Technical feasibility study of Voltage Optimization Unit

Technical evaluation of distribution transformer with single phase on load tap changer for increasing hosting capacity of photovoltaic

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Technical feasibility study of VOU,
Technical evaluations of distribution transformer with single phase on load tap changer for allocating increasing PVs

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PREFACE

In this EUDP project ‘Energy saving by voltage management’ three reports will be provided by Technical University of Denmark (DTU) covering the simulation studies and experimental work.

This first report presents the simulation results regarding the technical evaluation of on-load tap changers in solving the voltage problems in presence of photovoltaic distributed generation. The second report will present the results of a coordinated voltage control solution between the OLTC control and reactive power provision of PV inverters. The last report will present the experimental results. Both the simulation study and experimental work are implemented at DTU.

SUMMARY

This report provides an analysis on the benefits of a transformer with on load tap changers on each phase that can be applied in the distribution system to accommodate more renewable generations such as photovoltaic power. The main purpose of this research is to verify whether power distribution transformer with OLTC per phase is necessary and valuable. The main conclusion is that power distribution transformer with OLTC control on each phase can significantly improve the PV hosting capacity in the analyzed unbalanced scenarios.

To investigate the verification problem, a simulation study is performed using the softwares DigSilent PowerFactory and Matlab. In this simulation study, a real low voltage network from Dong Eldistribution is modeled in Powerfactory. The measured data of the real low voltage network is analyzed and the resulting loading profiles including active and reactive power are used as load basics for the analysis. In term of PV generation profiles, a realistic PV output power is assumed. Four relevant indicies such as phase neutral voltage, netural potential voltage, unbalanced factor (VUF), and power losses are evaluated in the present study.

The simulation tests include two network layouts, considering a base case (passive network) and an active layout considering the PV integration. For each case, we compared the results of three scenarios firstly operating the network without OLTC transformer, then enabling the OLTC synchronously on three phases and finally with the OLTC acting independently on each phase. The simulations show that in the PV case the system hosting capacity reaches up to 105 kW for a very unbalance PV phase connection scenario (50% of the PV is connected on phase a and 50% of the PV is connected on phase b) and 210 kW for a less unbalanced PV phase connection (50% of the PV is connected on phase a, 30% of the PV is connected on phase b and 20% of the PV is connected on phase c), with the regulation of three single phase OLTC.

TABLE OF CONTENT

ABBREVIATION

VOU: Voltage optimization unit

OLTC: on-load tao changer

1 phase OLTC: 3 signle-phase OLTCs

3 phases OLTC: The tap-changer mechanism changes the taps on all three phases simultaneously.

Voltage unbalances:

Voltage unbalance takes place when the magnitudes of phase or line voltages are different and the phase angles differ from the balanced conditions, or both.

1 INTRODUCTION

1.1 Background

Network operators nowadays face difficult challenges: they need to ensure a stable voltage in the low voltage grid and at the same time to integrate an increasing amount of renewable energy. According to European standard EN 50160, the range of variation of the r.m.s. magnitude of the supply voltage, whether line to neutral or line to line to phase, is Un±10% or Uc±10% for 95% of a week[1]. In the practice, a maximum voltage rise of 3-5% percent is available to renewable energies in the low voltage grid since the rest is reserved for the medium voltage grid, voltage drops, and the setting imprecisions. Fig. 1 shows the situations within the current setting up.

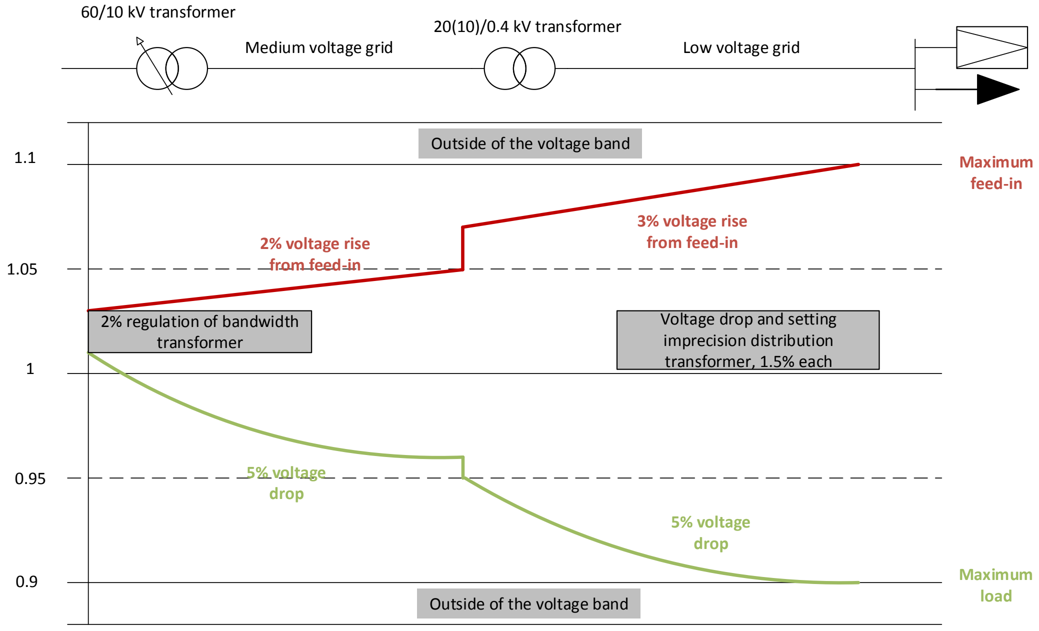


Figure 1: Potential problems faced by the network operator in the presence of no OLTC

The increasing penetration of PVs will raise the risk of violation of the voltage band. Network operators are being forced into expensive expansion work even though the capacities of their operating equipment are far from exhausted. Besides the voltage band violation problem, voltage unbalance problem could also assume more importance in

[1] In practice, the r.m.s value could be determined over a fixed interval of 20 milliseconds and the basic measurement could be made by determining the average of these values over a period of 10 minutes. The assessment of compliance over an observation period of one week, including Saturday and Sunday, could be then performed checking that 95% of the ten minutes values fall within the specified range.

the near future, considering the increasing penetration of PV connected to single phases of the distribution grid. According to EU standard, under normal operating conditions, during each period of one week, 95 % of the 10 min mean r.m.s. values of the negative phase sequence component (fundamental) of the supply voltage shall be within the range 0 % to 2 % of the positive phase sequence component (fundamental).

To address the mentioned problems, this study, a part of the EUDP funded project 'Energy saving by voltage management', aims to develop and demonstrate two new energy optimization units whose objectives are the improvement of distribution network power quality and the reduction of the private household energy consumption. The two units are 10/04 VOU (Voltage Optimization Unit) and DVC (Digital Voltage Control).

DTU is responsible for analyzing the technical feasibility of the 10/04 VOU in different grid cases and for studying the benefits that it can provide to the network either alone or in coordination with the DVC. Our project partner is responsible for analyzing the technical and economical feasibility of the DVC as well as making the prototype pf the DVC.

Although the main functions of the VOU are defined, the specific product type is not discussed. To fulfill the function of the VOU, a voltage regulator or a transformer faciliated with OLTC are both relevant products. Without too much elaboration, this study focuses on the research of OLTC.

The transformer is provided with a certain number of taps in order to adjust the voltage ratio of the transformer. These taps are provided along the winding with connections to a tap-changing device that makes the physical change in the in-service tap. The tap changing device is usually placed on the winding with the higher voltage to minimize the current to be switched and can be 'off-circuit' or 'on-load' type. OLTC are mostly equipped on oil immersed transformers connecting HV networks to MV systems. Because the majority of power companies stipulated a voltage variation of ±10% in the power contract, the tap changer is provided with an equivalent range of voltage regulation of ±10% in 16 or 32 steps: 16 step tap changer provides 5/4% voltage change in each step, while a 32 step tap changer provides 5/8% voltage change in each step thus preferred for a more precise control.

By using VOU, the network operator can increase the grid capabilities by dynamically adapting the voltage by decoupling the voltages of low voltage and medium voltage grid. This may result in an 11 percent rather than a 3 percent voltage rise being available in the low voltage grid for feed-in from renewable energies. This kind of action may help improving the hosting capacity without expensive grid expansion investments.

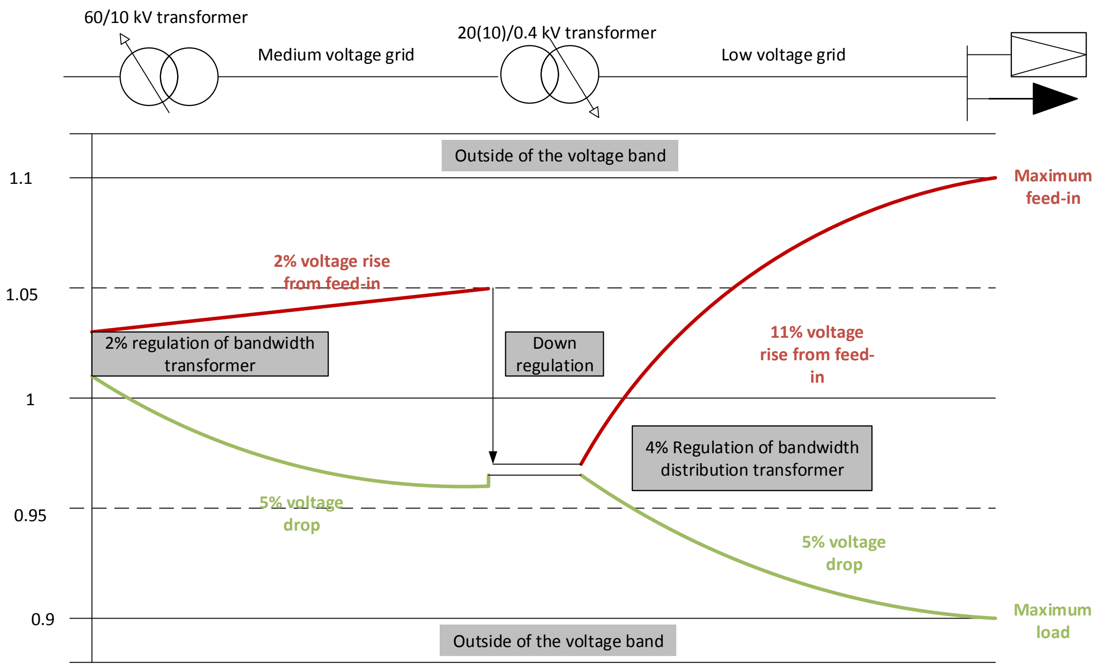


Figure 2: Advantages offered to the network operator in the presence OLTC

1.2 Problem analysis and overall objectives

The simulations consider two different kinds of OLTC devices: 3-phase OLTC and 3 single-phase OLTCs (for simplicity, 3 single-phase OLTCs are named 1-phase OLTC afterwards of this report). The OLTC changes the ratio of a transformer by adding or substracting turns from either the primary or secondary winding. The transformer is therefore equipped with a regulating/tap winding which is connected to the OLTC.

In order to test the technical feasibility of the 10/04 VOU, two representative grid cases (Base case and PV case) are defined firstly in the beginning of this study. For each case, three different scenarios are considered. Table 1 presents the key parameters that are investigated in this study.

Table 1: Key parameters investigated in the two representative grid cases associated with three scenarios

	Base grid case	PV grid case
Without OLTC	• Votlage drop • Voltage imbalance	• Voltage drop • Voltage imbalance • Voltage rise • Power losses
3 phase OLTC	• Votlage drop • Voltage imbalance	• Voltage drop • Voltage imbalance • Voltage rise • Power losses
1 phase OLTC	• Votlage drop • Voltage imbalance	• Voltage drop • Voltage imbalance • Voltage rise • Power losses

Within this project, the purpose is to study the benefits of the OLTC, especially the 1 phase OLTC. In this report, firstly an overview of the related studies and the similar products available in the market is given. Then, the methods used in this study are presented. Afterwards, the detailed simulation results are discussed. In the end of this report, the pros and cons of the proposed methods are addressed along with some conclusions.

2 RELATED STUDIES AND SIMILAR PRODUCTS

2.1 Related studies

In [1], the authors listed several solutions that have been suggested with the purpose of coping with the overvoltage phenomena at high PV penetration levels of distributed generation in LV. The listed methods include: 1) voltage control using reactive power generation from PV inverters; 2) voltage control at the LV side of the LV/MV transformer by on-load tap changers; 3) active power derating of the PV production in case of overvoltage conditions; 4) battery storage/energy buffer at PV generator and MV distribution level; 5) Network upgrade; 6) (Seasonal) changes of the tap position of the LV/MV distribution transformer. Each solution is currently investigated by different stakeholders and their feasibility is generally assessed in report [1].

