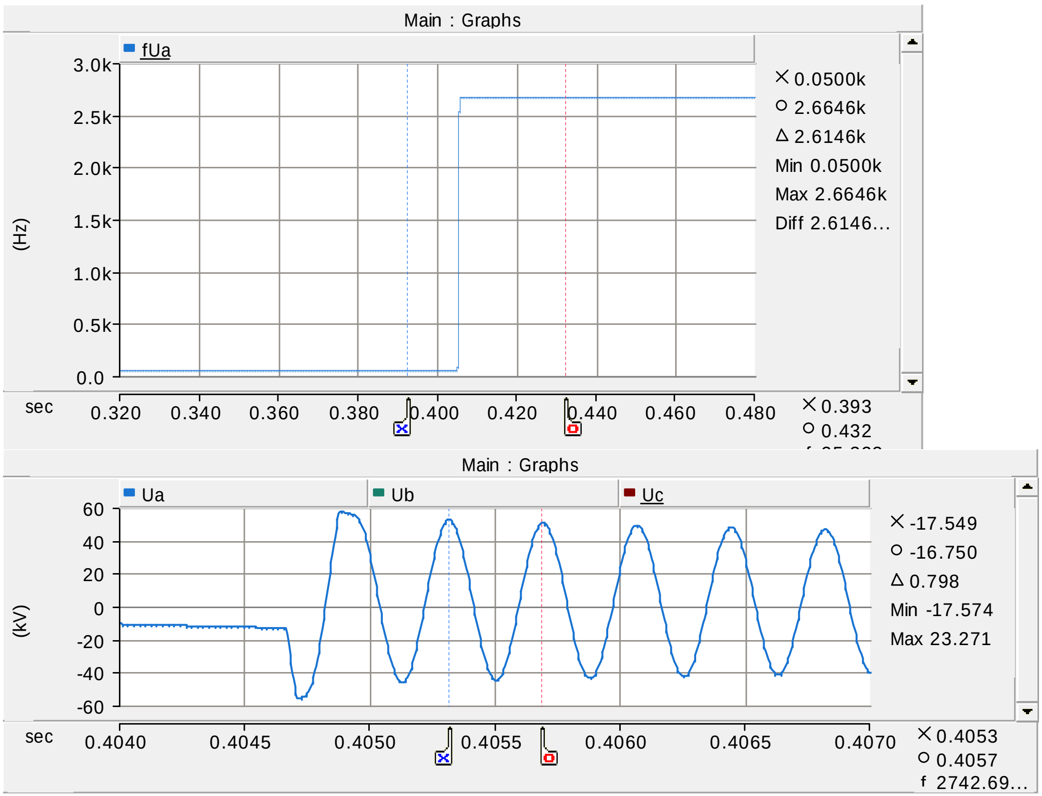

Figure 74. Ua phase Frequency on case 66.

A1.9 Case 78 Reactor 6 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 10 A

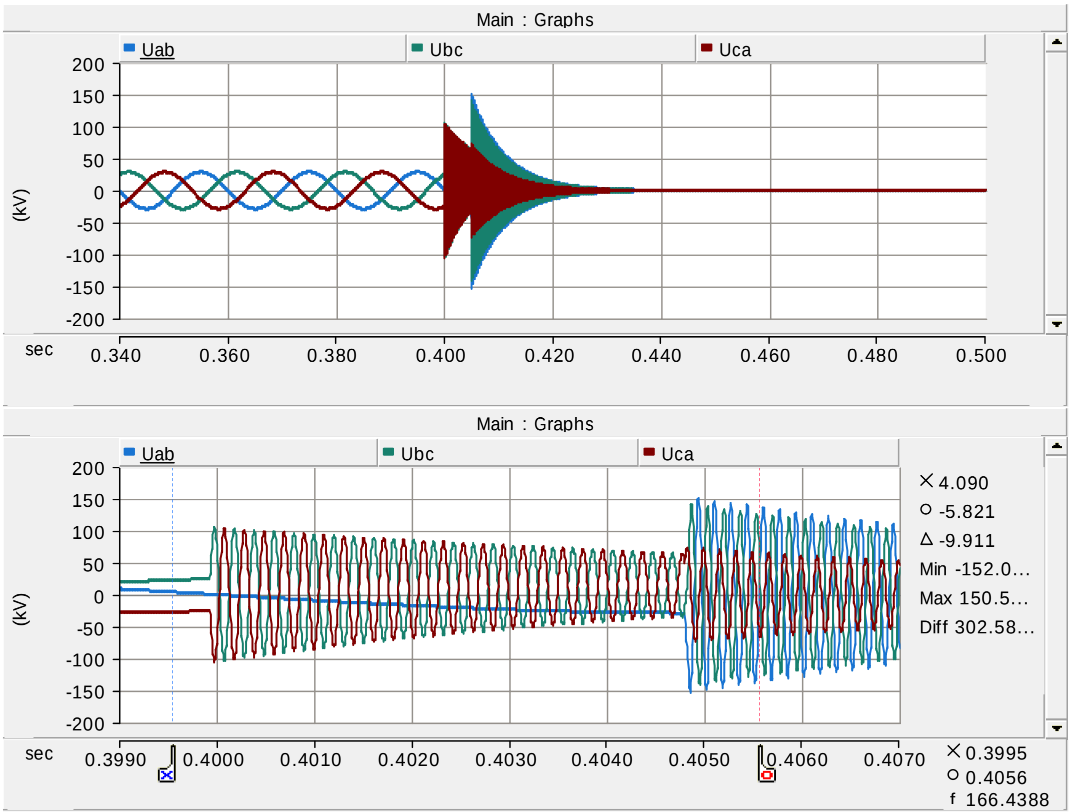

Figure 75. Reactor bus phase to phase voltages on case 78.

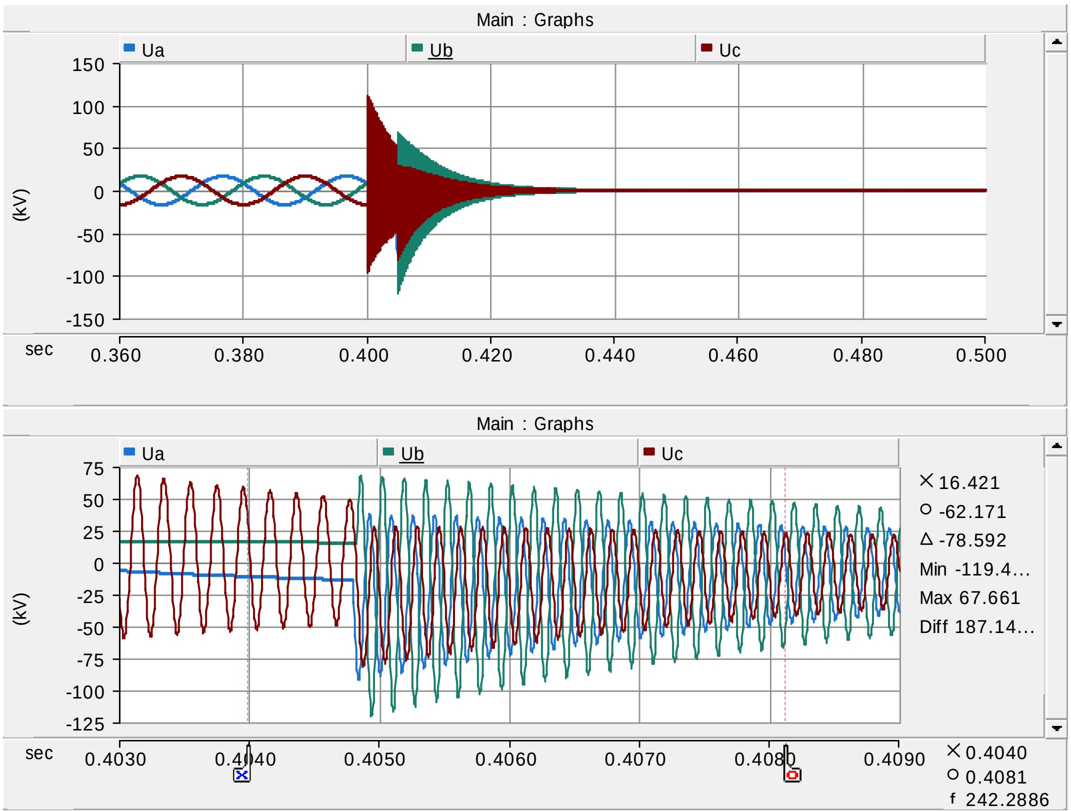

Figure 76. Reactor bus phase voltages on case 78.

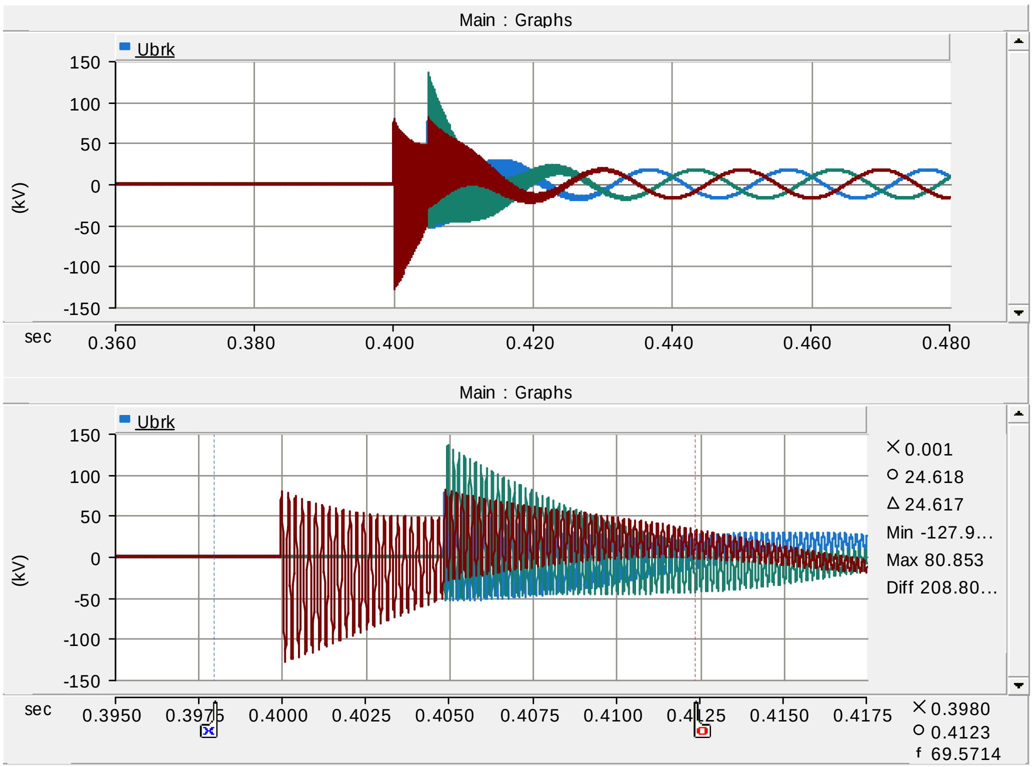

Figure 77. Breaker voltages before cable and reactor on case 78.

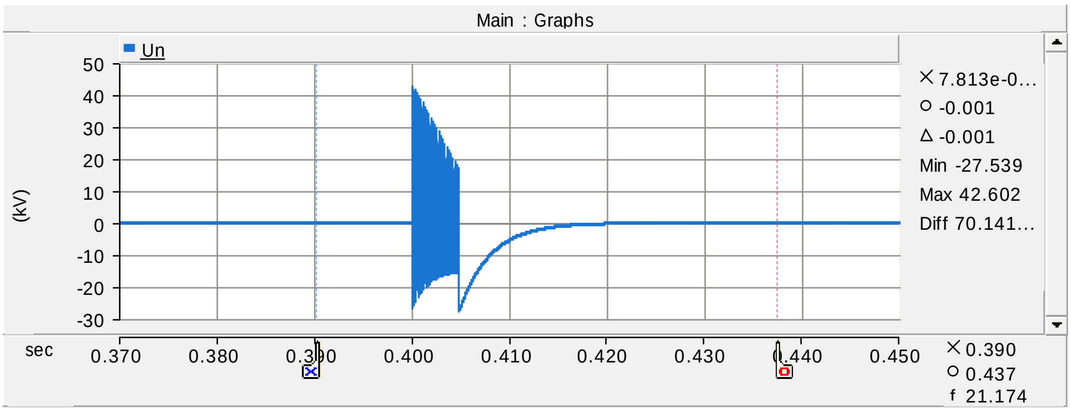

Figure 78. Reactor star point voltage on case 78.

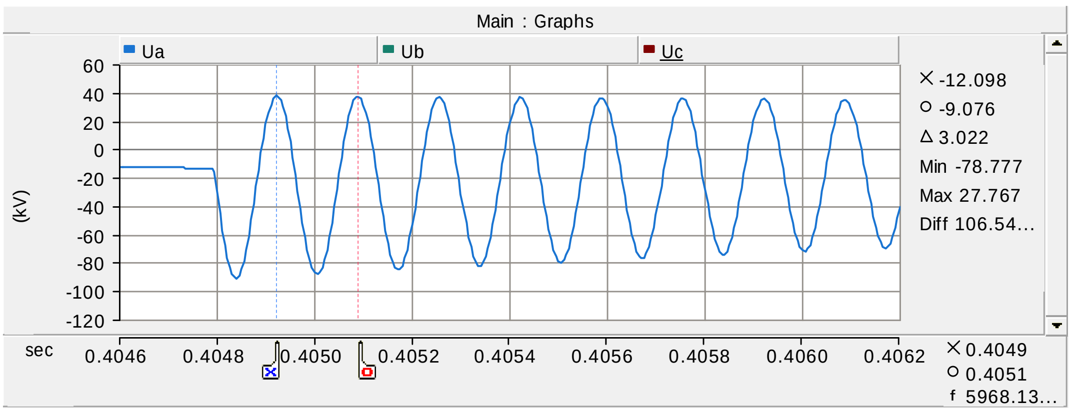

Figure 79. Ua phase Frequency on case 78.

A1.10 Case 88 Reactor 6 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 10 A

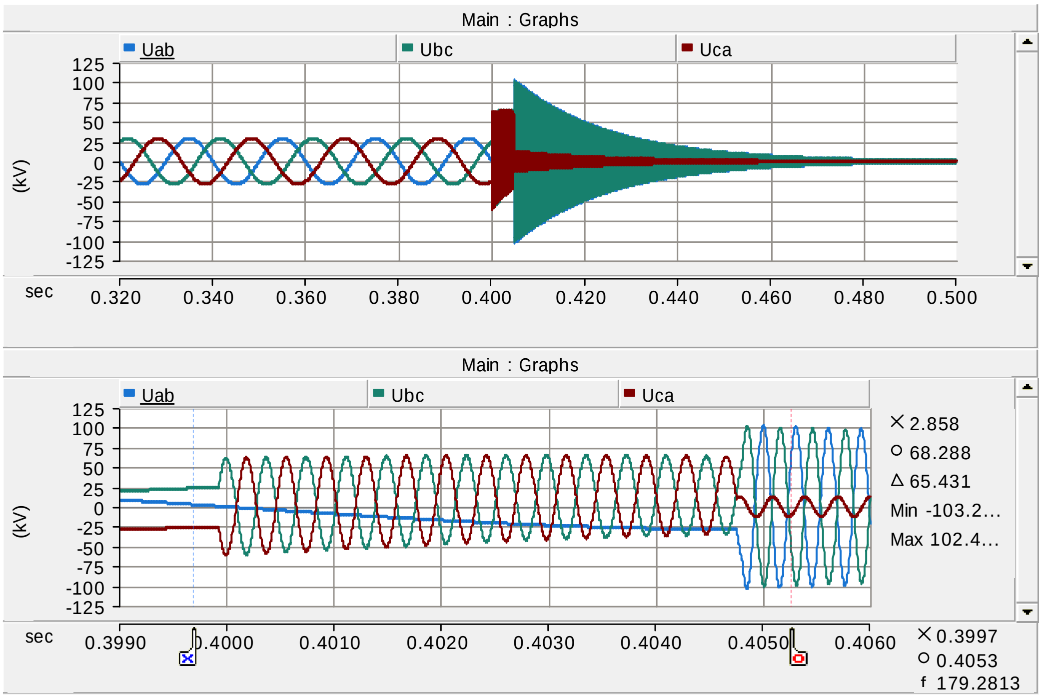

Figure 80. Reactor bus phase to phase voltages on case 88.