The authors in [2] show that PV technology has matured sensibly over the last decade. Nowadays, PV components (especially inverters) with good efficiencies and reliability are commercially available. Specifically, issues such as voltage rise and voltage fluctuation, current harmonics and DC injection, unintentional islanding, contribution to short circuit capacity, added value capabilities of modern inverters are discussed. It is reported that a large number of PV systems are connected to voltage regulated distribution lines, the voltage at the customer's terminals might increase depending upon the relative sizes of the load and PV generation.

Ref [3] provides a review of current grid codes in some countries with high PV penetrations. In addition, the paper presents a number of country-specific case studies on different approaches for improved integration of PV systems in the distribution grid. In particular, they consider integration approaches using active and reactive power control that can reduce or defer expensive grid reinforcement while supporting higher PV penetrations. It is stated that the typical technical problems in distribution systems related to a high local PV penetration[2] are local voltages and equipment overloading. To address this proplems, grid connection requirements in Germany, Japan, USA etc., are introduced in the paper. Generally, the requirements in medium voltage and low voltage are different. For example, the reactive power provision methods according to the German

[2] Although no common definition of high penetration PV scenarios yet exists, there is common understanding that high PV penetration exists, if local additional efforts are necessary to maintain a secure and reliable distribution system operation.

technical guideline for the connection to the medium voltage network are reviewed and presented in the following table:

Table 2: Reactive power provision methods according to the German technical guideline for the connection to the medium voltage network.

Method	*Description*	*Response time*
Fixed cosφ	Fixed power factor	------
Cosφ(P) characteristic	Power factor depending on current active power output	Within 10s
Fixed Q	Fixed amounted of reactive power	-----
Q(U) droop function	Amonut of reactive power depends on voltage magnitue at the loca point of common coupling	Between 10 and 60s
Remote set values	Set values for reactive power or power factor via remote control	Within 60s

In [4], the authors perform a technical and economic assessement of two different reactive power control methods and one combined reactive power/active power control method. The results are gained by performing 12 month root-mean-square simulations with a 1 min resolution, using the model of a real distribution grid as well as complex generation and load model. The simulations show that local reactive power provision methods as well as temporal active power output curtailment methods are capable of reducing the necessity of voltage-driven grid reinforcement. However, it is also learned in the study that the economic benefit of those voltage control strategies highly depends on the parameterization of the respective control algorithm.

For the above mentioned reactive power provision control methods, several claimed disadvantages are: need for overrating the PV inverter, increasing the losses in the grid due to reactive current circulation, compensation in the MV network of the generated inductive reactive currents. All the previously mentioned control methods are intended to function autonomously.

Besides the reactive power provision method to address the voltage problem, on-load tap changer methods have been investigated as well.

In [5], DG DemoNet project is introduced and the project objective is to develop and test a intelligent voltage control method in an active distribution grid. The voltage control method focuses on the coordination of OLTC and reactive power exchange between

the DSO and the PV inverter. Several articles [6]–[9] have been published regarding this project. The results obtained in the DG DemoNet project provide a fruitful experience for the ESVM project.
In [10], the authors discuss the voltage control with on load tap changers in medium voltage feeders in presence of distributed generation. Two kinds of technology are discussed for the conventional distribution gird: on load tap changers without and with line drop compensation (LDC). With the provided background, the authors studied the effect of the DG to the OLTC and OLTC provided with LDC. The analysis shows that OLTC is robust against DG, whereas DG can affect the effectiveness of the voltage regulation provided by LDC. It is also shown that with proper coordination between DG and LDC, it is possible to ensure voltage regulation without unnecessarily restricting the integration of DG.
In [11], the authors presented a proposal for an active management of the distribution system through an innovative controller that coordinates the on load tap changer action with the regulation of reactive exchanges between DG plants and feeders.

However, the OLTC studied in the above research basically belongs to the 3 phase synchronous OLTC type. The studies can not fully meet the requirements and the realities in the distribution system since in most case the PV inverters are connected on single phase of the system. The single phase connection of the PV would results in a high voltage in one phase while the other two phases might be heavily loaded. In such scenario, the 3 phase OLTC can not solve the problem, so it is important for this study to investigate the 3 single phase OLTC in presence of distributed generation.

2.2 Similar products

Two similar products available in the market are introduced in the following: GRIDCON transformer from Maschinenfabrik Reinhausen Gmbh, Germany and FITformer REG from SIEMENS. These two transformers are specifically designed for voltage regulation in the low voltage grid with the purpose of allocating more PVs. Both transformers are equipped with 3-phase OLTC and they are briefly introduced in this report.

GRIDCON transformer

GRIDcon® Transformer provides different features to deal with autonomous voltage regulation in distribution networks:

- The transformation function transforms upper voltage into lower voltage.
- The on-load switching function allows the ratio between the upper and lower voltage in the transformer to be dynamically adjusted under load
- The drive function guarantees reliable switching
- The regulator function – including sensors – measures the voltage and derives the switching operations required

FITformer REG SIEMENS

The power range of the regulated distribution transformers extends uo to 630 kVA, with a maximum operating voltage of 36 kV and a low-voltage control range in three stages.

3 SYSTEM MODELING AND PARAMETERS

In this chapter, the distribution network model, the load modeling method, the electricity consumption profiles, the definition of the PV penetrations in a distribution network, and the voltage unbalance definitions are introduced.

3.1 Distribution network modelled in PowerFactory

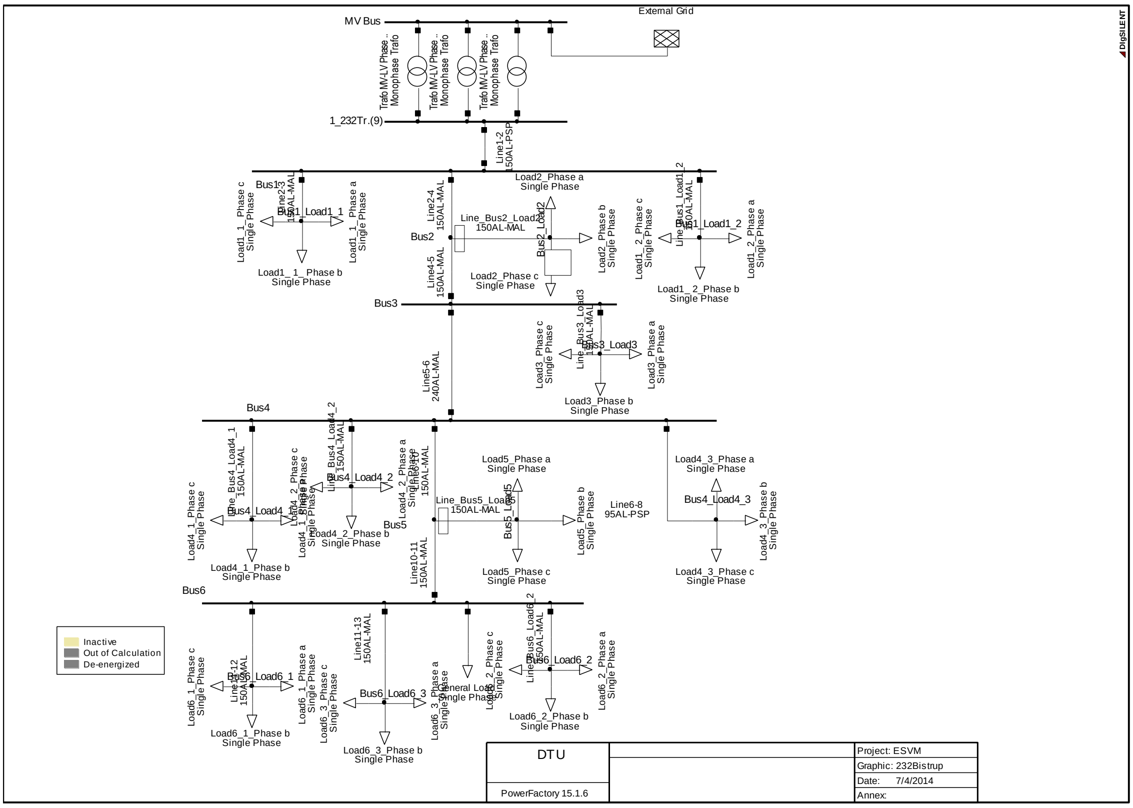


Figure 3 Low voltage distribution network modelled in PowerFactory (Base grid)

The low voltage distribution network (0.4 kV system connected to a 10 kV MV grid) is a real network provided by Dong Energy Elsdistribution previously used in the Danish iPower project [12]. Starting from the network shown in Fig. 3 (passive case) the grid layout has been modified in order to consider several PV installations as depicted in Fig. 4, hypothesizing different penetration scenarios. Note that the orange filled rectangular box indicates the position of the PV invertes in the distribution network. All the loads and the PV inverters are connected in the system via single phase cable.

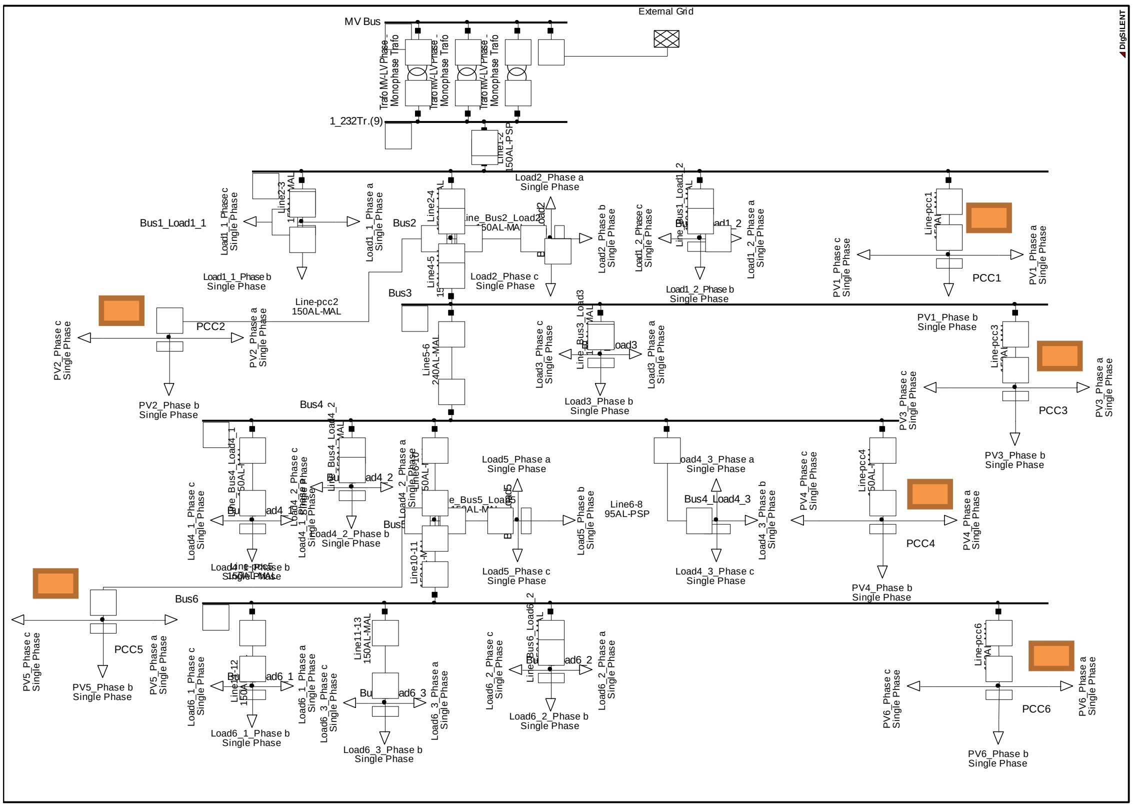


Figure 4 Low voltage distribution network with PV connections modelled in PowerFactory (PV grid)

To perform the RMS (root mean square) simulation, a dynamic transformer model [13] and a dynamic load model [14] are required. The details of modeling approach are presented in the following sections.

3.2 Dynamic 3 phase and 1 phase transformer modeling

In the base grid case, without any DG unit, the OLTC is used to raise the voltage level due to the increasing power consumptions. The general OLTC working principle comprises following steps:

- Power consumption rises, the network's voltages levels drops due to the higher energy demand.
- The OLTC adjusts the voltage level according to a voltage regulator which constantly monitors the voltage level at the controlled bus.
- If the voltage level exceeds the pre-defined range for a certain period of time, a switching pulse is released, a mechanical switching process is then activated and the transformer's tap positions are changed in order to compensate the voltage drop.

In the PV case study, the same approach has been implemented to take care of the voltage rise problem and the control logic is to tap down the transformer when the voltage exceeds the limitations.

Based on this principle, the control logic for 3-phase and 1-phase OLTC has been designed and implemented it in the software PowerFactory version15.1.

The approach used to define the tap-controller of the 3 phase and 1 phase OLTC transformers is illustrated in Fig. 5. Each transformer has the same frame-block that is composed by three measurement blocks, the Tapping log. ElmTap* block, the Actuator-ElmE^s* block and finally the Transformer ElmTr2* block. Because of the different test requirements of the project (no tap action, 3-phase coordinated tap action, and 1 phase continuous tap action) three measurement blocks (instead of just one) are used. In this way the same frame-block can be adapted to any scenario. The measured voltages are phase-n voltages and the measurement point is the bus-bar at the end of the line.

The voltages measured at the controlled busbar (uA, uB or uC) are the inputs of the second block. The second one (namely "Tapping log." slot) is the 'heart' of the control system: its operations are based on a continuous tapping logic which according to the x-values (i.e. voltage values) provides corresponding tap selector positions (y-values). The output signal goes into the Actuator- ElmE^s* block which is a delay-integrator block, whose output signal goes into the last block, that applies the new tap position to the single-phase transformers.

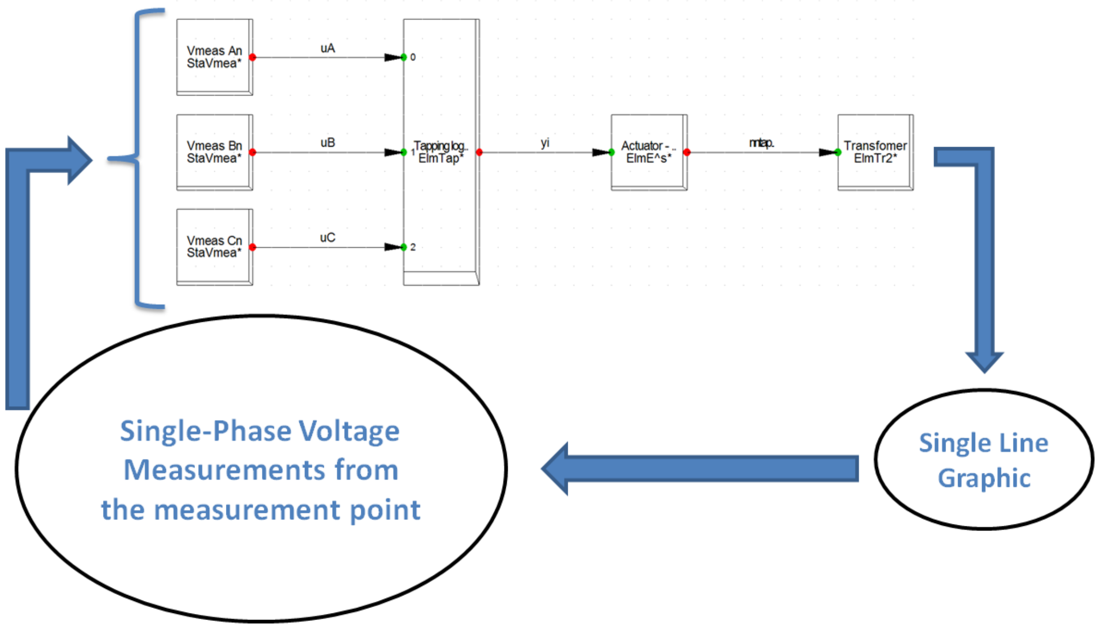


Figure 5: Frame of 3 phase and 1 phase OLTC controller

The equations used in the Tapping log. block are the following:

```
inc(nntap) = 0;
inc(uA) = 1;
inc(uB) = 1;
inc(uC) = 1;

u = flagA*uA+flagB*uB+flagC*uC;
! Note that:
-In the 3 phase case, it is specificed flag A=1, flagB=flagC=0, (it is also possible that either flagB or flagC are specified as 1) because only one measurement that can be used at one time, therefore, the three phases have same tapping sequences.
-In the 1 phase case, for each phase, the measured value is different and therefore the tap controller gives different tapping logics in each phase.
nntap = lapprox(u,array_V);
```

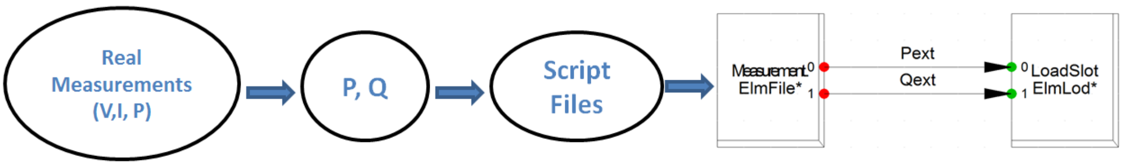
The equations used in the Delay block /Actuator block are presented as follows:

```
limits(T)=[0,)
inc(yo)=yi
yo=delay(yi,T)
```

3.3 Dynamic load modeling

ComLoad - ComLoadMod

The load profiles are characterized by using single phase measurement data on voltages, currents and active powers with a 10 minutes resolution during a 24-hours interval. In order to simulate the real behavior of the loads, it is necessary to link all the loads in the single line graphic to the real measurement data. The measurement data[3] are used to extract the active and reactive power at each bus, then the values are processed through several Matlab script-files to obtain the loads' power values. Each load has the same frame-block named ComLoad which, as can be seen in the right side of Fig. 6, is composed by the Measurement ElmFile* block and the LoadSlot ElmLod*. The first one imports the active and reactive power values from an external file and gives them out as two outputs. These values (Pext and Qext) are the input data of the second block, which applies those values to the load, characterizing it with real time-depending power quantities.



[3] Please see details in section 3.4.

Figure 6 Framework of the dynamic load modeling.

It has been noticed that there was no perfect correspondence between the measured power absorption and the input power data of the Script Files. This was due to the constant impedance load model used when running RMS simulations instead of a constant power model. The PV generation plants are considered in this work as ‘constant-power’ active loads. According to these considerations, it is important to modify the previous developed dynamic model and adapt it for PV model base on the ‘ZIP Theory’.

ZIP THEORY

Each real load can be modeled with reference to its physical characteristics: it could simply be a ‘constant-power load’, a ‘constant-current load’ or a ‘constant-impedance load’, or it could be represented as a mix of the previous characteristics. The following equation is used to describe the ZIP theory:

$$P = P_0\left[a_1\left(\frac{V}{V_0}\right)^2 + a_2\left(\frac{V}{V_0}\right) + a_3\right]$$

The three coefficients a_1, a_2, a_3 represent, respectively the shares of the constant-impedance, constant-current and constant-power contributions.

Another possible model is the Exponential Model, which considers a simple exponential law where the exponent α is an index related to the load nature. The three extreme load cases – ‘constant-power’, ‘constant-voltage’ and ‘constant-impedance’ – are represented respectively by α=0, 1, 2.

$$P(V) = P_0\left(\frac{V}{V_0}\right)^{\alpha}$$

It has been noticed that the PowerFactory software for RMS simulations considers loads according to the ‘constant-impedance’ model, which means that their behavior is described by the Exponential Model equation, assuming α=2. This is the proper cause of the aforementioned power mismatching; in fact the PV generation plants (modelled as active loads) in the analyzed LV network are supposed to be ‘constant-power loads’.

Due to this, it has been necessary to change the frame-block of these loads, by adding a block able to change the load behaviors from ‘constant-impedance’ to ‘constant-power’. The new added ‘Voltage Corrector ElmCom*’ shown in figure 7 implements the following equation, where P_{ref} is the active power read from the Script File and P_{mod} is the modified active power, which will effectively go into the LoadSlot block:

$$P_{mod} = P_{ref}\left(\frac{1}{V}\right)^2$$

As seen in the equation, the voltage V needs to be measured: three measurement blocks (instead of just one) are used. By managing these three blocks (enabling one at a time), the same frame-block can be used to refer the operations to the elements connected to different phases.

The modified frame-block – named ComLoadMod – can be seen in the following picture, where a concept scheme is presented too.

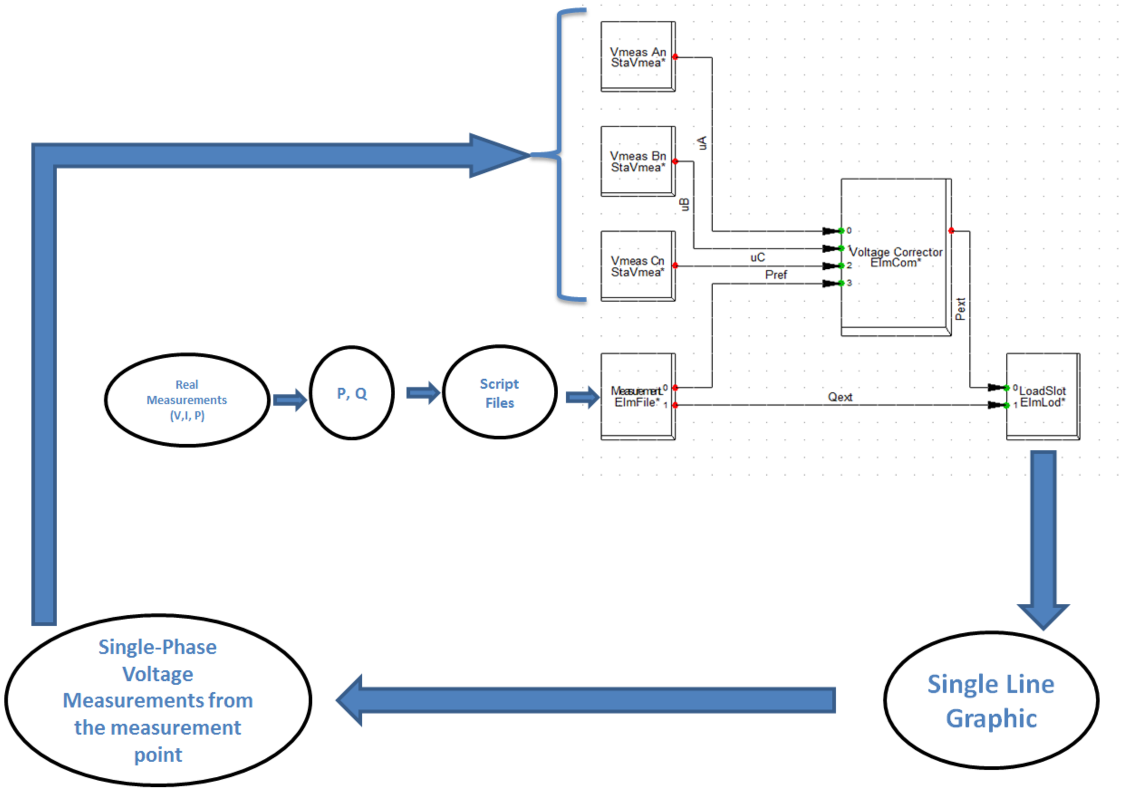


Figure 7: Framework of the corrected dynamic load model, used for PV generation.

The equations which the Voltage Corrector block refers to are the following:

```
inc(uA) = 1;
inc(uB) = 1;
inc(uC) = 1;

!uA = flagA*sqrt(sqr(ur_A)+sqr(ui_A));
!uB = flagB*sqrt(sqr(ur_B)+sqr(ui_B));
!uC = flagC*sqrt(sqr(ur_C)+sqr(ui_C));

u = flagA*uA+flagB*uB+flagC*uC;
!note: the flag is needed because we are reading all 3 phase meas.
! we want to select just one input at the time
```

```
!inc(u)=1;
Pmod = Pref*sqr(1/u) ;
```

After the discussed change, it has been possible to have effectively 100% correspondence between the measured power absorption and the input power data of the Script Files for the PV plants.

To summarize, the ‘ComLoad’ block has been used for the passive loads, while the modified one – ‘ComLoadMod’ – has been used for the PV plants.

3.4 Loading profile of the network

The loading profiles adopted in the simulations are derived from the Danish ipower project. In iPower workpackage 3.2, a real measurement of the Danish residential load is used. In a short word,

- For each load modelled in the PowerFactory, a time series loading profiles of one day is used (10 minutes time resolution).
- Data is analyzed and processed since quite a number of bad data exists.
- Reactive of the load is estimated according to the measurement.

In the end, P and Q is the input of the load.

3.5 Definition of PV penetration for the electrical network

The PV penetration levels are defined in this study according to the definition used in [15][16] and it is expected that an economical investment in a residential solar plant under the present legislative framework will result in an installed capacity of 5 kVA. The PV penetration defined in this study is calculated as the number of the customers installing a 5 kVA solar divided by the total number of customers. The total installed PV in a LV network is determined by the number of customers, the maximum rated power of one PV inverter (5 kVA) as well as the penetration.

$S_{PV} = n_{loads} . S_r . PV\ level\ in\ \%.$

Regarding the orientation of the PV panels in the residential area, it is assumed that the PV systems are scattered in various orientation and inclination. The typical output power from a 1 kW PV system in ‘clear sky’ conditions used in [15] is also utilized in this study and the following figure presents the output power.