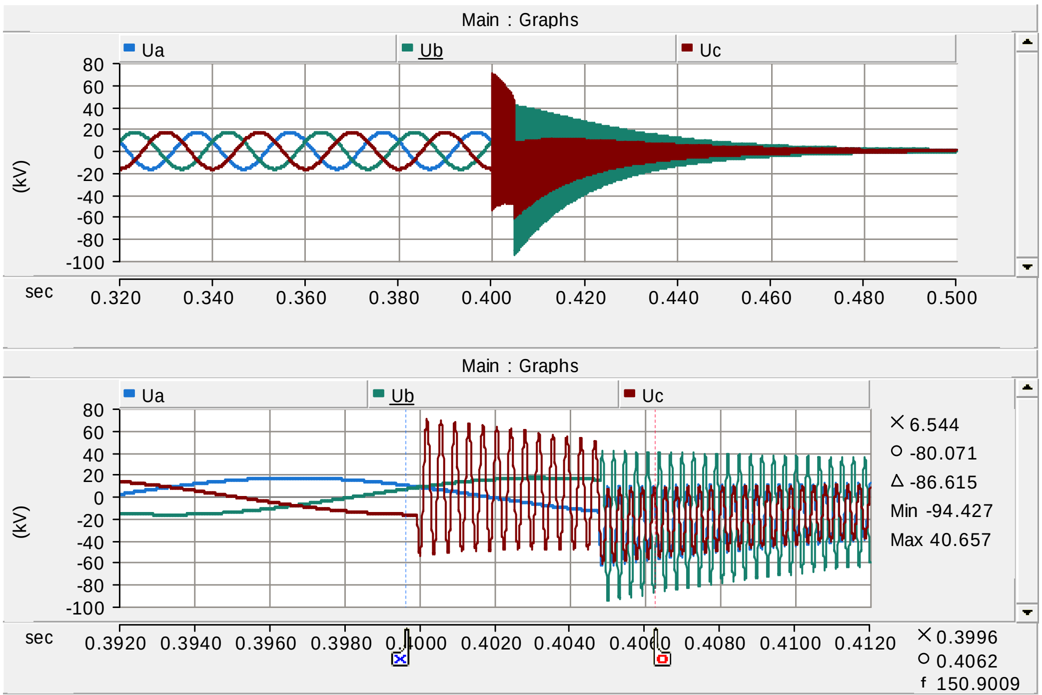

Figure 81. Reactor bus phase voltages on case 88.

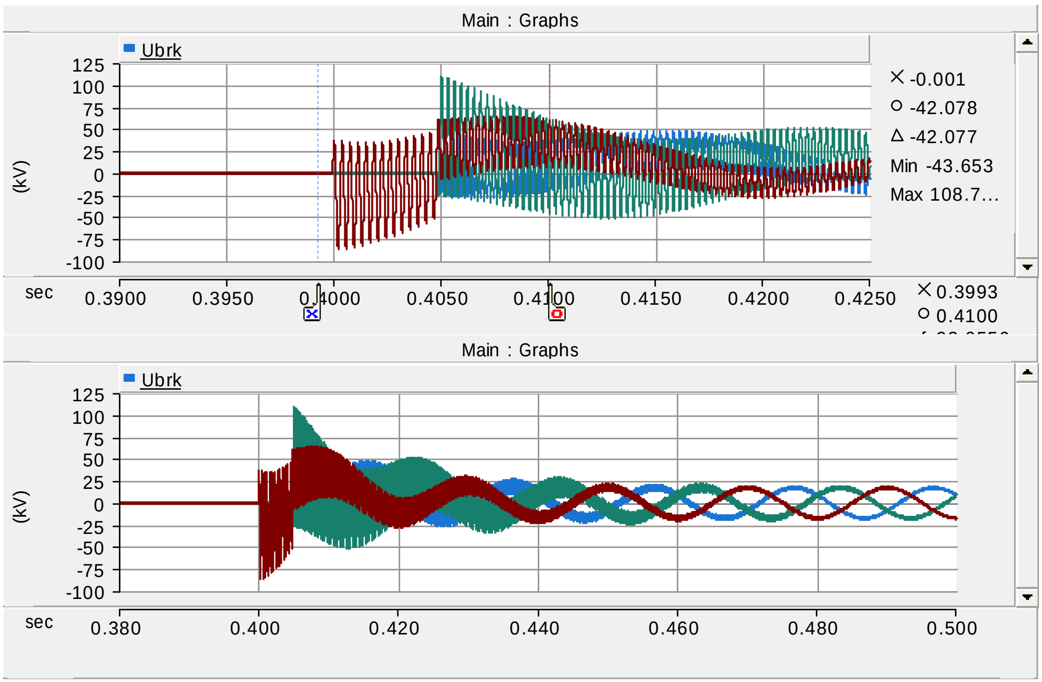

Figure 82. Breaker voltages before cable and reactor on case 88.

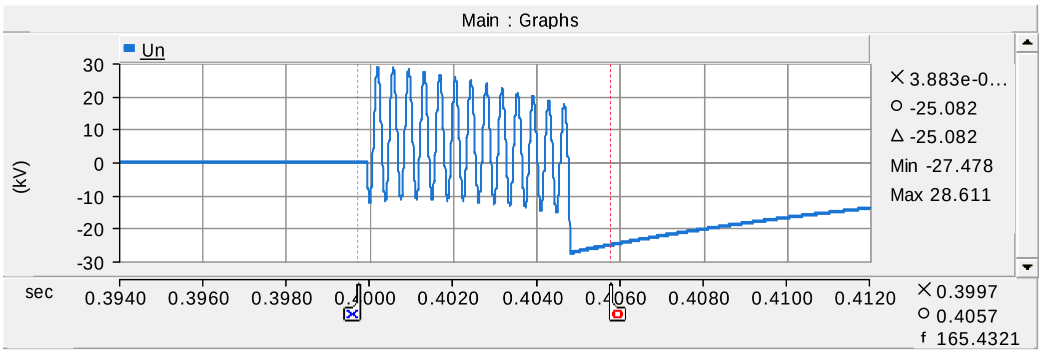

Figure 83. Reactor star point voltage on case 88.

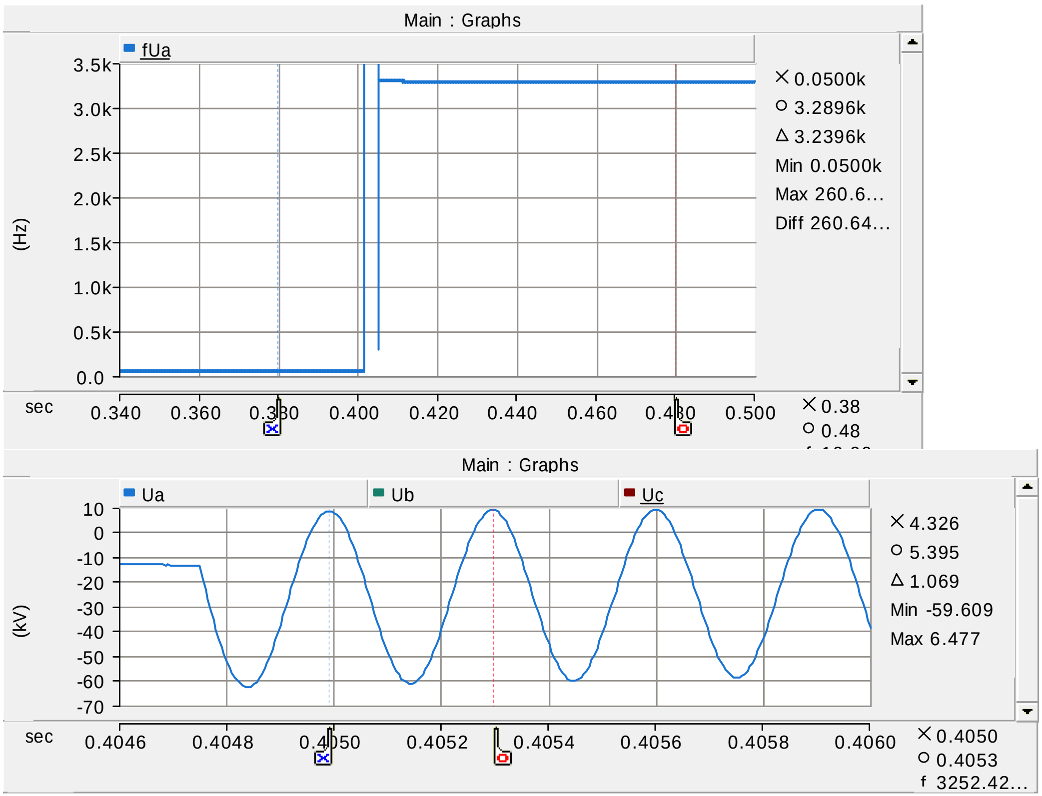

Figure 84. Ua phase Frequency on case 88.

A1.11 Case 93 Reactor 6 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 10 A with surge arrester

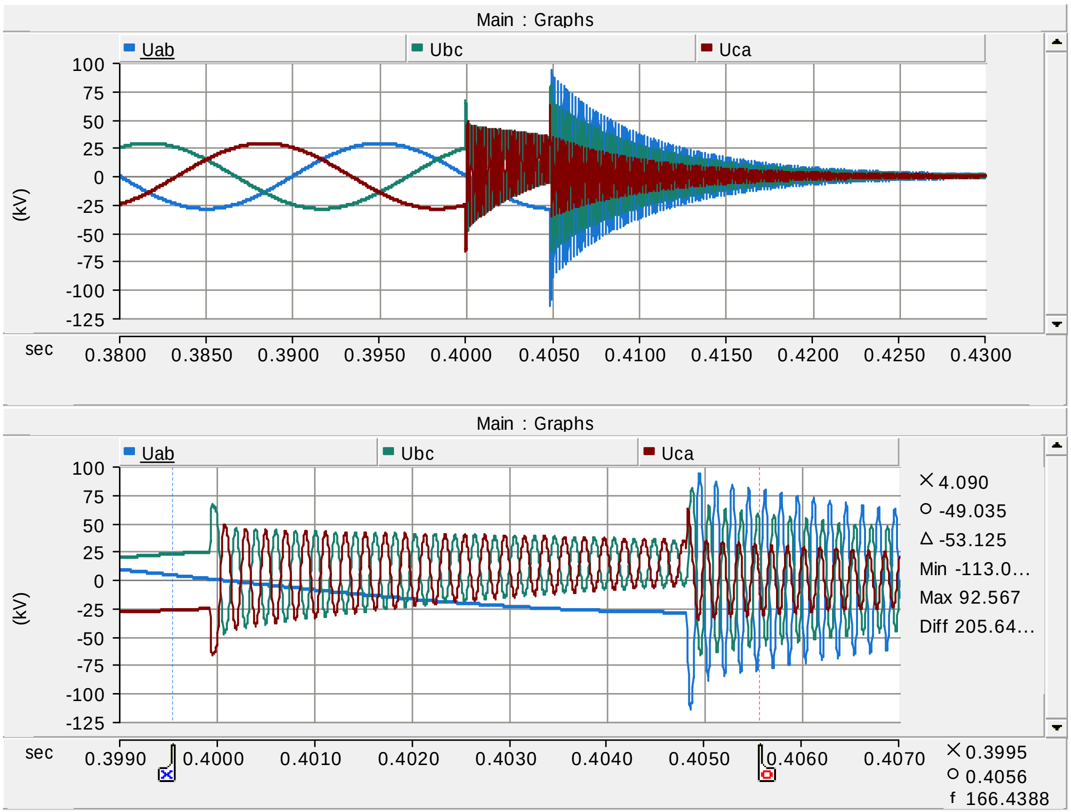

Figure 85. Reactor bus phase to phase voltages on case 93.

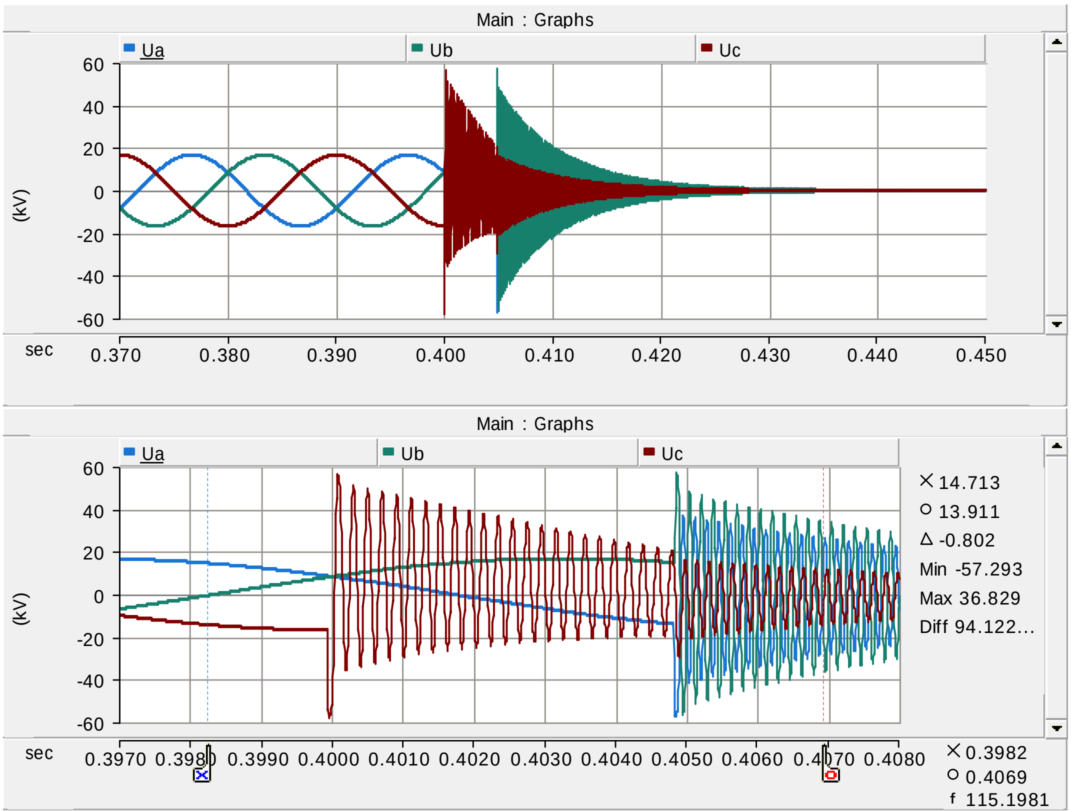

Figure 86. Reactor bus phase voltages on case 93.

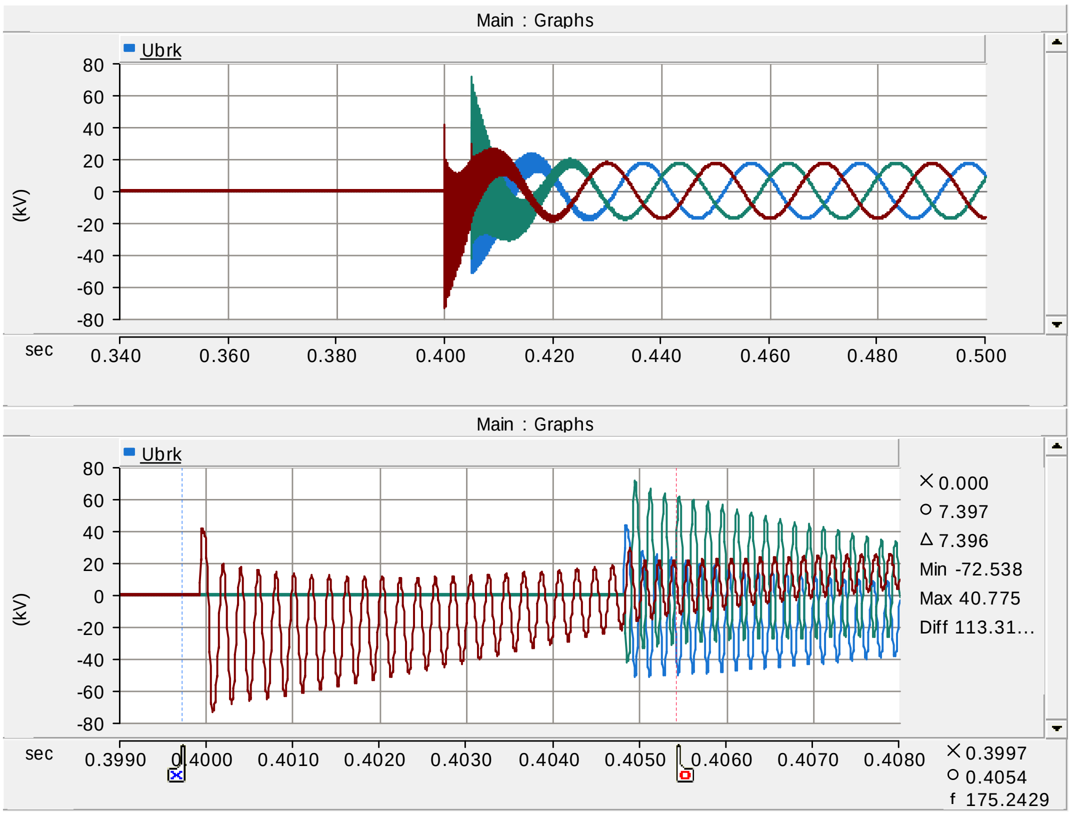

Figure 87. Breaker voltages before cable and reactor on case 93.

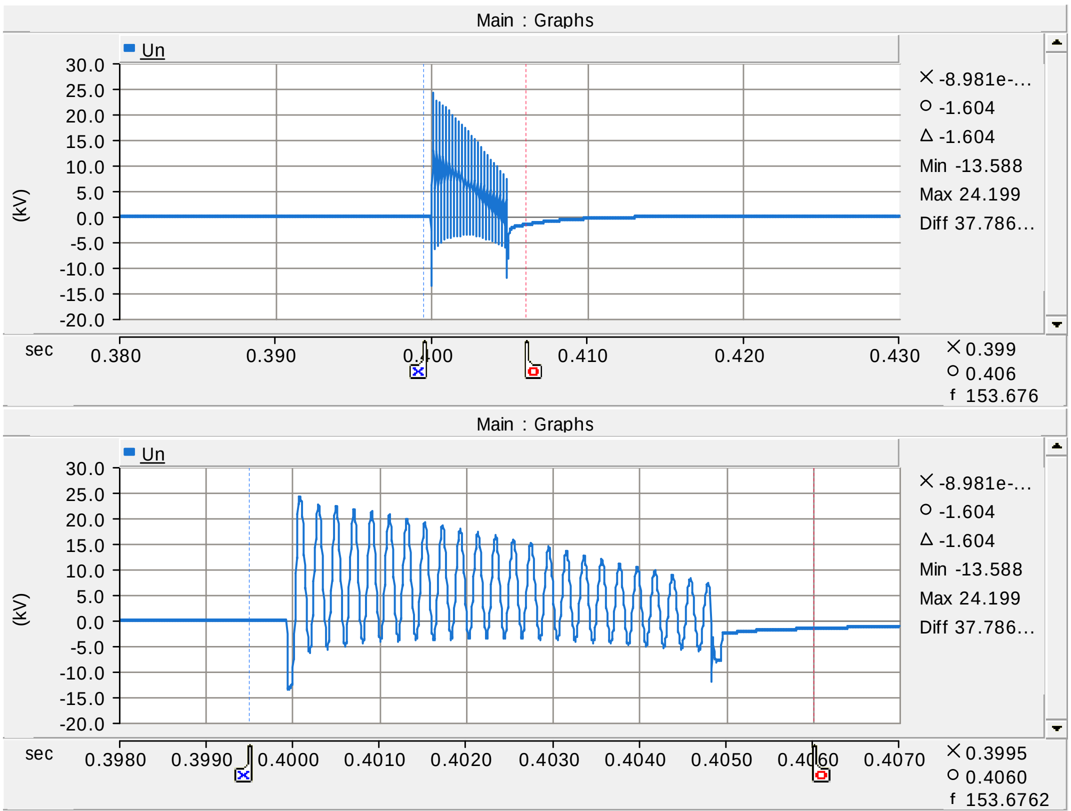

Figure 88. Reactor star point voltage on case 93.

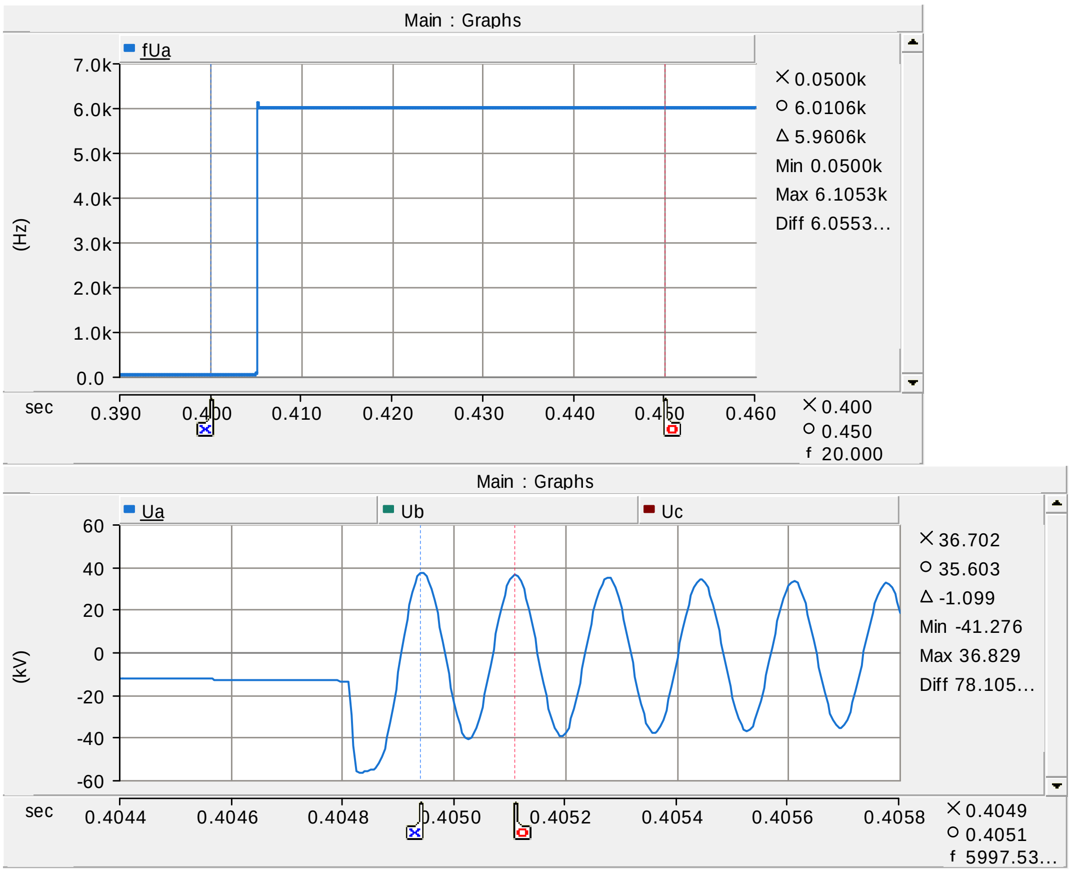

Figure 89. Ua phase Frequency on case 93.

A1.12 Case 100 Reactor 6 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 10 A with surge arrester

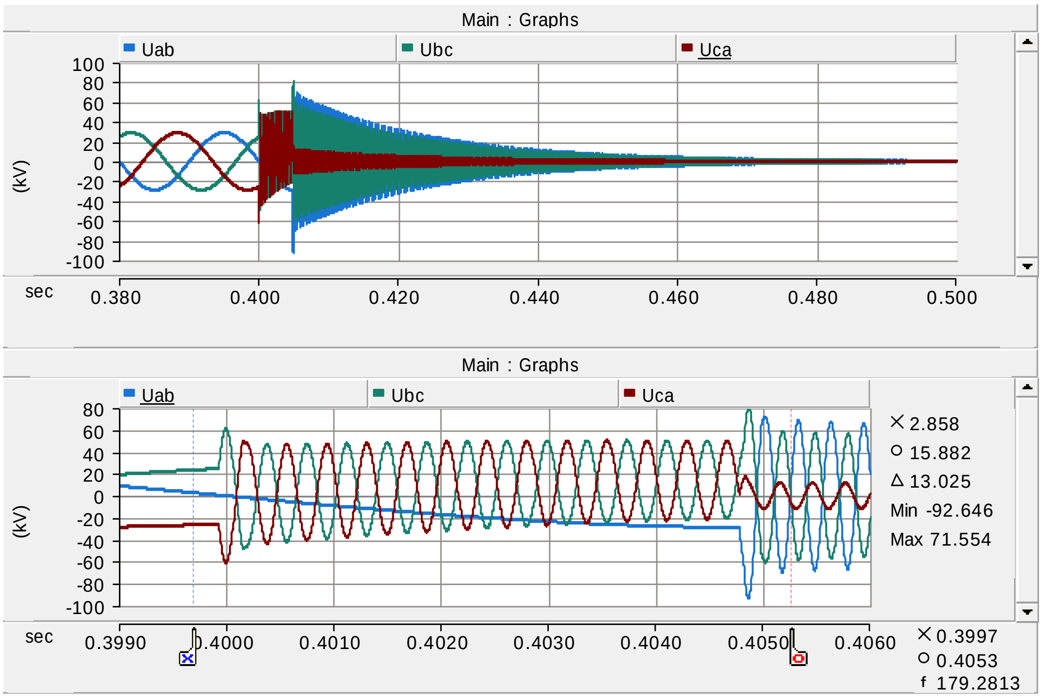

Figure 90. Reactor bus phase to phase voltages on case 100.

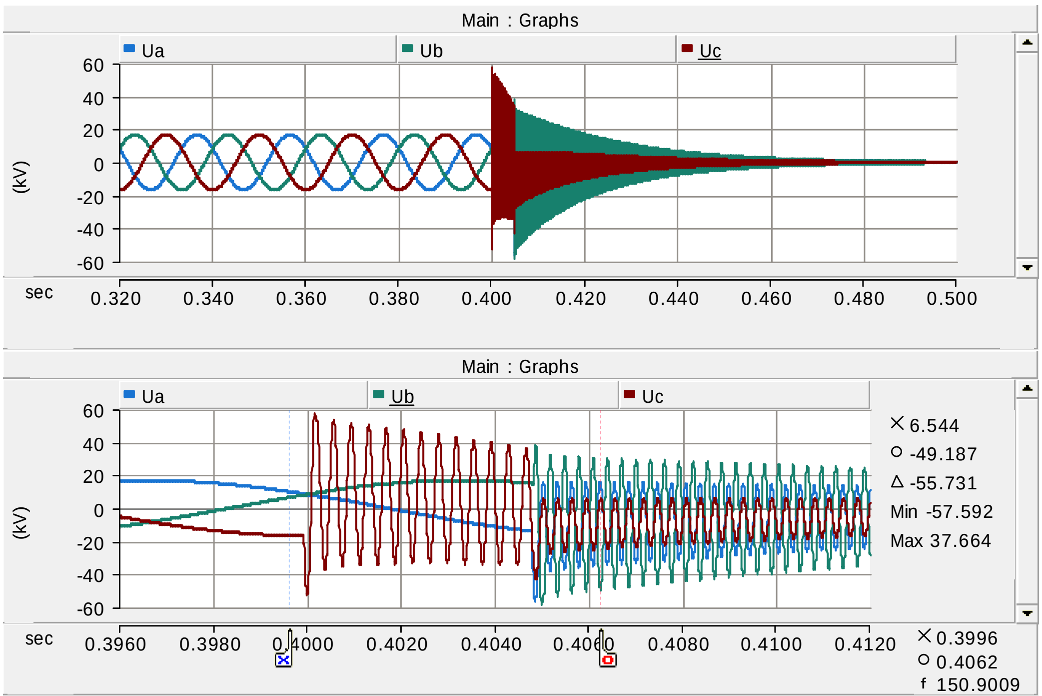

Figure 91. Reactor bus phase voltages on case 100.

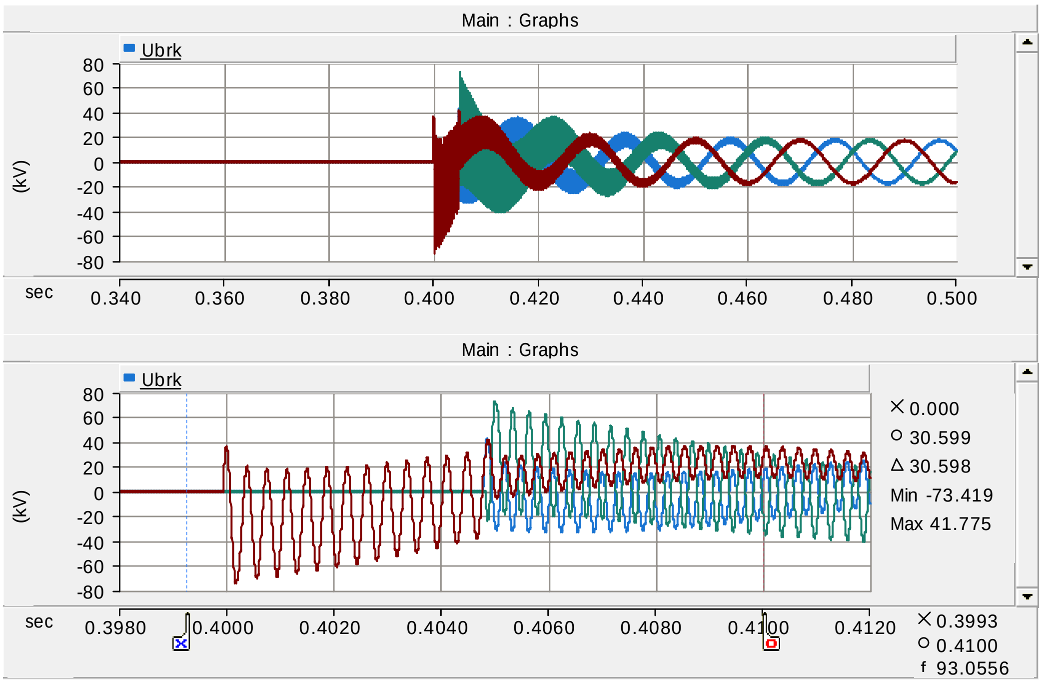

Figure 92. Breaker voltages before cable and reactor on case 100.