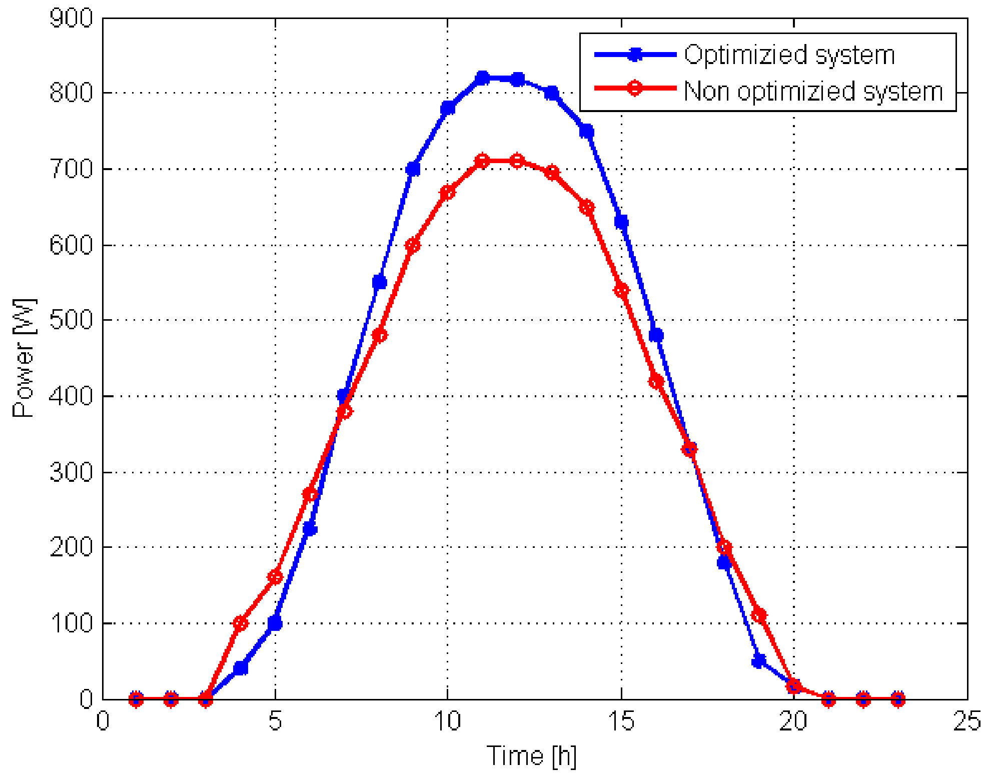


Figure 8: Typical output power from a 1 kWp PV system in "clear sky" conditions. The blue curve shows the power from aggregated systems pointing all south. The red curve shows the corresponding power for 10 systems which are scattered from East to West with 30° and 45° inclination. Resource of [15].

3.6 Three definitions of voltage unbalances

Voltage unbalance takes place when the magnitudes of phase or line voltages are different and the phase angles differ from the balanced conditions, or both. In [17], three definitions of voltage unbalance are stated and analyzed and three definition are briefly introduced as follows:

1. NEMA (national equipment manufacturer's association) definition, also known as the line voltage unbalance rate (LVUR), is given by

$$\%LVUR=\frac{\max voltage\ deviation\ from\ the\ avg\ line\ voltage}{avg\ line\ voltage}*100$$

The NEMA definition assumes that the average voltage is always equal to the rated value, which is 480 V for the US three-phase systems and since it works only with magnitudes, phase angles are not included.

2. IEEE definition, also known as the phase voltage unbalance rate (PVUR), is given by

$$\%PVUR=\frac{\max voltage\ deviation\ from\ the\ avg\ phase\ voltage}{avg\ phase\ voltage}*100$$

The IEEE uses the same definition of voltage unbalance as NEMA, the only difference being that the IEEE uses phase voltages rather than line-to-line voltages. Here again, phase angle information is lost since only magnitudes are considered.

3. True definition: The true definition of voltage unbalance is defined as the ratio of the negative sequence voltage component to the positive sequence voltage component . The percentage voltage unbalance factor (% VUF), or the true definition, is given by

$$\%VUF=\frac{\text{negative sequence voltage component}}{\textit{positive sequence voltage component}} * 100$$

In this study, the true defintion is used to calculate the unbalance factor of the system.

4 SIMULATION RESULTS

4.1 Base grid case

4.1.1 Overall result analysis

In the base case the simulation results are discussed showing two key parameters: voltage drop and voltage balance. Specifically, for each scenario of the base case, the results carried out are the voltage profiles at the transformer level and at bus 6, the unbalance factor and the power losses ratio. To summarize the result, table 3 presents the mean and minimal values as well as the standard deviation of the phase voltages at bus 6.

Table 3 Mean, minimal and standard deviation value of the voltage at bus 6

	Bus 6 voltage (mean value)			Bus 6 voltage (minimal value)			Bus 6 voltage (standard deviation)		
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c
Base case	0.9811	0.9941	0.9824	0.9532	0.9757	0.9641	0.0098	0.0053	0.0049
3 phase OLTC	0.9881	1.0012	0.9894	0.9630	0.9841	0.9714	0.0088	0.0058	0.0047
1 phase OLTC	0.9914	0.9939	0.9930	0.9768	0.9893	0.9881	0.0033	0.0015	0.0014

Based on the performed simulations which are presented in section 4.1.2 to 4.1.4, the following observations can be made:
1) The voltage profiles are improved when the 3 phase OLTC and 1 phase OLTC are introduced to the power transformer.
2) The voltage profiles keep closely when the 1 phase OLTC is introduced for the power transformer since each phase can be controlled individually.

Besides, as shown in Fig. 12, 16, and 20, the power losses don’t change significantly. As indicated in Fig. 11, 15, and 19, the voltage unbalance doesn’t reach values high enough to represent a problem.