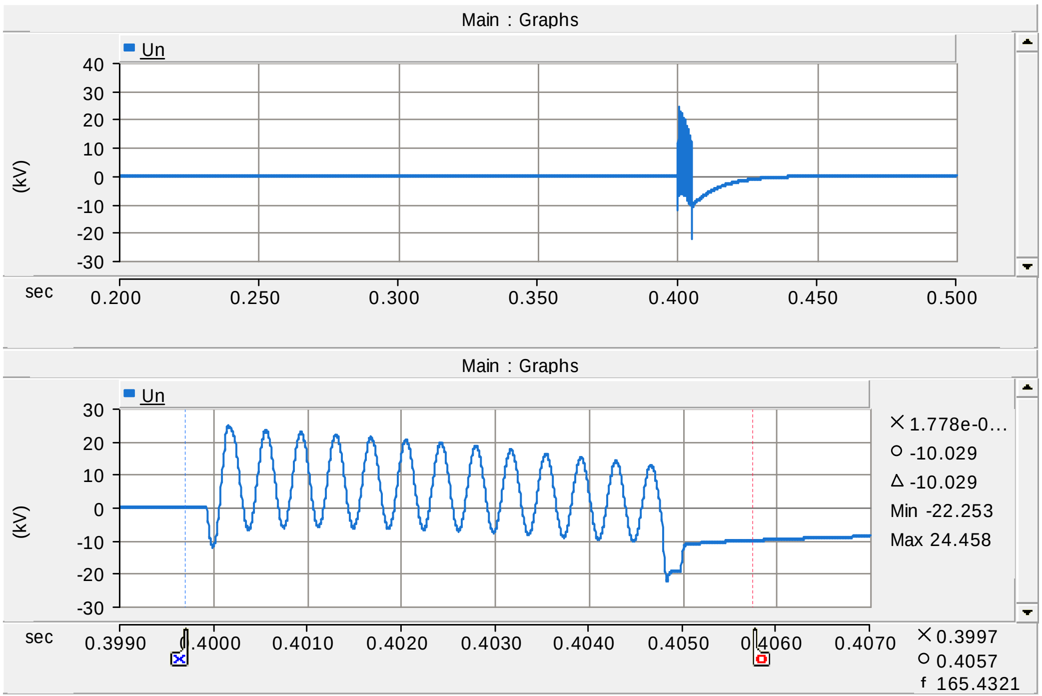

Figure 93. Reactor star point voltage on case 100.

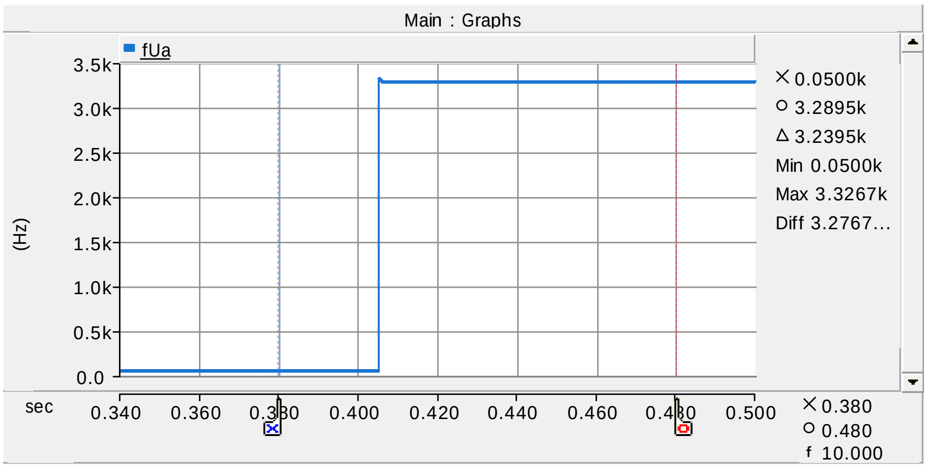

Figure 94. Ua phase Frequency on case 100.

A1.13 Case 107 Reactor 1 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 5 A with surge arrester

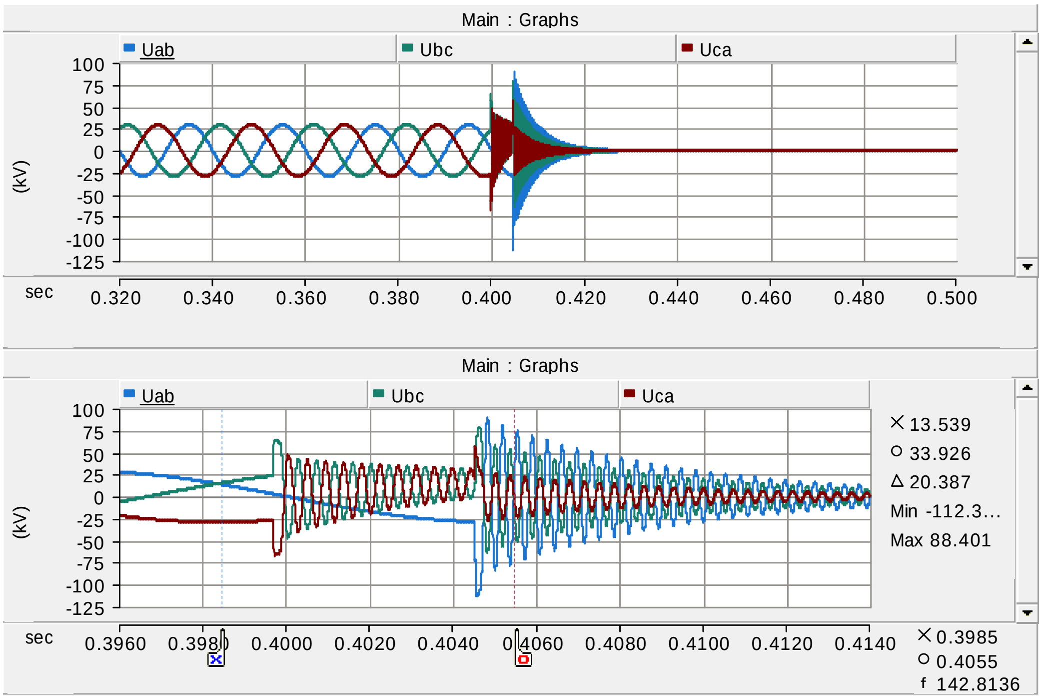

Figure 95. Reactor bus phase to phase voltages on case 107.

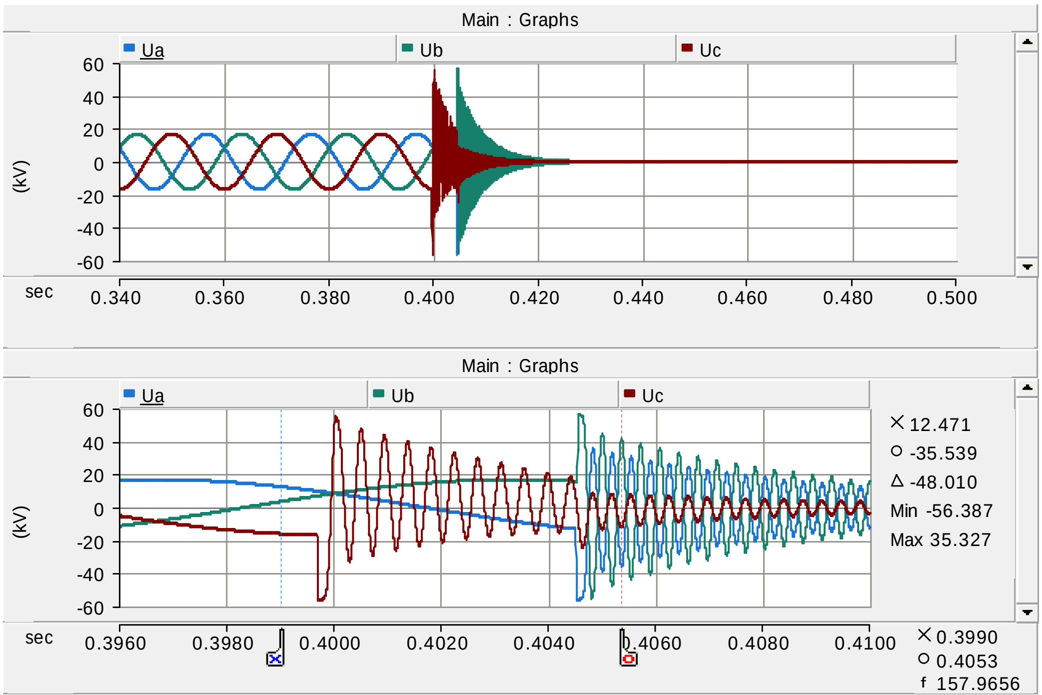

Figure 96. Reactor bus phase voltages on case 107.

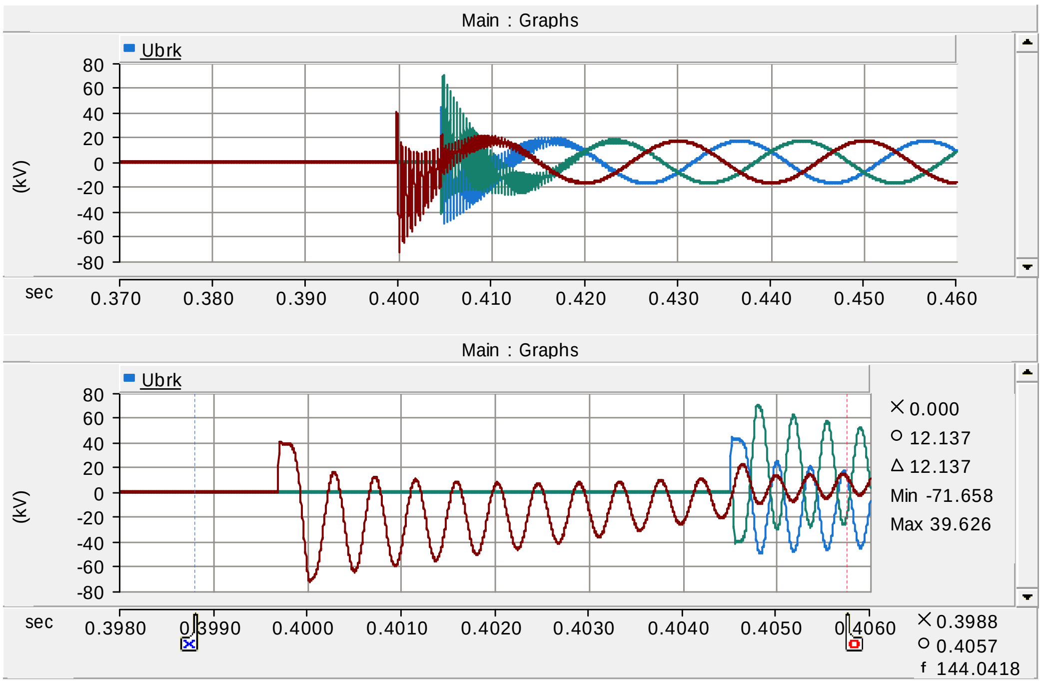

Figure 97. Breaker voltages before cable and reactor on case 107.

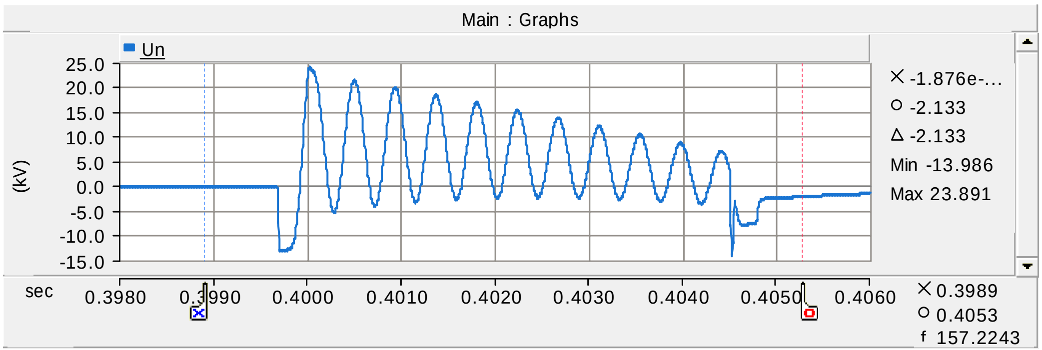

Figure 98. Reactor star point voltage on case 107.

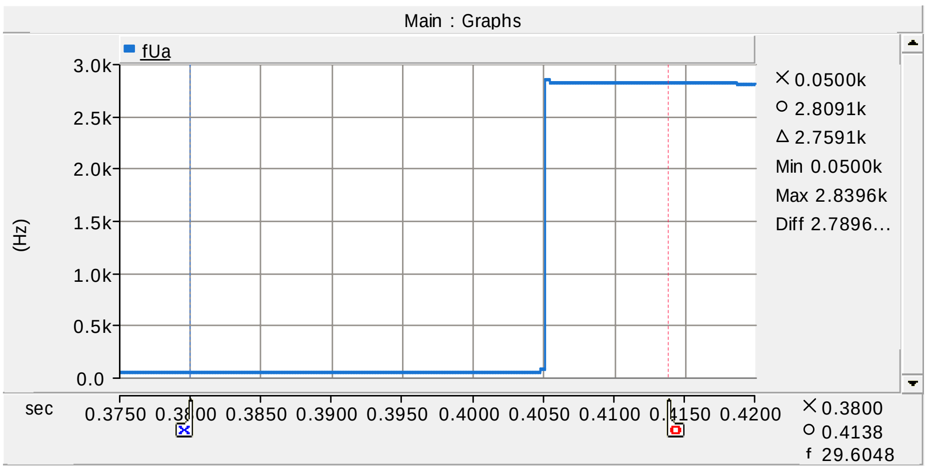

Figure 99. Ua phase Frequency on case 107.

A1.14 Case 114 Reactor 1 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 5 A with surge arrester

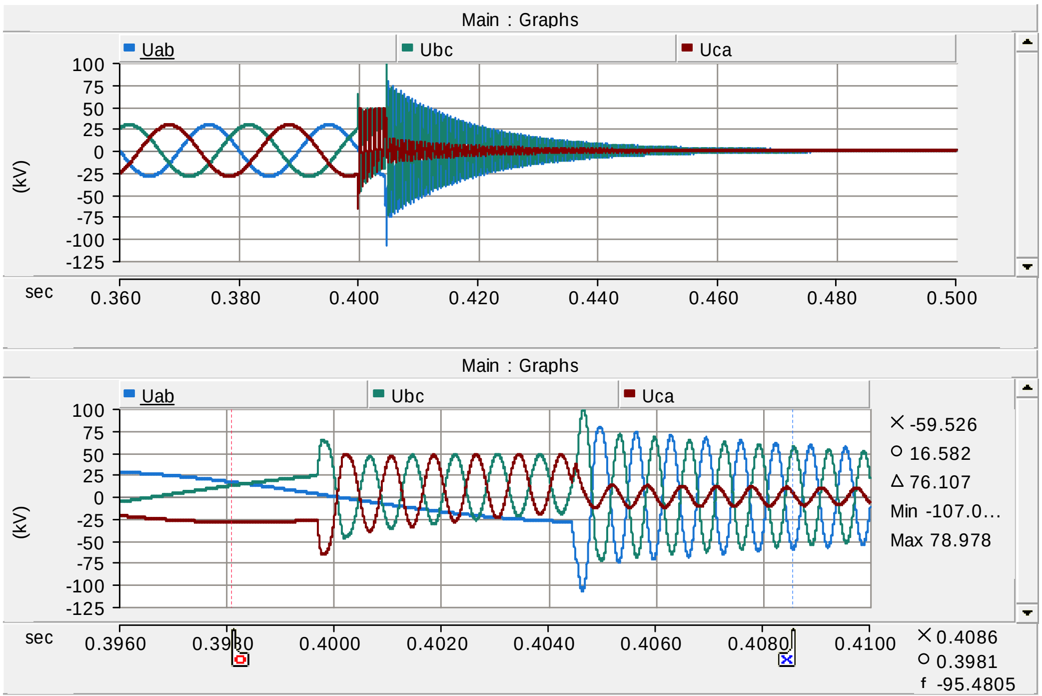

Figure 100. Reactor bus phase to phase voltages on case 114.

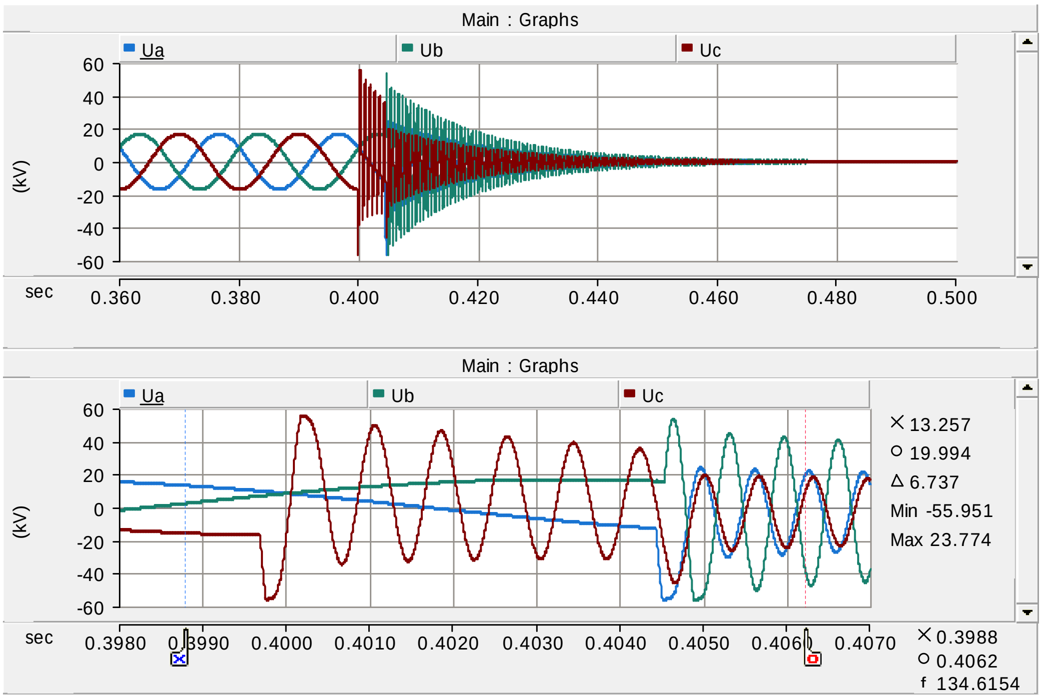

Figure 101. Reactor bus phase voltages on case 114.

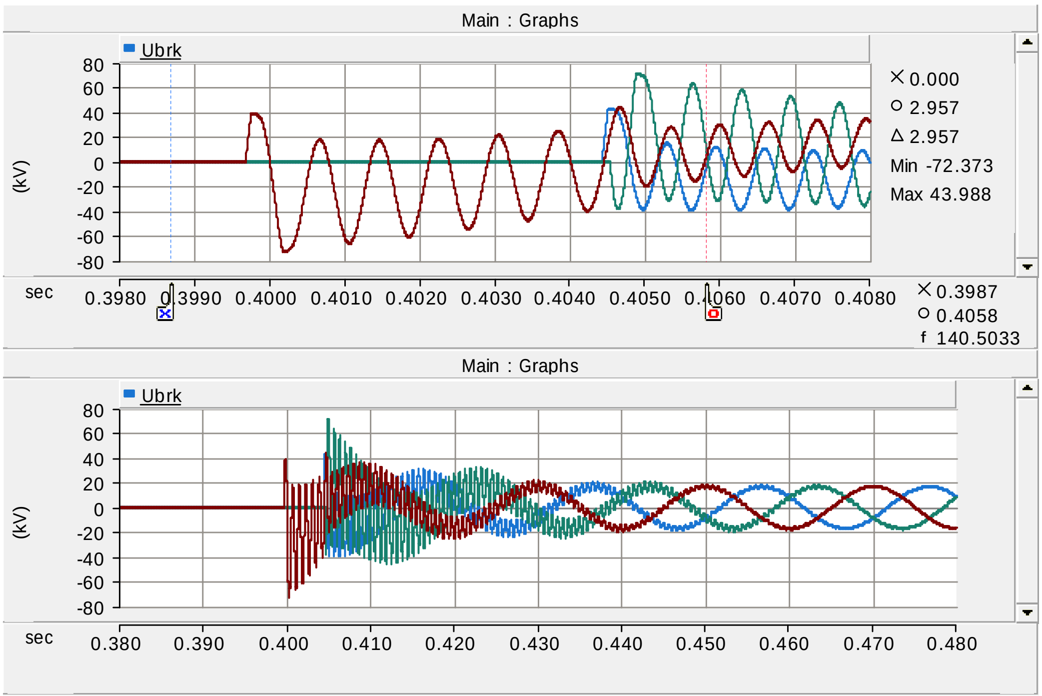

Figure 102. Breaker voltages before cable and reactor on case 114.

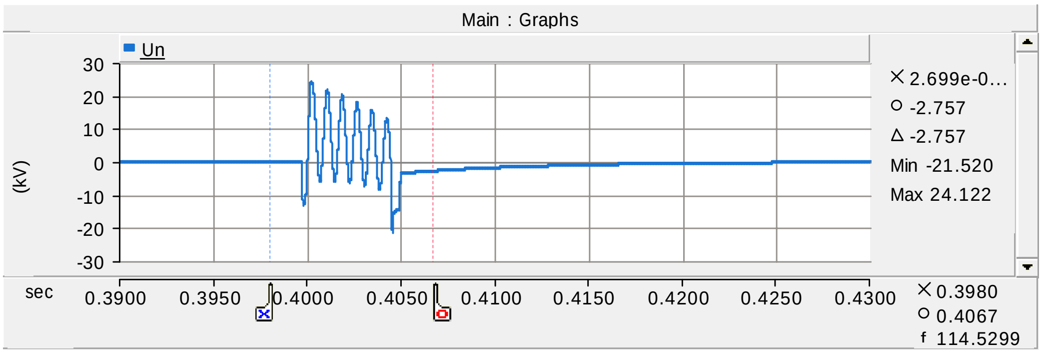

Figure 103. Reactor star point voltage on case 114.

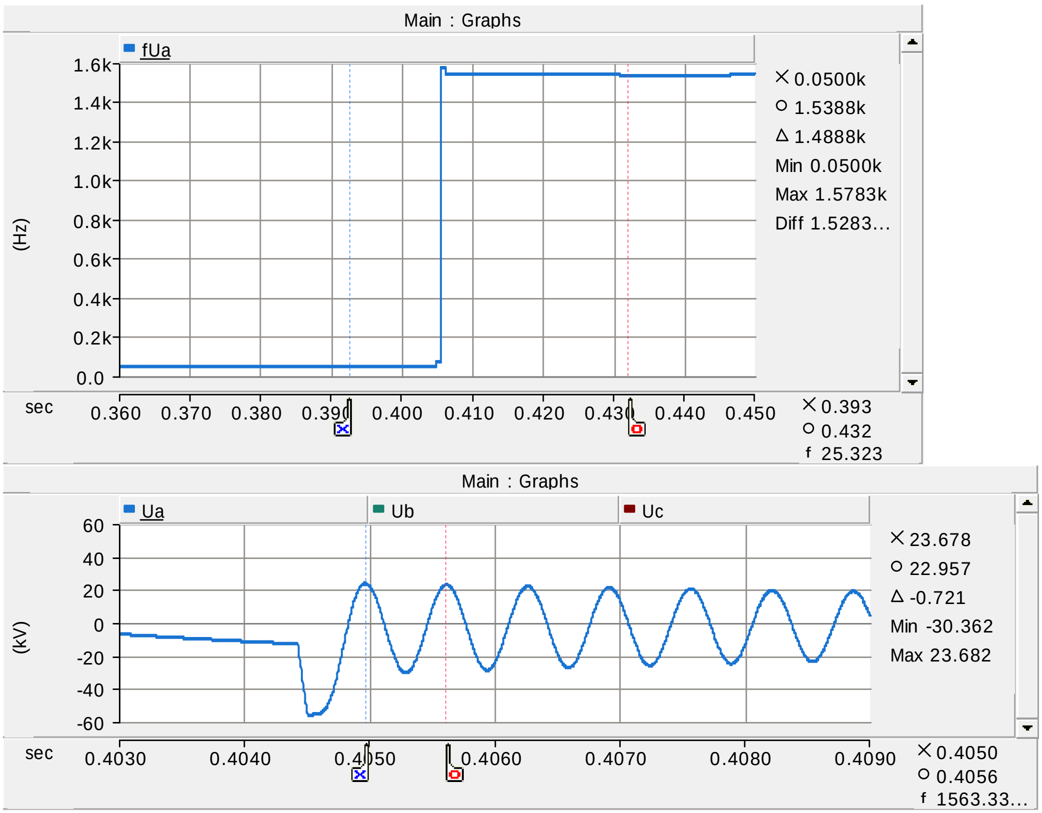

Figure 104. Ua phase Frequency on case 114.

A1.15 Case 128 Reactor 3 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 5 A with surge arrester

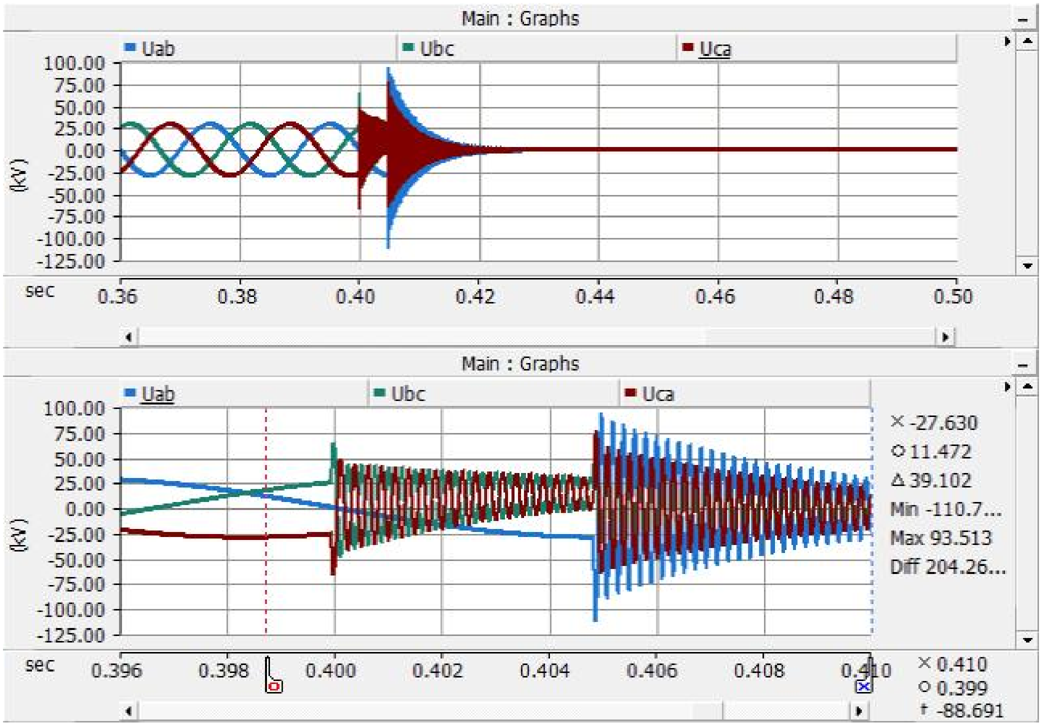

Figure 105. Reactor bus phase to phase voltages on case 121.

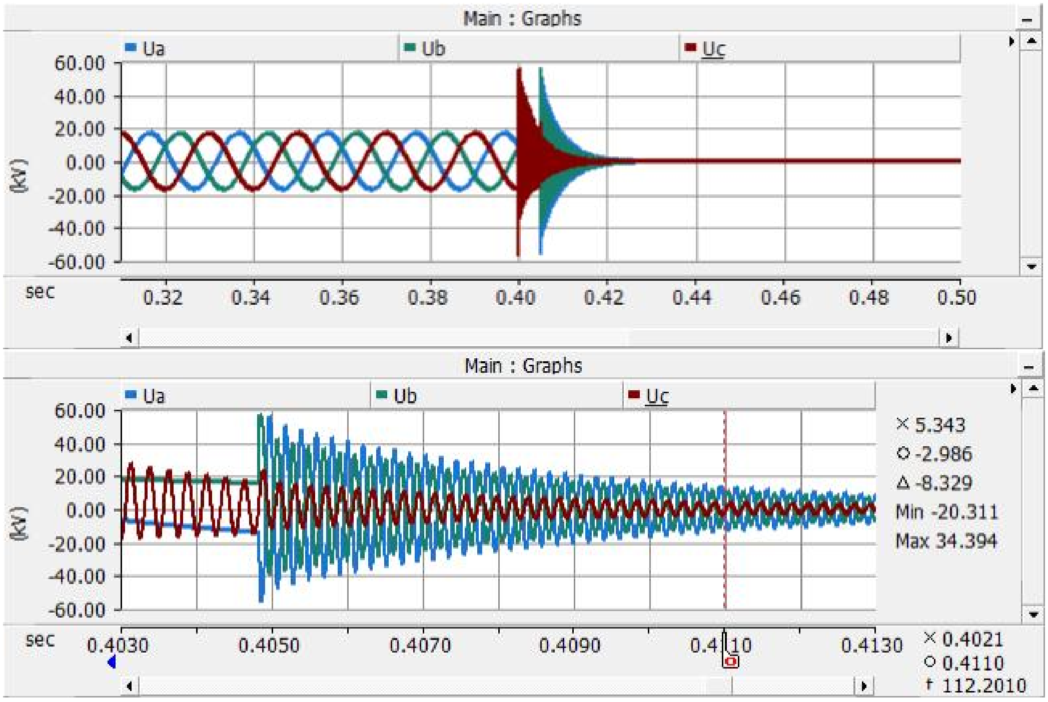

Figure 106. Reactor bus phase voltages on case 121.