4.1.2 Transformer without on load tap changer

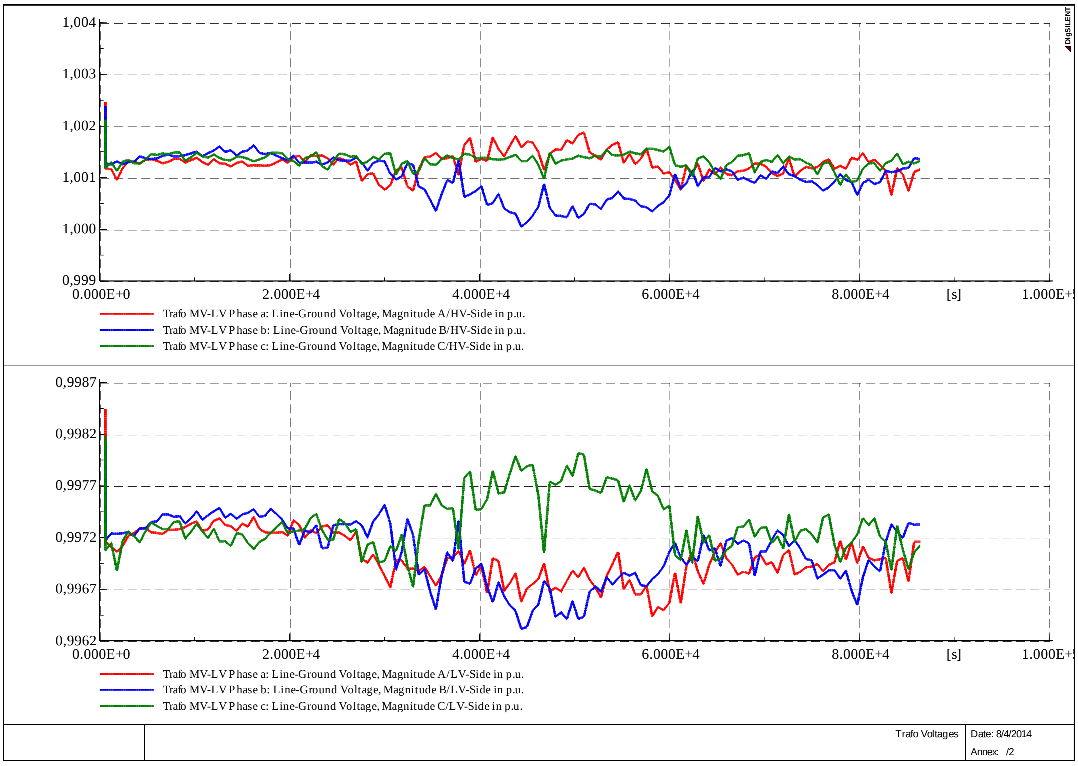


Figure 9 Voltage profile at the transformer level

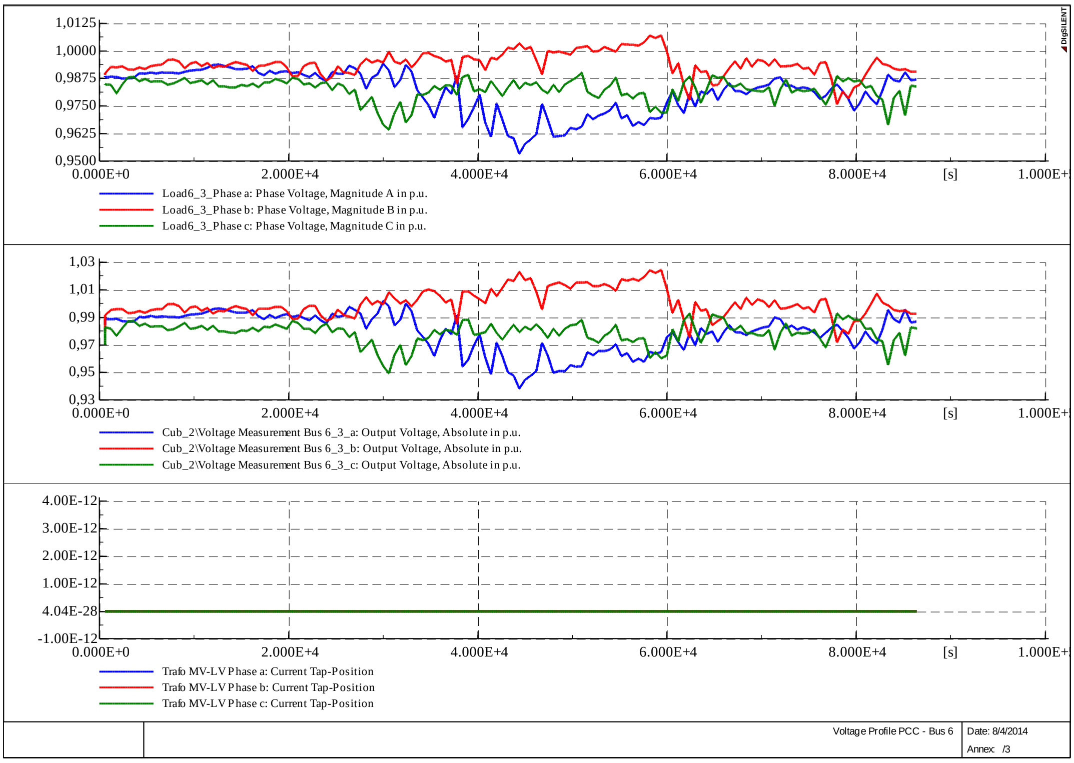


Figure 10 Voltage profile at the Point of Common Coupling PCC bus 6

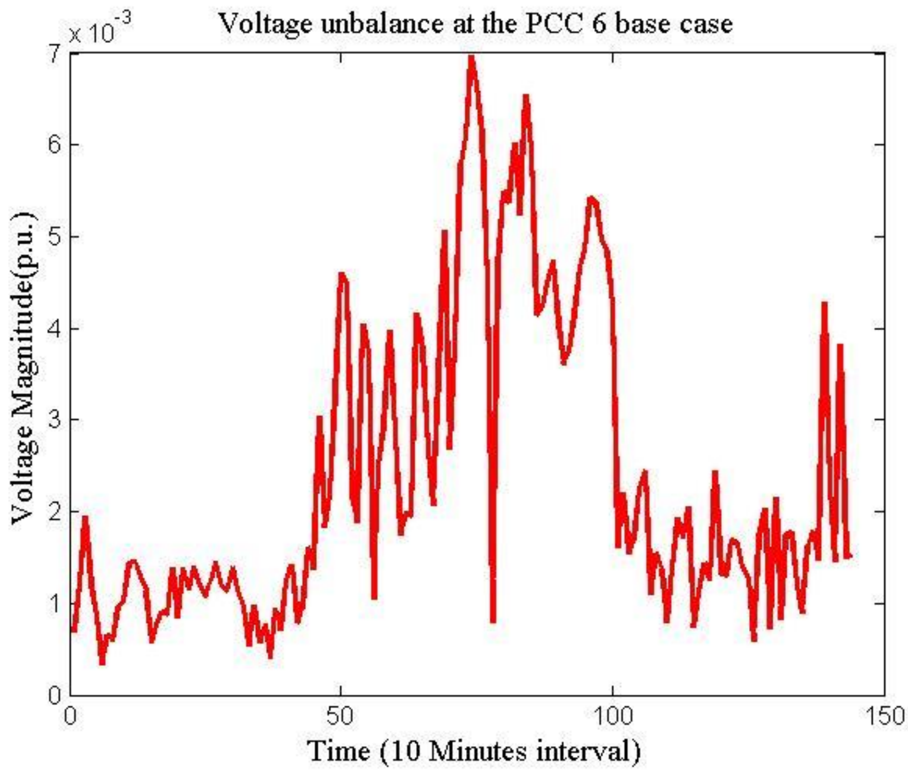


Figure 11 Unbalance factor

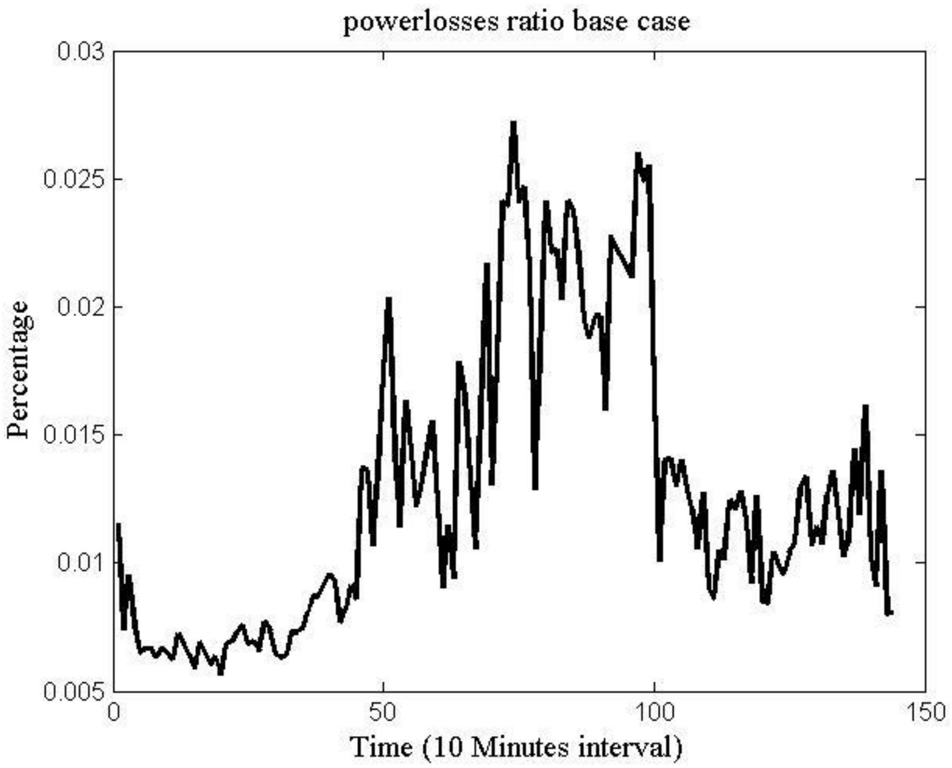


Figure 12 Power losses and power loss ratio

4.1.3 Transformer with 3 phase on load tap changer

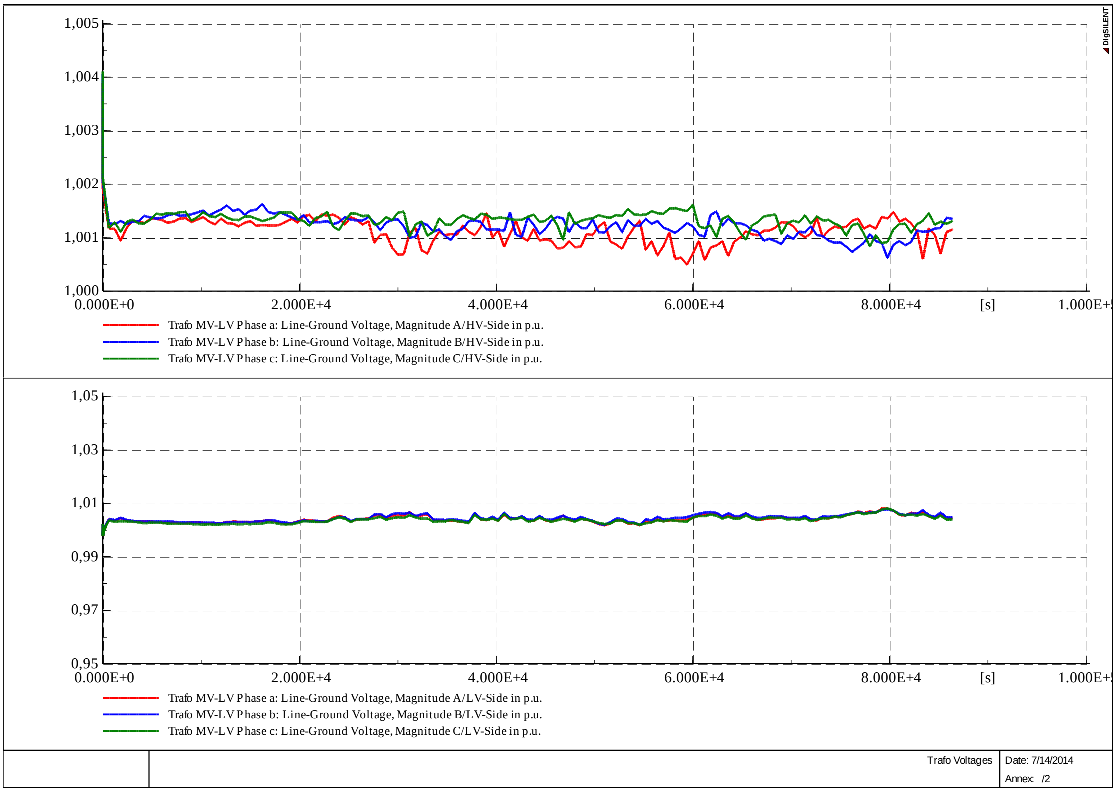
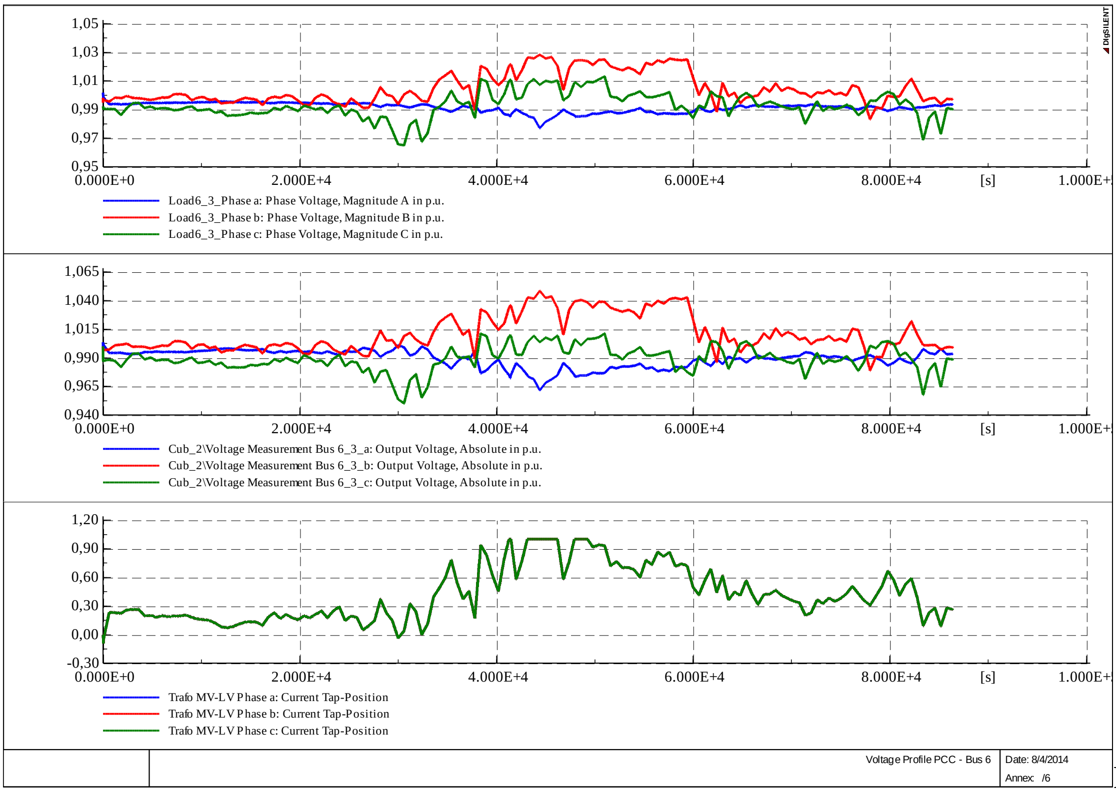