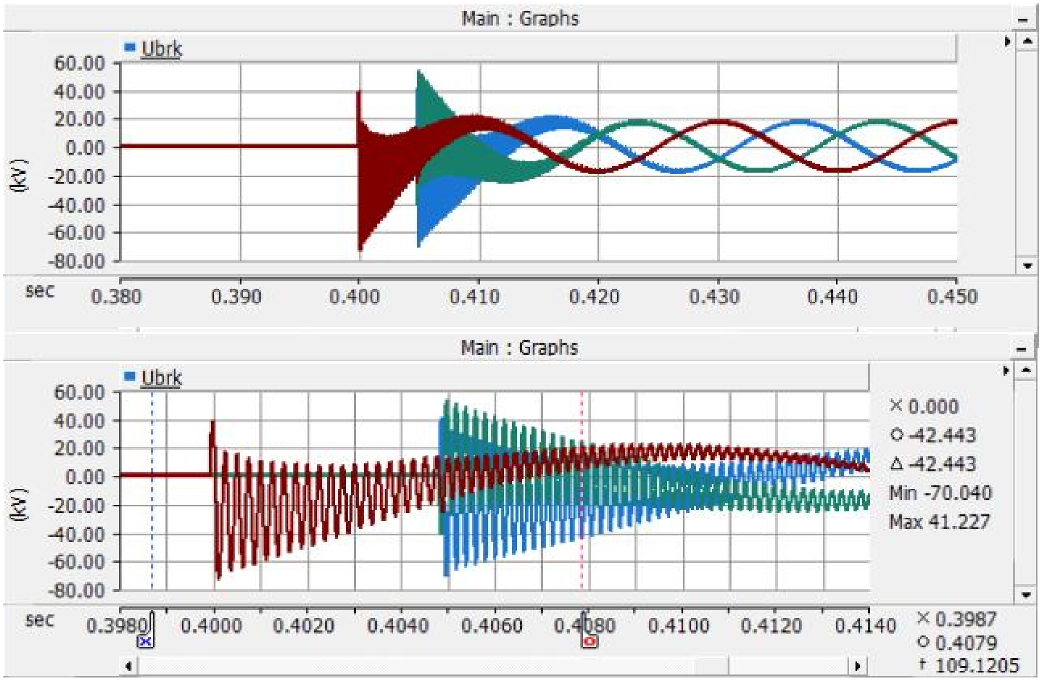

Figure 107. Breaker voltages before cable and reactor on case 121.

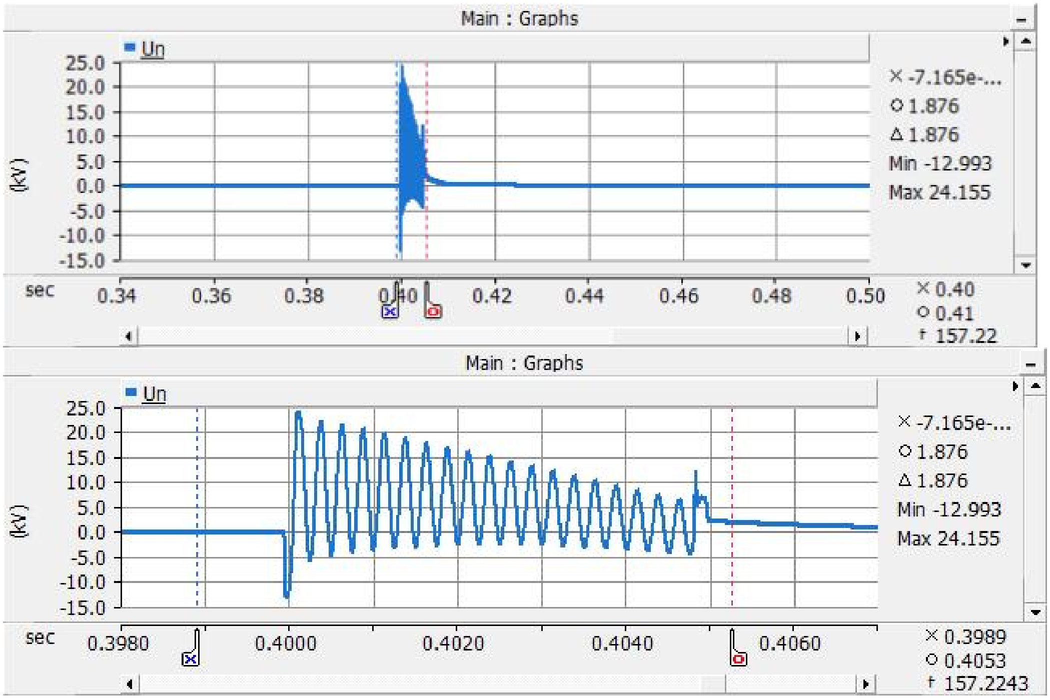

Figure 108. Reactor star point voltage on case 121.

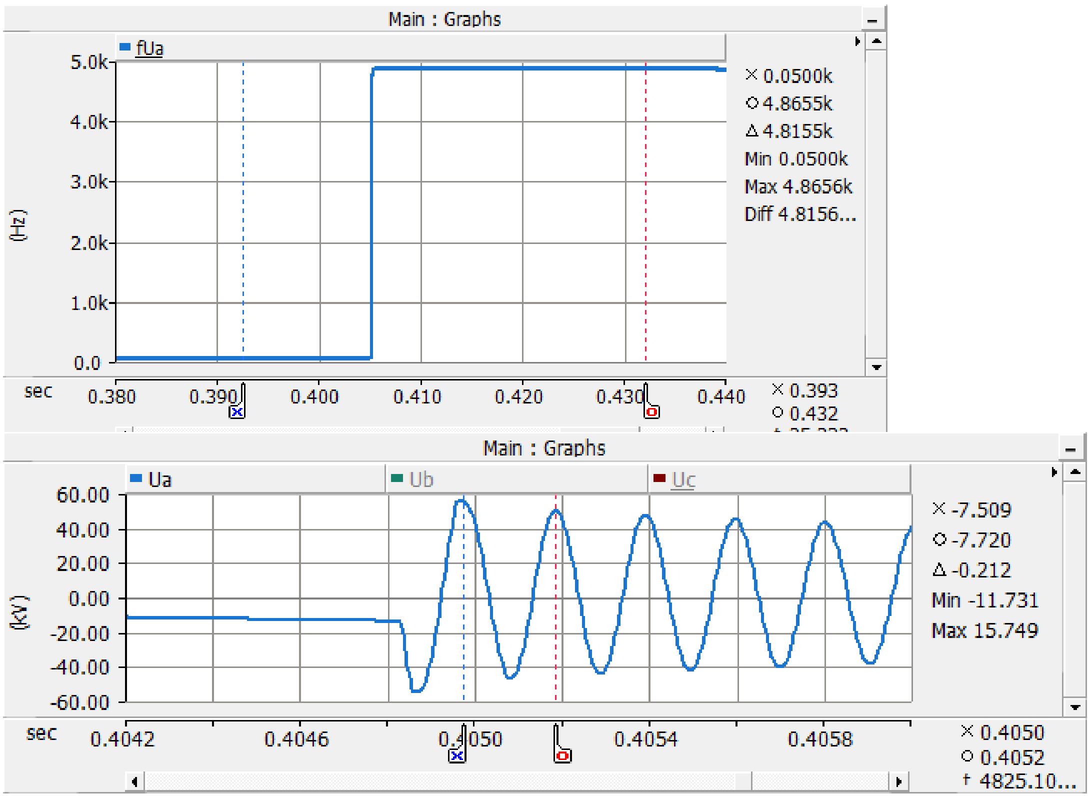

Figure 109. Ua phase Frequency on case 121.

A1.16 Case 128 Reactor 3 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 5 A with surge arrester

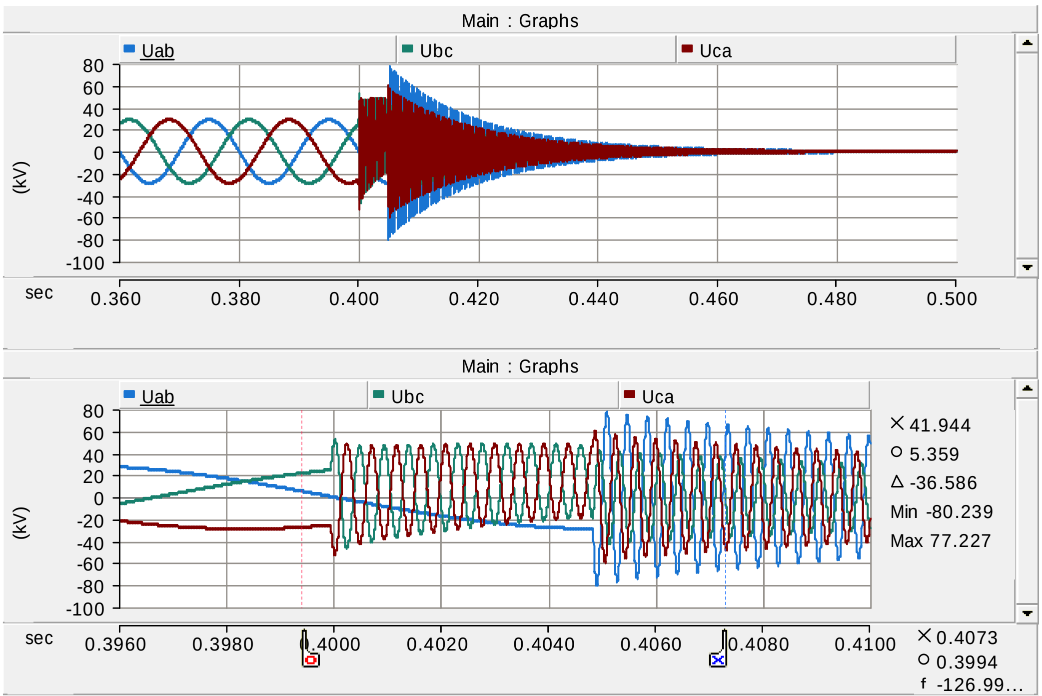

Figure 110. Reactor bus phase to phase voltages on case 128.

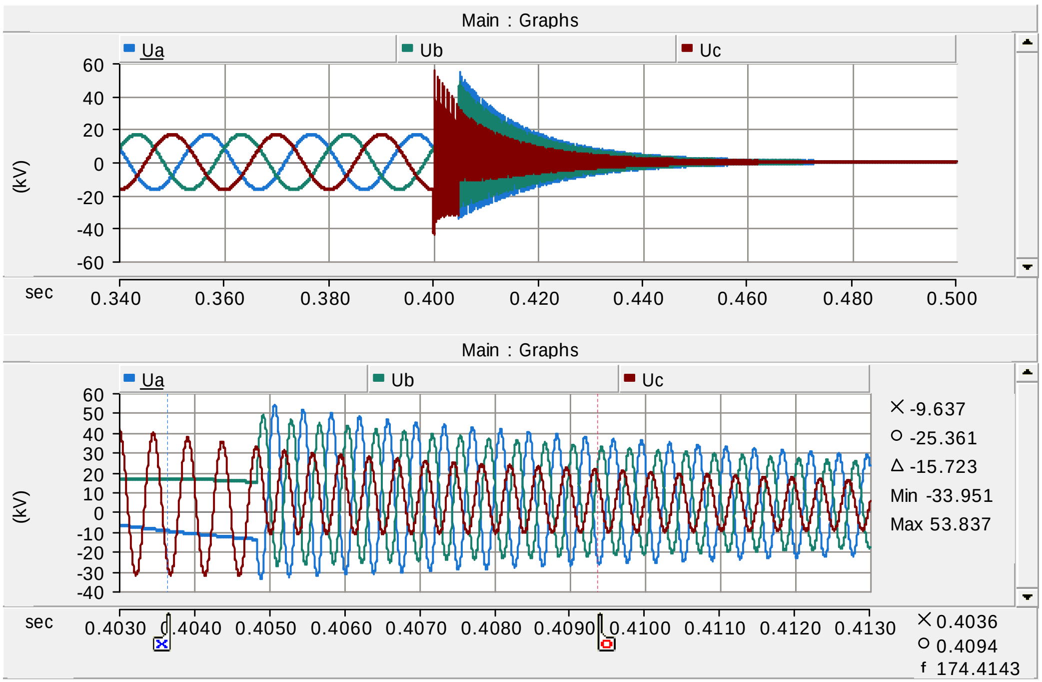

Figure 111. Reactor bus phase voltages on case 128.

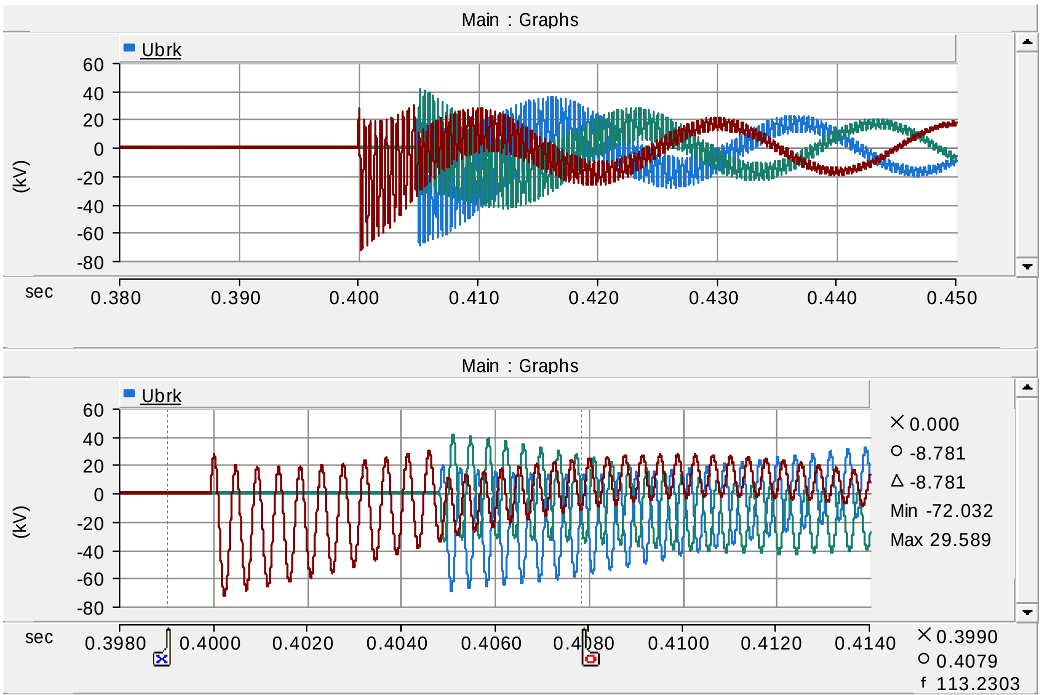

Figure 112. Breaker voltages before cable and reactor on case 128.

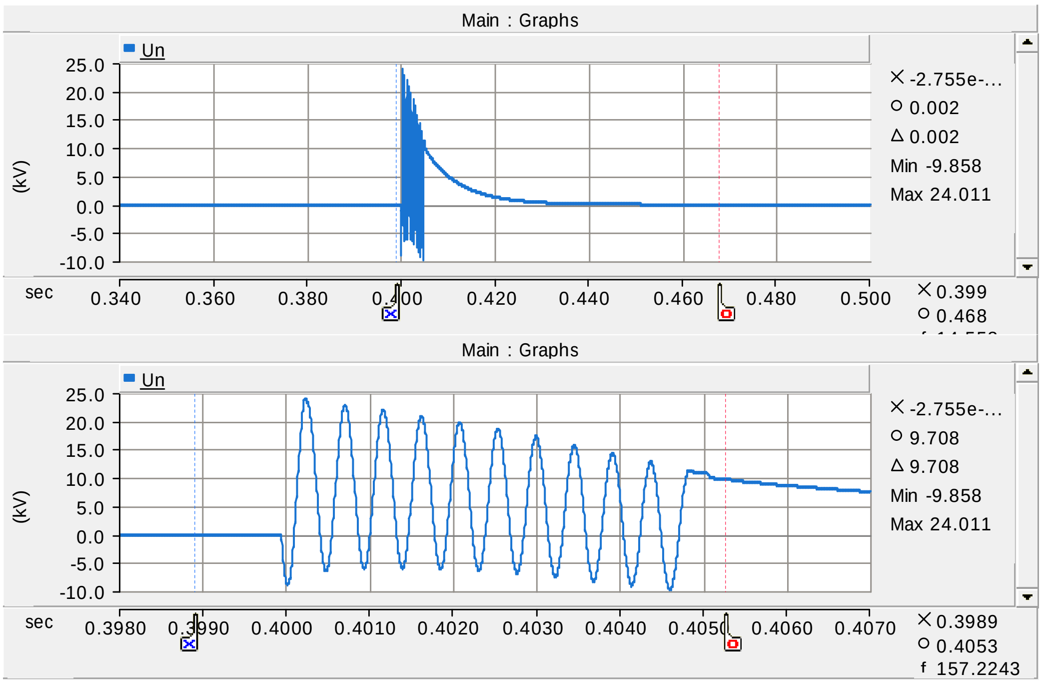

Figure 113. Reactor star point voltage on case 128.

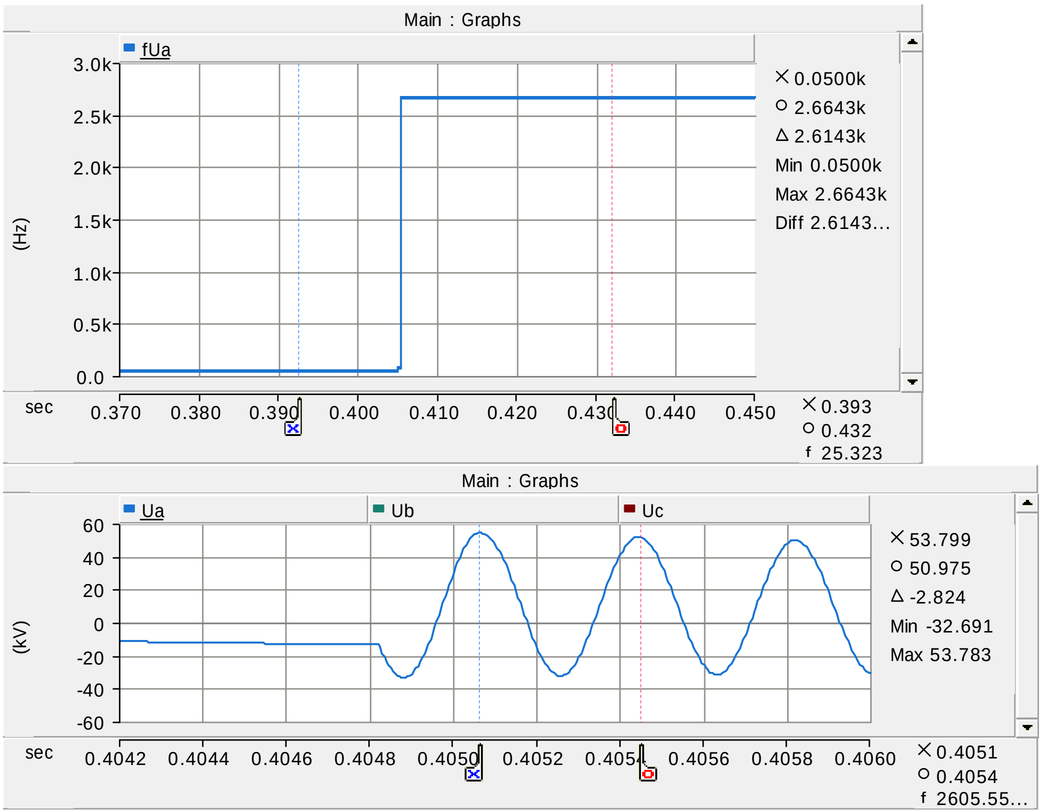

Figure 114. Ua phase Frequency on case 128.

A1.17 Case 135 Reactor 6 MVAr, connection cable 15 m, main transformer 25 MVA, CCL 5 A with surge arrester

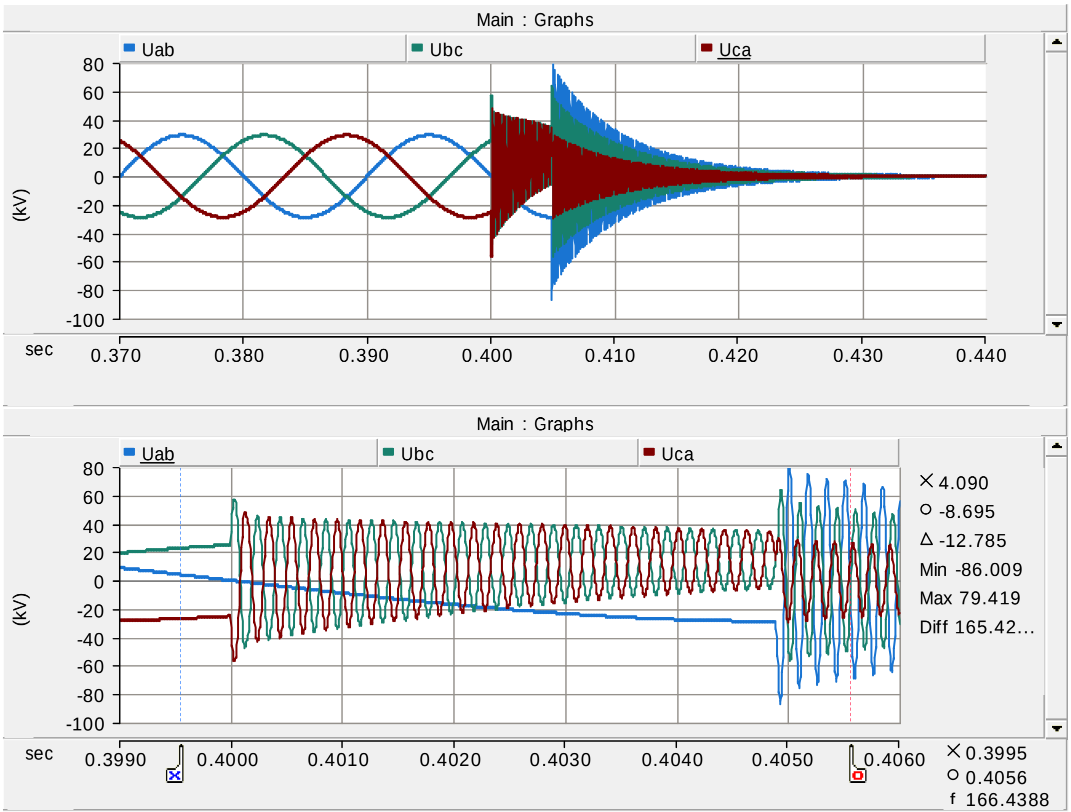

Figure 115. Reactor bus phase to phase voltages on case 135.

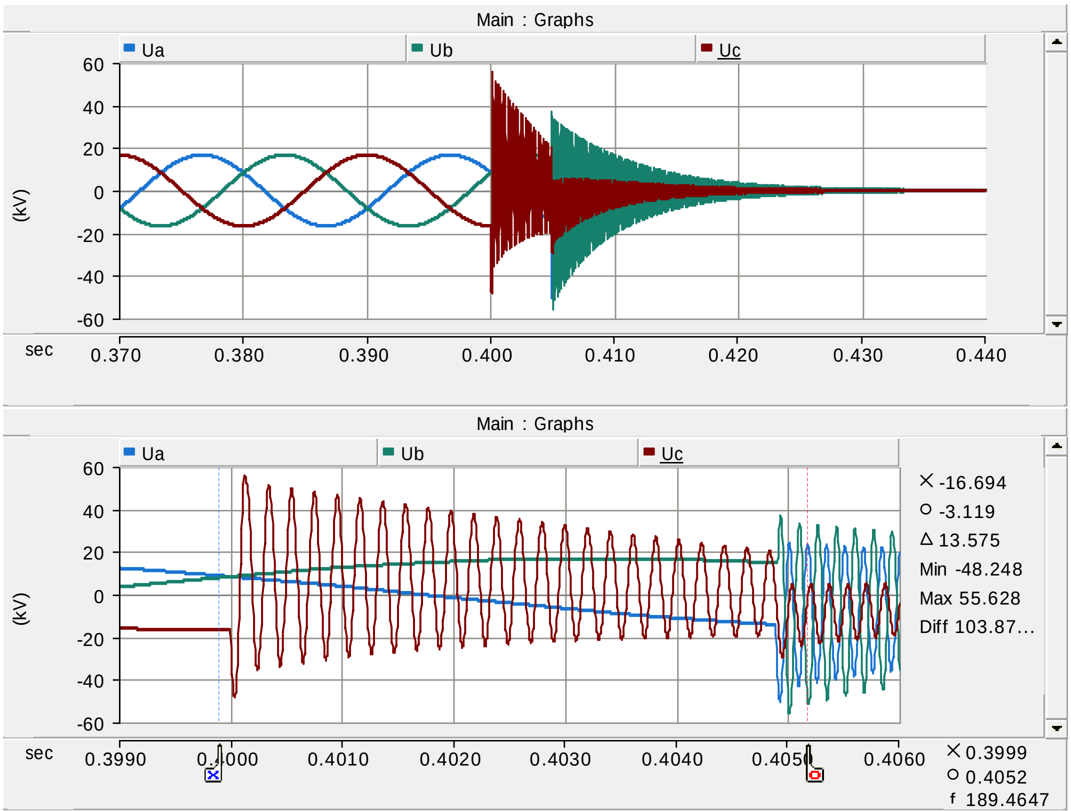

Figure 116. Reactor bus phase voltages on case 135.

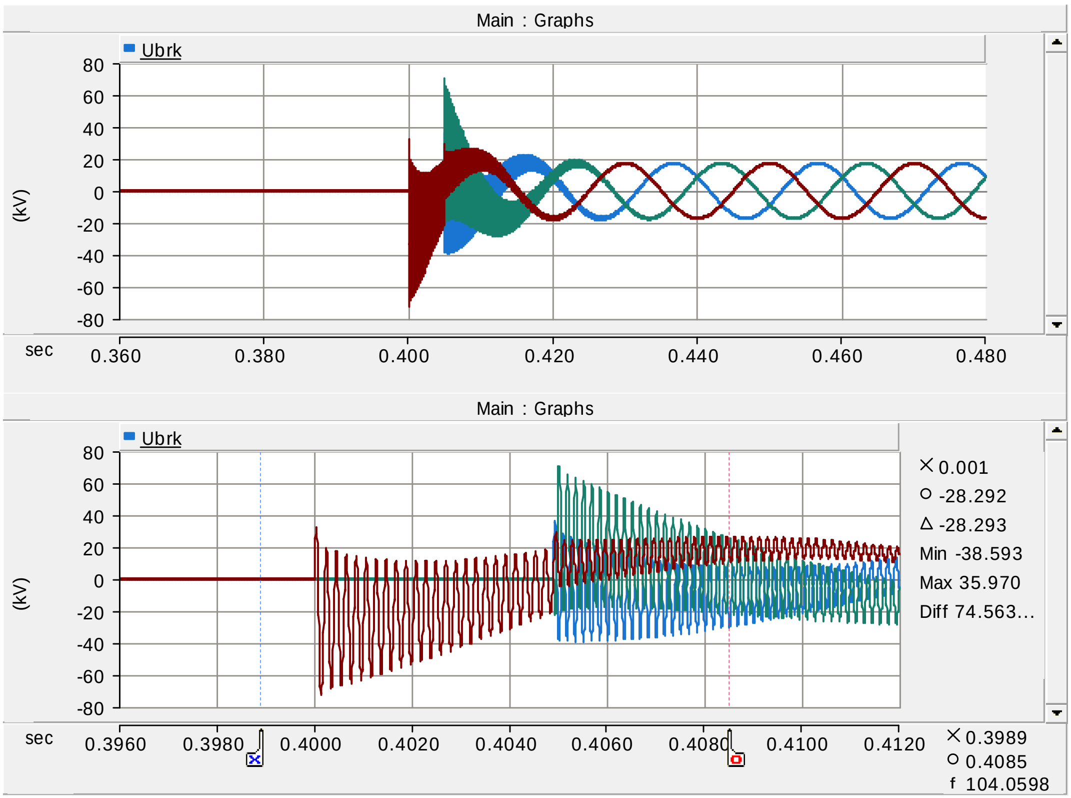

Figure 117. Breaker voltages before cable and reactor on case 135.

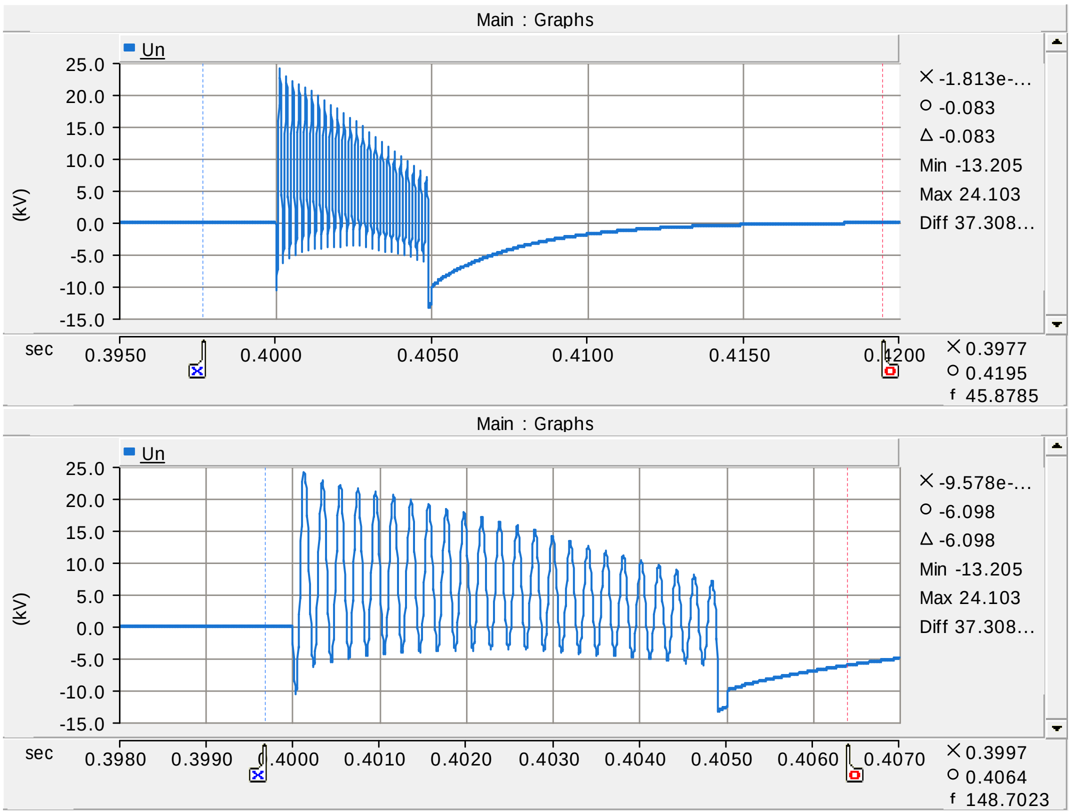

Figure 118. Reactor star point voltage on case 135.