Figure 13 Voltage profile at the transformer level



F

igure 14 Voltage profile at the Point of Common Coupling PCC bus 6

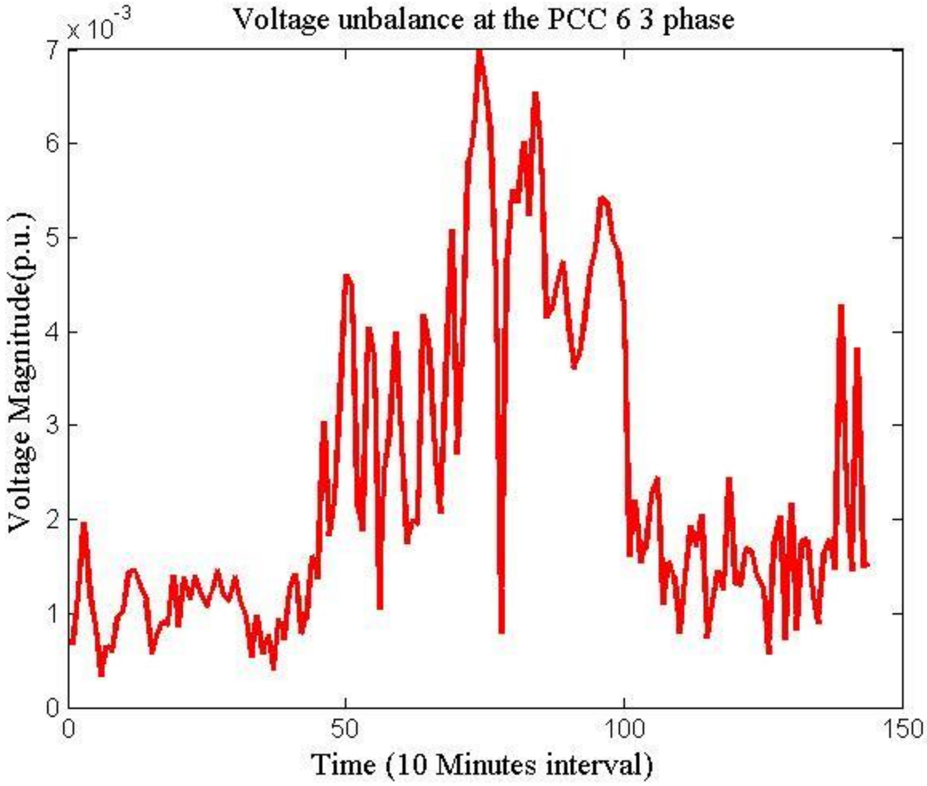


Figure 15 Unbalance factor

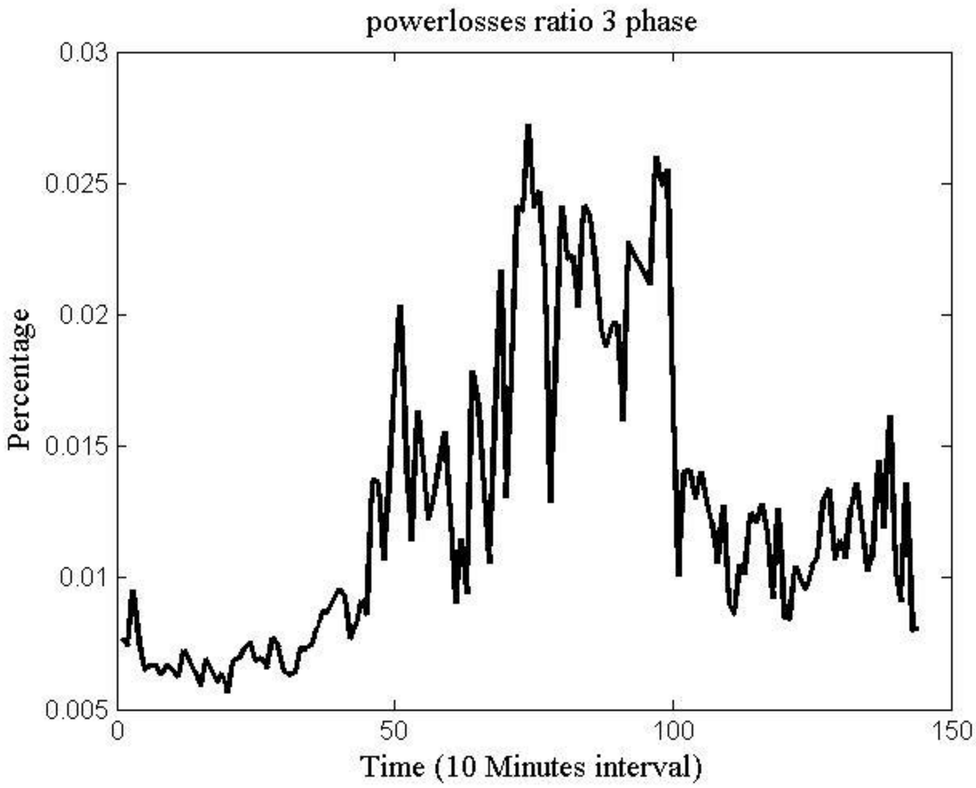


Figure 16 Power losses and power loss ratio

4.1.4 Transformer with 1 phase on load tap changer

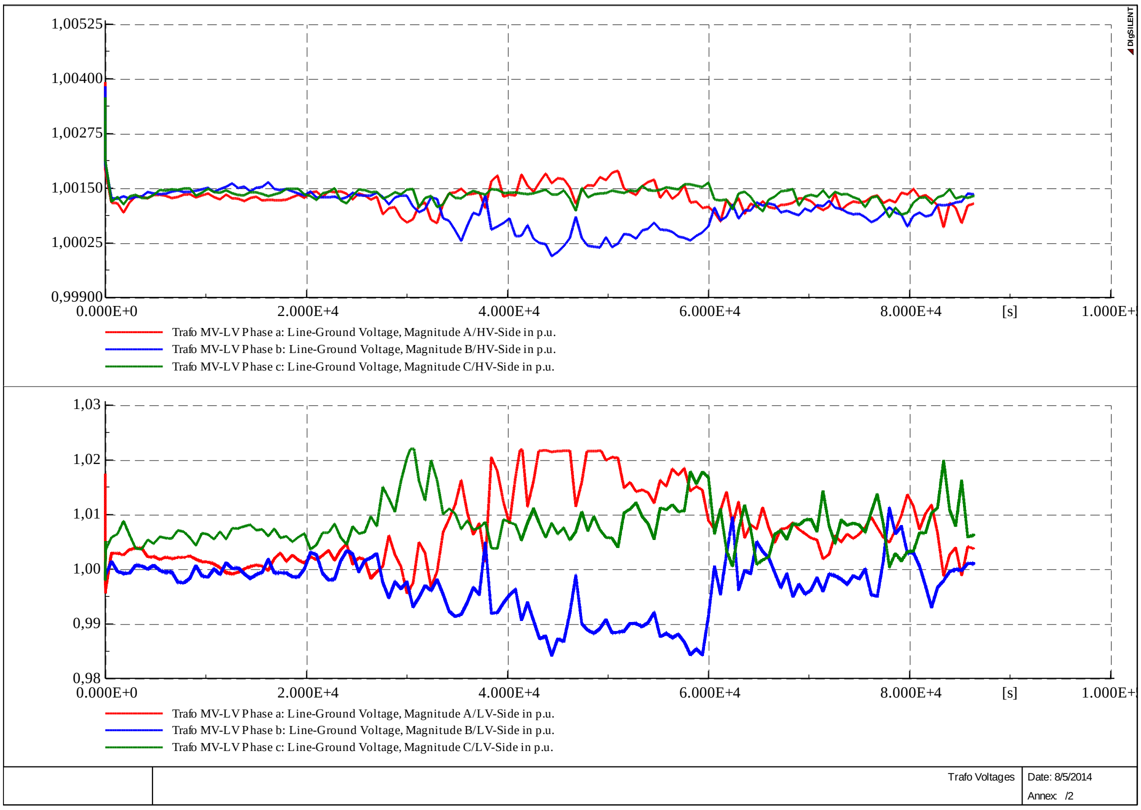


Figure 17 Voltage profile at the transformer level

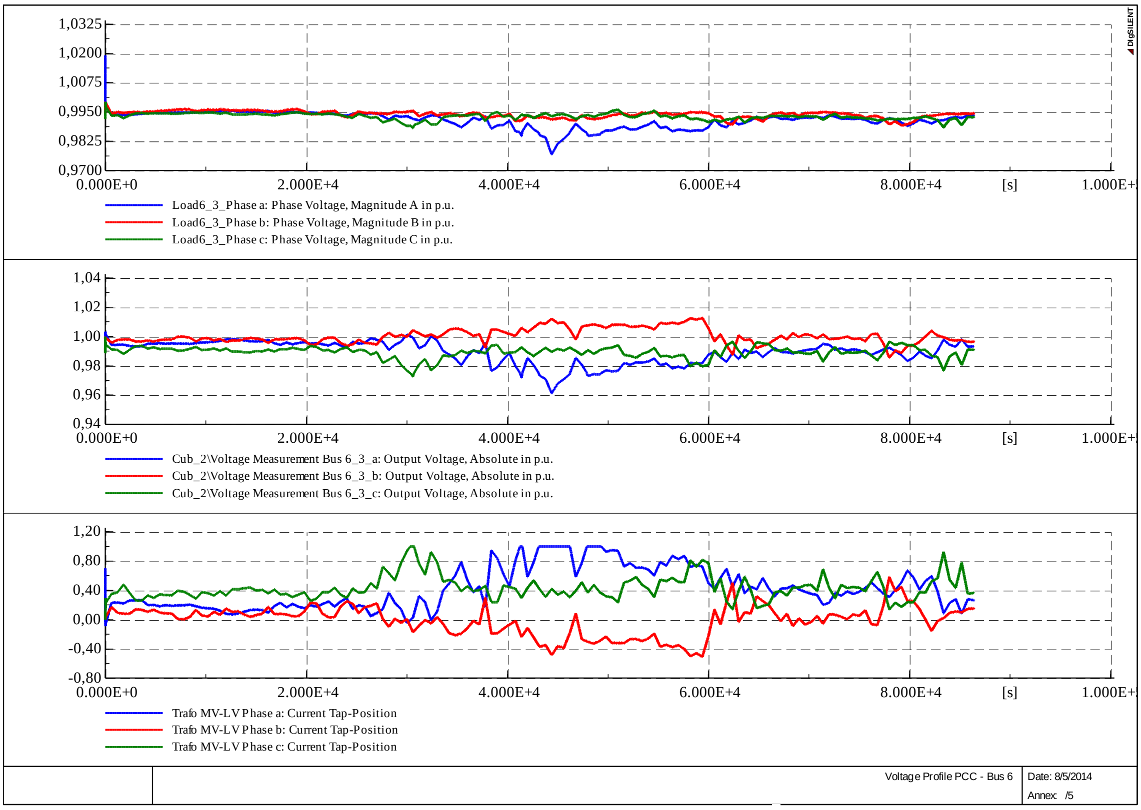


Figure 18 Voltage profile at the Point of Common Coupling PCC bus 6

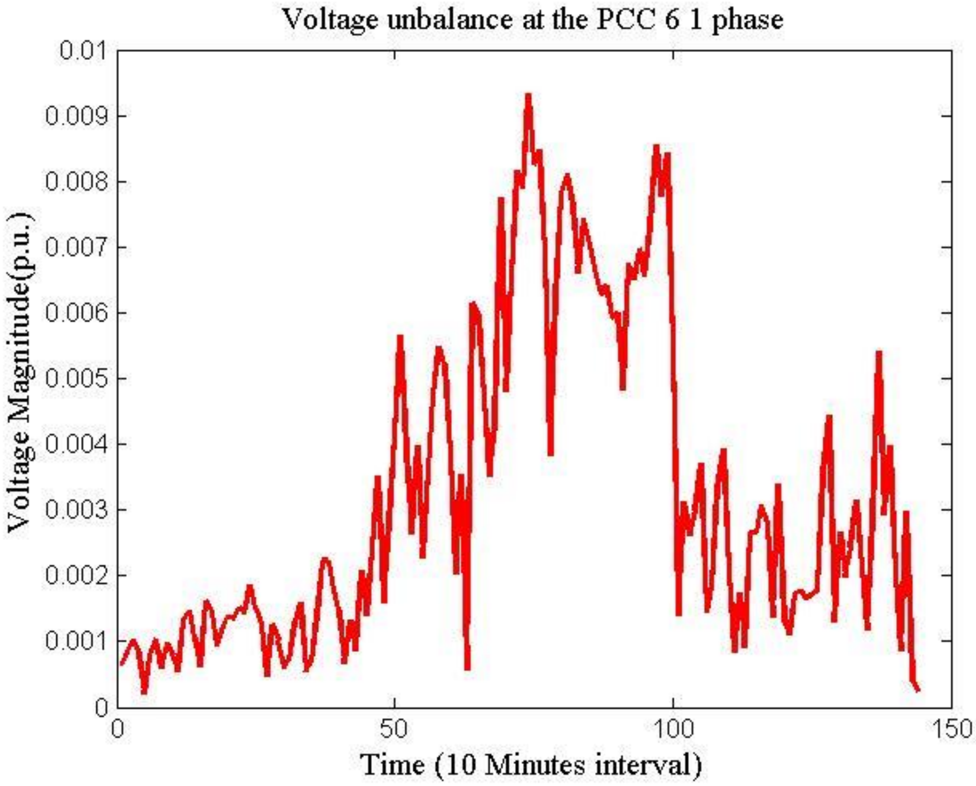


Figure 19 Unbalance factor

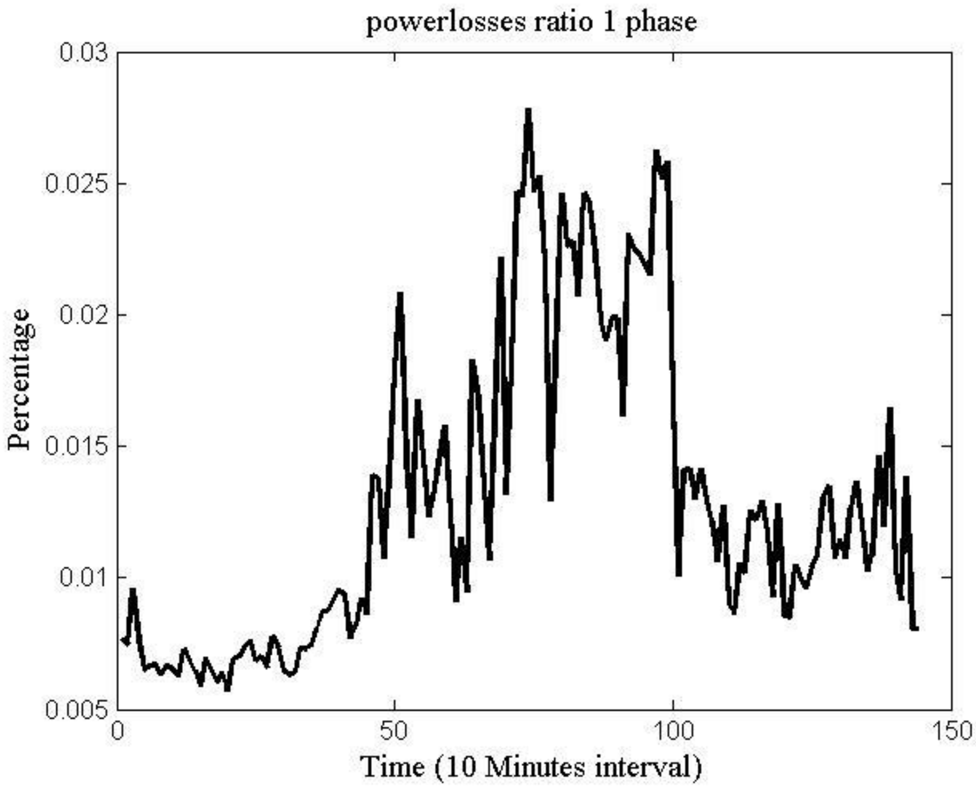


Figure 20 Power losses and power loss ratio

4.2 PV grid case with a very unbalanced connection

The following table presents the assumptions on the PV connection in the network leading to the different penetration scenarios and it could be seen that a very unbalanced situation has been considered.

PV penetration level [%]	Total PV power for a LV network with 70 customers [kVA], one PV inverter 5 kW.	Phase connections (A,B,C with different penetration %)	Number of customers
0	0	N.A	0
10	35	A	7
20	70	A	14
30	105	A,B (50,50)	21
40	140	A,B (50,50)	28
50	175	A,B (50,50)	35
60	210	A,B (50,50)	42
70	245	A,B,C (50,30,20)	49
80	280	A,B,C (50,30,20)	56
90	315	A,B,C (50,30,20)	63
100	350	A,B,C (50,30,20)	70

4.2.1 Overall result analysis

After testing all of the above mentioned scenarios, the results highlighted a hosting capacity limit of 105 kW (30 % PV penetration) given the same passive loads profiles as the one in the base grid case.