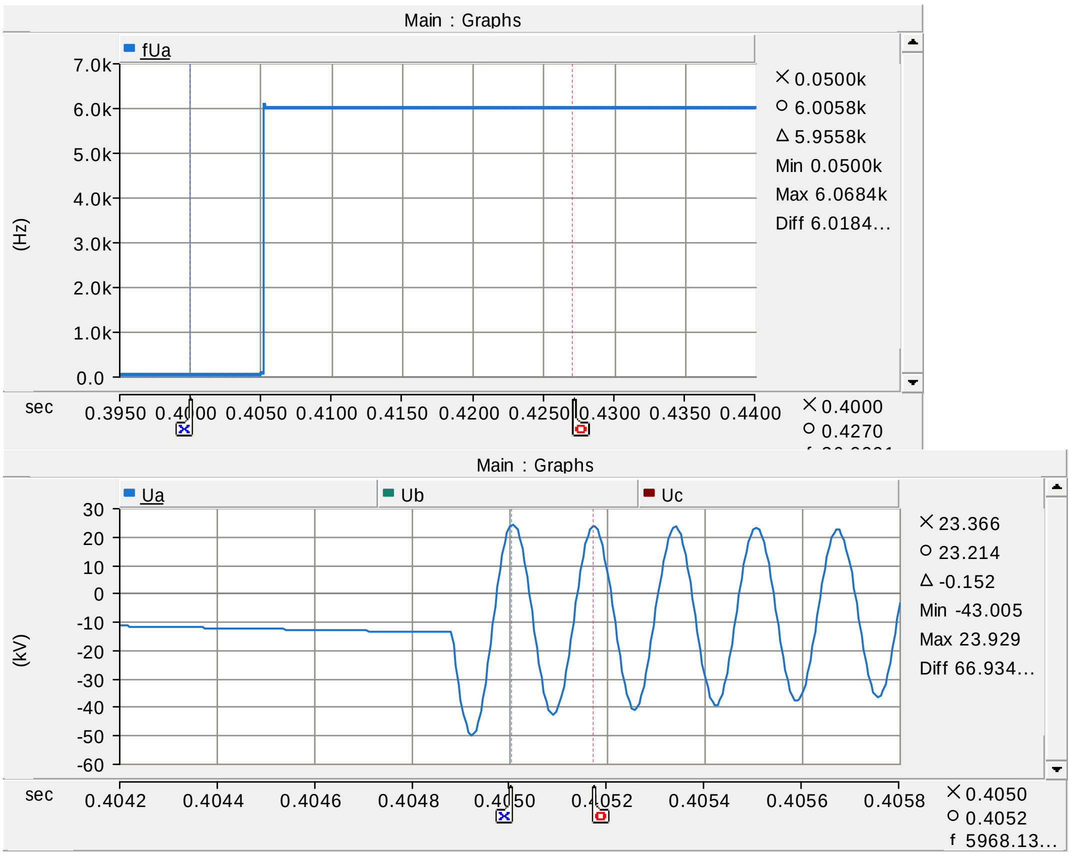

Figure 119. Ua phase Frequency on case 135.

A1.18 Case 142 Reactor 6 MVAr, connection cable 50 m, main transformer 25 MVA, CCL 5 A with surge arrester

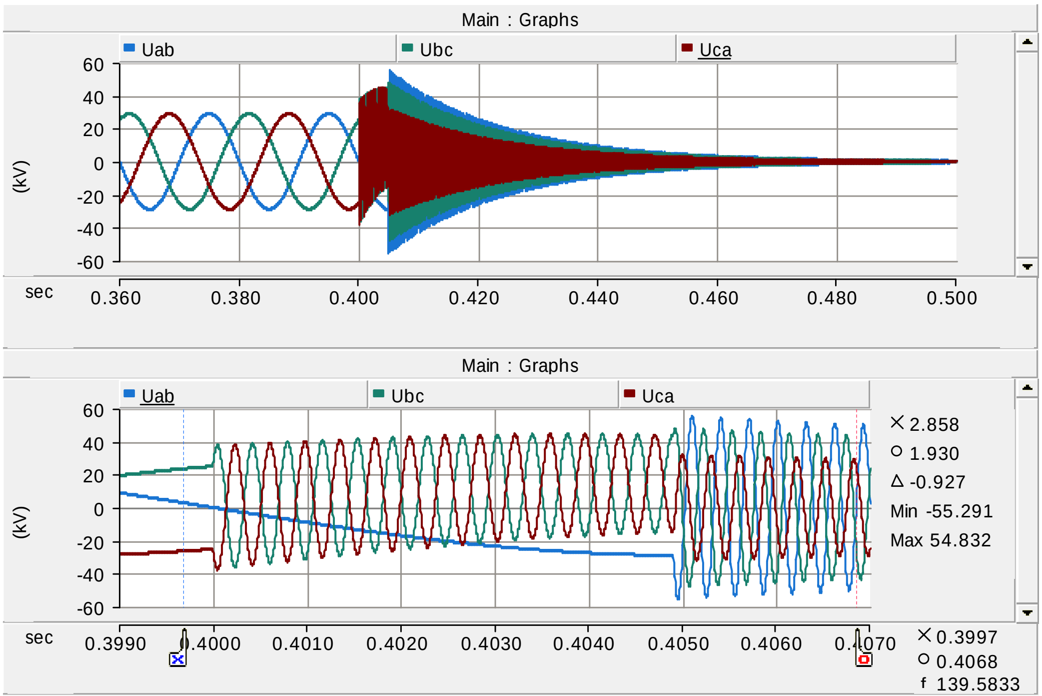

Figure 120. Reactor bus phase to phase voltages on case 142.

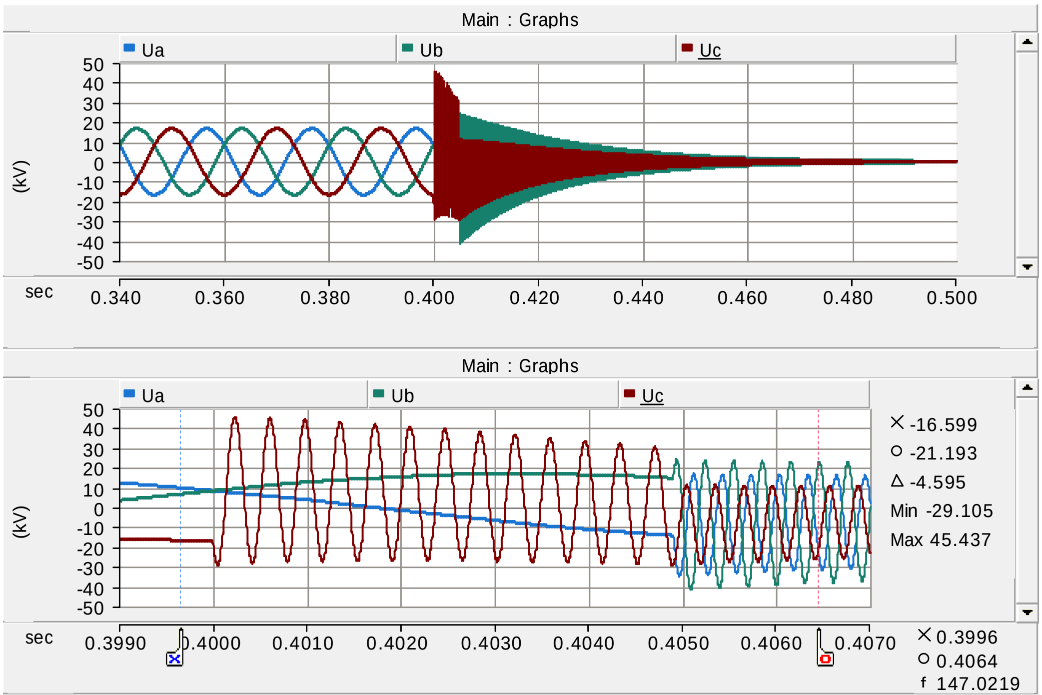

Figure 121. Reactor bus phase voltages on case 142.

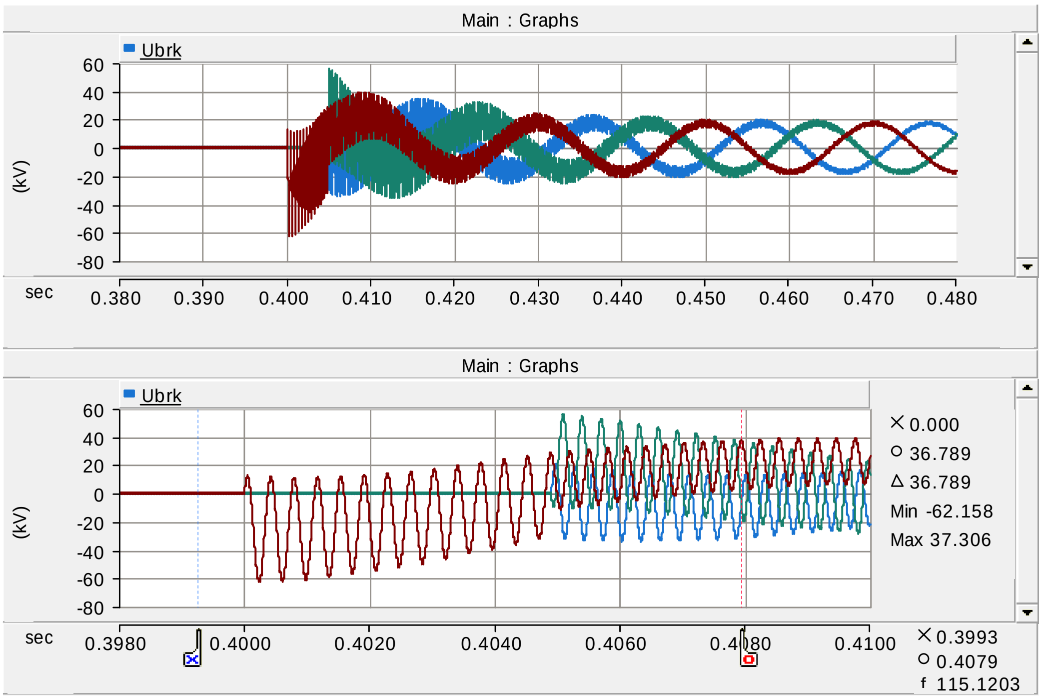

Figure 122. Breaker voltages before cable and reactor on case 142.

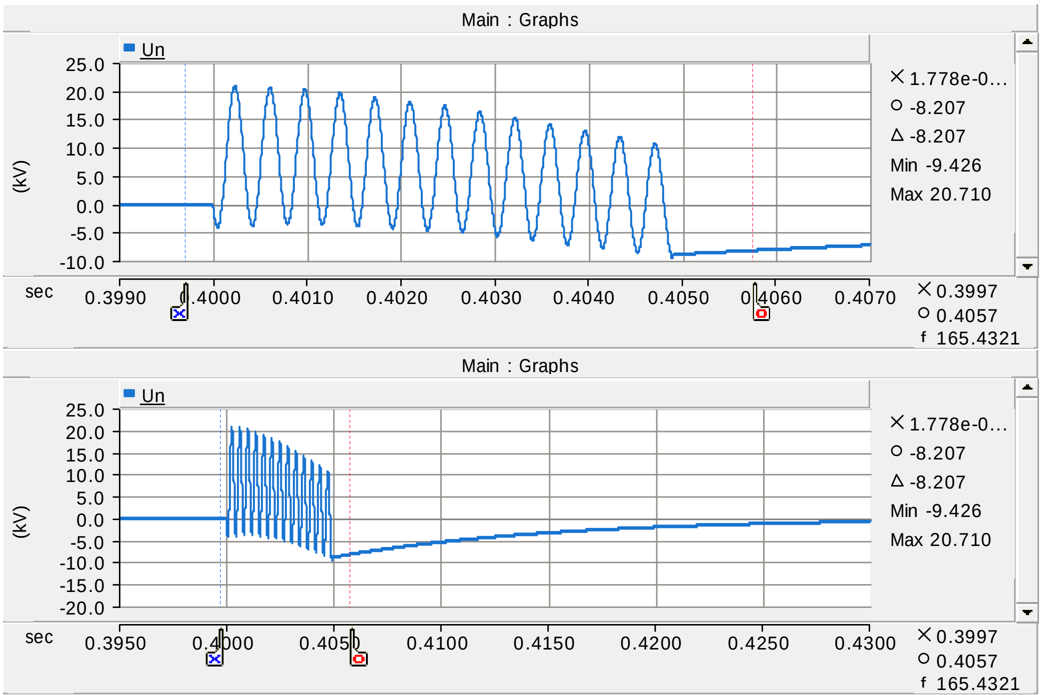

Figure 123. Reactor star point voltage on case 142.

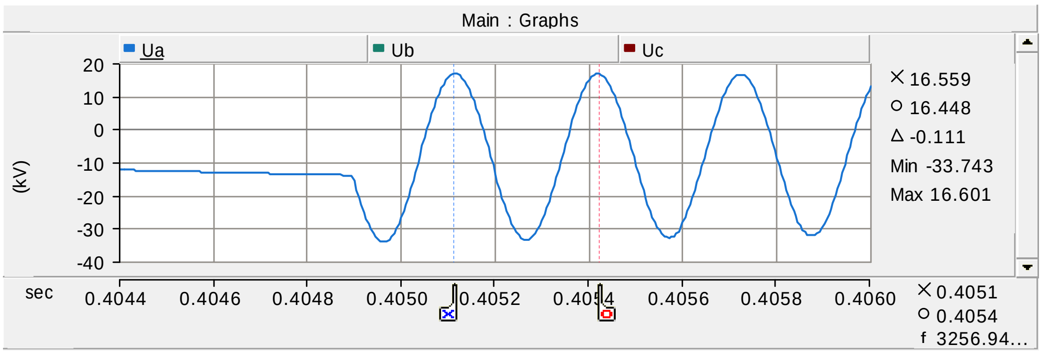

Figure 124. Ua phase Frequency on case 142.