<u>10% PV penetration Case (Simulation results are presented in section 4.2.2)</u>

The 10% case refers to the situation of 35kW of PV connected to the phase a. It is seen that the situation is acceptable even without OLTC actions:

- phase-neutral voltages at the final bus are within the range -5%/+5%;
- phase-neutral voltages at the transformer level are practically staying at the nominal values;
- neutral-ground voltages at around 2% of the nominal phase to ground voltage (230V);
- VUF under 1,2%;
- amount of energy losses is 6,45kWh and the maximal energy-power loss ratio is 1.5%.

The situation of the 3 phase OLTC case is similar to the one without OLTC, in which the phase-neural voltages at the final bus stay within the range -7%/+3%. The VUF is not changing. The total energy loss is around 6,59kWh which means +2,18% increasing compared to the case without OLTC. In the 1 phase OLTC case, the value of voltages and VUF is getting better, while the energy losses rises a bit:

- phase-neutral voltages at the final bus within the range -2,5%/+2,5%;
- phase-neutral voltages at the transformer level within the range -3%/+2,5%;
- neutral-ground voltages at around 2% of the nominal phase to ground voltage (230V);
- VUF under 1,3%;
- amount of energy losses of about 6,66kWh, which means around +3,33% compared to the base case; the maximal energy-power loss ratio is 1,6%.

The amount of the energy absorbed by the loads, injected by the PVs and the transformer and the corresponding energy loss, can be read in the following table, which contains values of the three study cases:

Three scenarios	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the transformer [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%, compared to base case]
Base case	749,43	244,53	511,35	6,45	+0,00%
3 Phase	756,92	244,49	519,02	6,59	+2,18%
1 Phase	761,75	244,48	523,93	6,66	+3,33%

<u>30% PV penetration Case (Simulation results are presented in section 4.2.3)</u>

About the 30% case, it refers to the situation of 105kW of PV connected to phases a and b in the system. It is noticed that in the 3 phase OLTC case it is not possible to have phase-neutral voltages at the final bus which are within the acceptable range -10%/+10% of the nominal value and therefore it is concluded that the 3 phase scenario with 30% PV penetration level cannot be considered feasible with the current setup. So it can be deduced that the maximal PV hosting capacity of the network with the 3 phase tapping logic is 10%, (i.e. the unbalanced connection of 35kW to phase a, without power injection into phases b and c) in this particular unbalanced load condition.

However, it is possible to obtain acceptable voltages, VUF and losses with two other scenarios, i.e., base case and 1 phase OLTC scenario. In the following a summary of the simulations is given.

Base case scenario results:

- phase-neutral voltages at the final bus stay within the range -8%/+8%;
- phase-neutral voltages at the transformer level stay at the nominal values;
- neutral-ground voltages is around 3,75% of the nominal phase to ground voltage (230V);
- VUF under 1.4%;

- amount of energy losses is 14,65kWh and the maximal energy-power loss ratio is about 2,6%.

1 Phase OLTC results:

- phase-neutral voltages at the final bus stay within the range -5%/+4%;
- phase-neutral voltages at the transformer level stay within the range -4%/+4%;
- neutral-ground voltages is under 4% of the nominal phase to ground voltage (230V);
- VUF under 1,9%;
- amount of energy losses is 15,24kWh, which means around +4,01% compared to the base case scenario; maximal energy-power loss ratio is around 2,7%.

The amount of the energy absorbed by the loads, injected by the PVs and the transformer and the corresponding energy loss, is reported in the following table, which contains values of the three study cases:

Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the transformer [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%, compared to base case]
Base Case	756,30	731,21	39,74	14,65	+0,00%
3 Phase	753,48	730,71	37,82	15,05	+2,73%
1 Phase	763,29	730,60	47,93	15,24	+4,01%

<u>40% and 50% Cases (Simulation results are presented in section 4.2.4)</u>

About the 40% and 50% cases, they refer respectively to the situation of 140kW and 175kW of PV connected to phases a and b. It is noticed that both in the 'without OLTC case' and 'the 3 phase OLTC case' it is not possible to have phase-neutral voltages at the final bus within the acceptable range -10%/+10% of the nominal value. It is therefore deduced that 40% and 50% of PV penetration level cases cannot be considered feasible with the base case and 3 phase scenario. Nevertheless, the 1-phase control can improve the phase-neutral voltage values at the final bus with acceptable losses, although this improvement has been seen to effect negatively the VUF value where the maximal values are around at 2,5% and 2,9% respectively for 40% and 50% cases. So, even if the 1 phase tapping control allows the three phase-neutral voltages to get close to the nominal value, negative effects on the unbalance level are caused due to the voltage sequences. In fact, the VUF increase is due to the reduction of the positive sequence magnitude, while the negative sequence magnitude increases during the PV production period. This can be seen in the following graphs reporting the results for the 40% penetration case where the solid lines represent the without OLTC case, while the dashed one shows the 1 phase case.

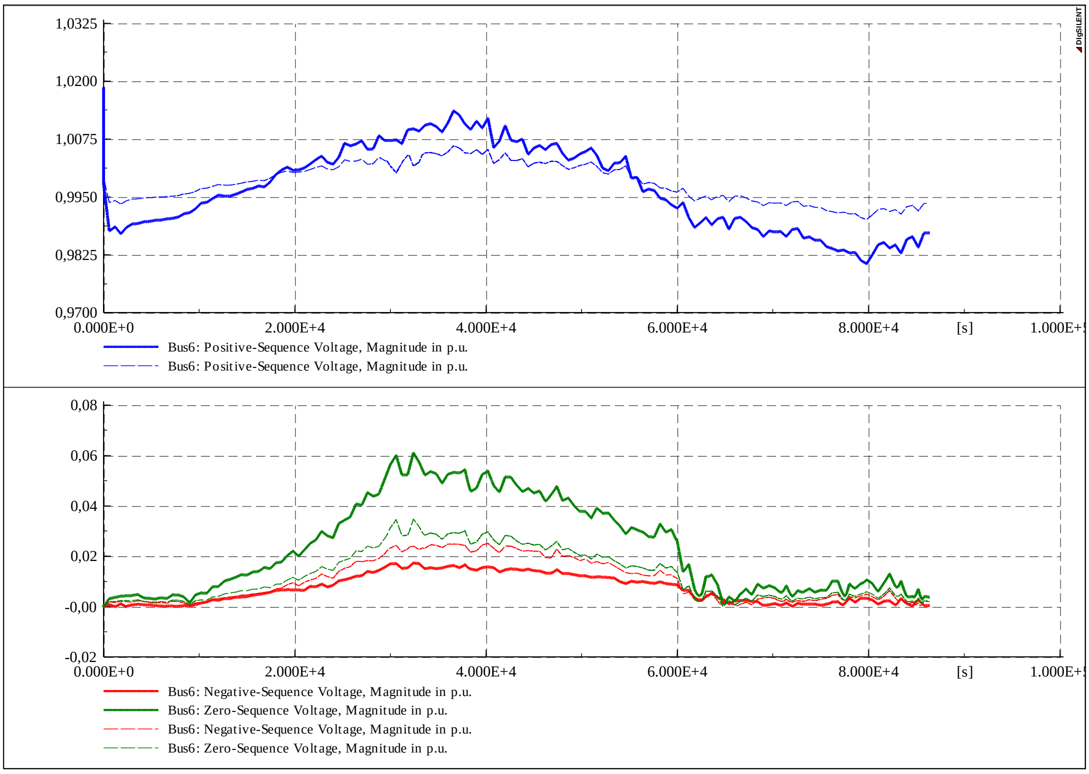
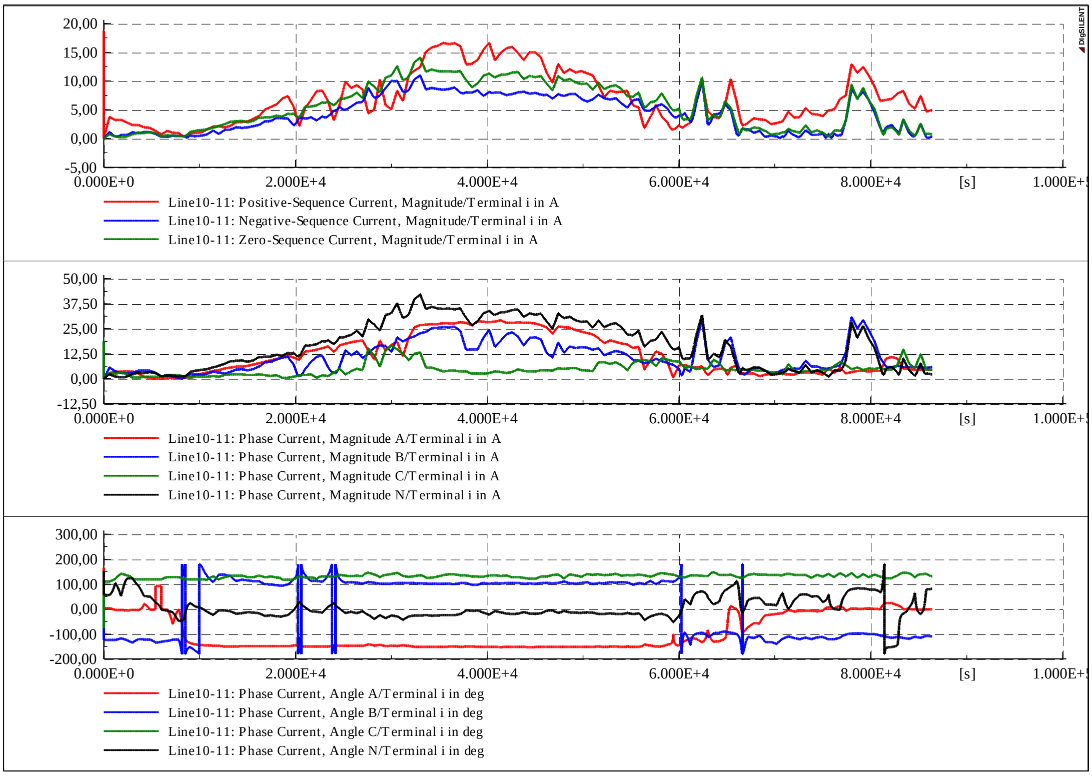


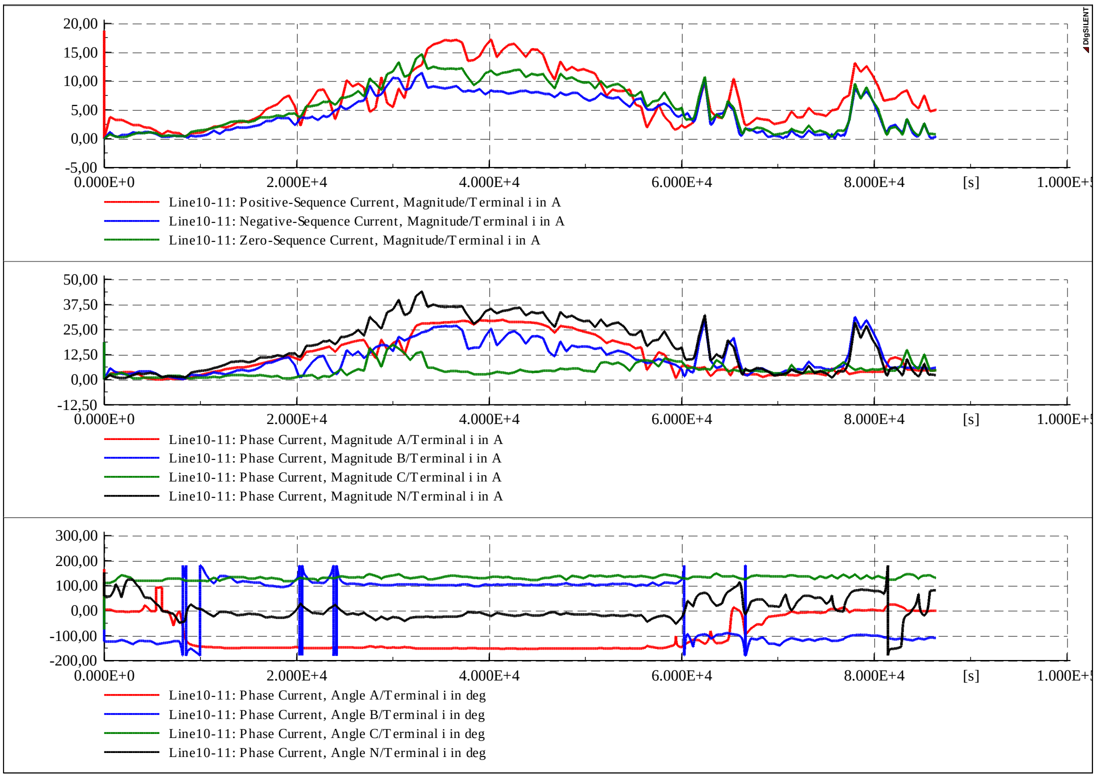
Figure 21 Positive, negative, and zero sequence voltage of bus 6.

According to the voltage sequences shown in figure 21, it has been decided to analyze the currents flowing in the final part of line: amplitudes, angles and sequences. A comparison between the ‘without OLTC case’ and ‘1 phase OLTC case’ has been performed. As indicated in paragraph 3.3, PV units have been modeled as constant power units while loads as constant impedances. For this reason, since in the PV production period the injected power is much higher than the loads absorption, the phase current is inversely proportional to the voltage; on the other hand when PVs are not producing, current and voltage are directly proportional.

Basically not any relevant difference can be noticed between the two cases, because the voltage variations in percentage (few percentage points) cause the discussed current variations.

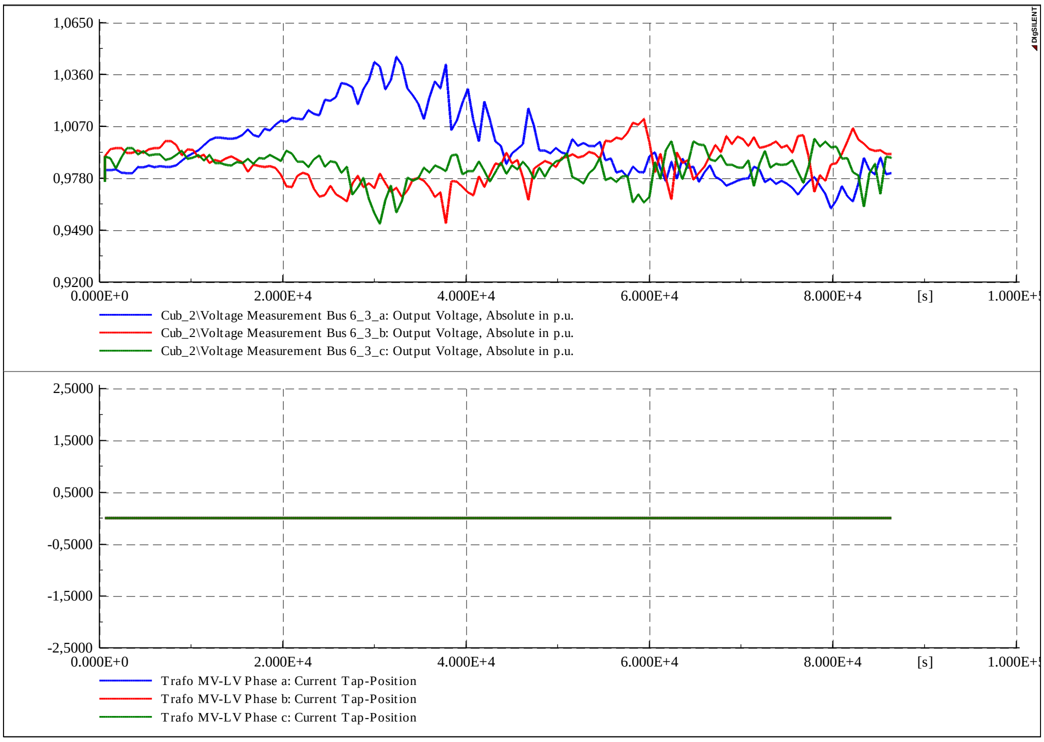
Anyway high values of both the inverse and the zero sequences compared to the positive one can be seen because the PV power injection has been chosen to be extremely unbalanced.


DIgSILENT
[s]
Line10-11: Positive-Sequence Current, Magnitude/Terminal i in A
Line10-11: Negative-Sequence Current, Magnitude/Terminal i in A
Line10-11: Zero-Sequence Current, Magnitude/Terminal i in A
Line10-11: Phase Current, Magnitude A/Terminal i in A
Line10-11: Phase Current, Magnitude B/Terminal i in A
Line10-11: Phase Current, Magnitude C/Terminal i in A
Line10-11: Phase Current, Magnitude N/Terminal i in A
Line10-11: Phase Current, Angle A/Terminal i in deg
Line10-11: Phase Current, Angle B/Terminal i in deg
Line10-11: Phase Current, Angle C/Terminal i in deg
Line10-11: Phase Current, Angle N/Terminal i in deg

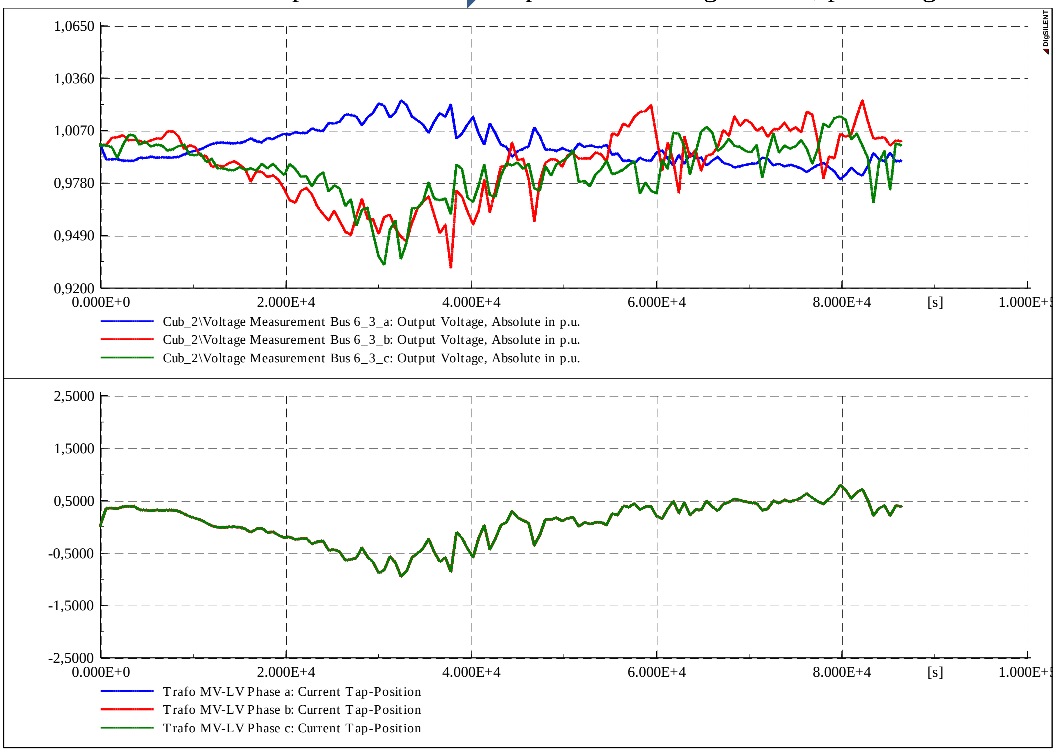

DIgSILENT
[s]
Line10-11: Positive-Sequence Current, Magnitude/Terminal i in A
Line10-11: Negative-Sequence Current, Magnitude/Terminal i in A
Line10-11: Zero-Sequence Current, Magnitude/Terminal i in A
Line10-11: Phase Current, Magnitude A/Terminal i in A
Line10-11: Phase Current, Magnitude B/Terminal i in A
Line10-11: Phase Current, Magnitude C/Terminal i in A
Line10-11: Phase Current, Magnitude N/Terminal i in A
Line10-11: Phase Current, Angle A/Terminal i in deg
Line10-11: Phase Current, Angle B/Terminal i in deg
Line10-11: Phase Current, Angle C/Terminal i in deg
Line10-11: Phase Current, Angle N/Terminal i in deg

4.2.2 Results Comparison – PV 10%: 35kW PV at phase a

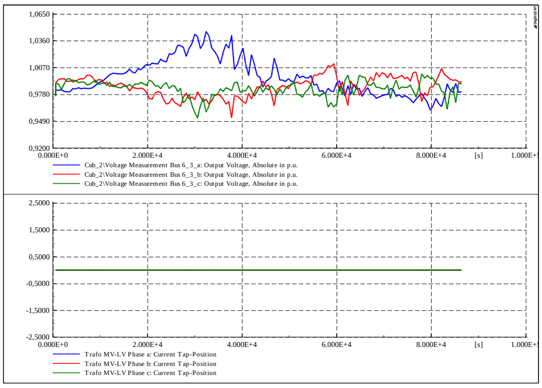
A. Voltage profile at the worst bus: BUS 6

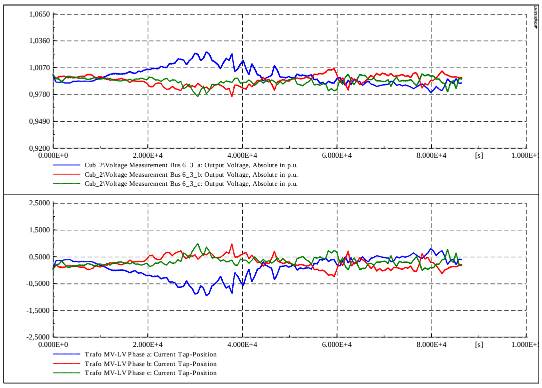


- From base case to 3 phase: ⇒ phases a and b get better, phase c gets worse



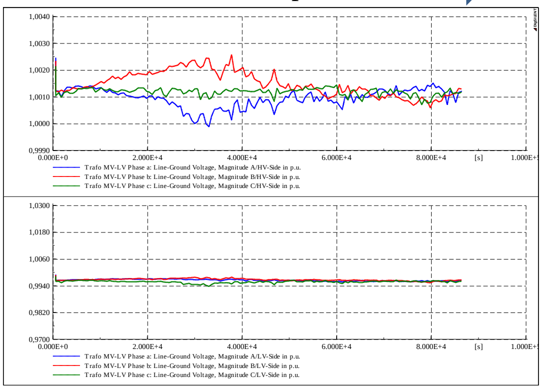
- From base case to 1 phase: ⇒ the three phases get better

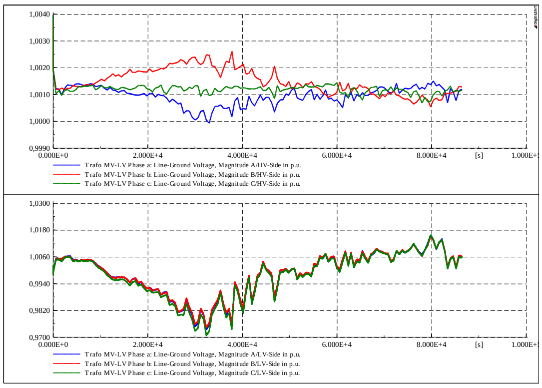




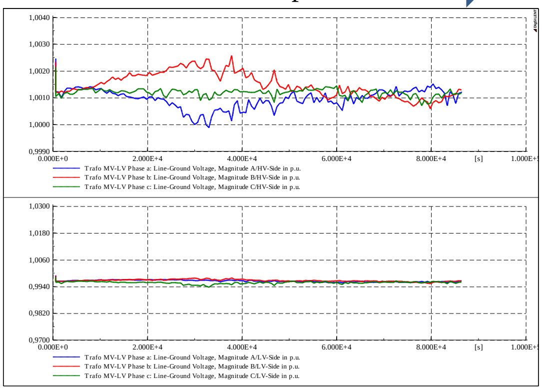
B. <u>Voltage profile at the transformer level (LV side)</u>

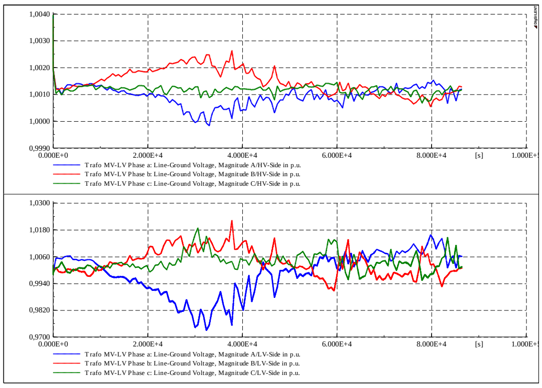
- From base case to 3 phase: ➡ the three phases get worse (-3%/+1,5%)





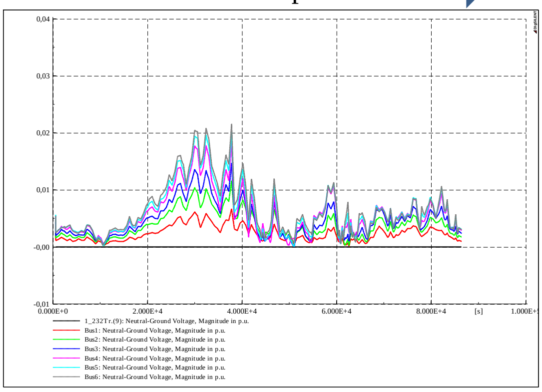
- From base case to 1 phase: ➡ the three phases get worse (-3%/+2%)

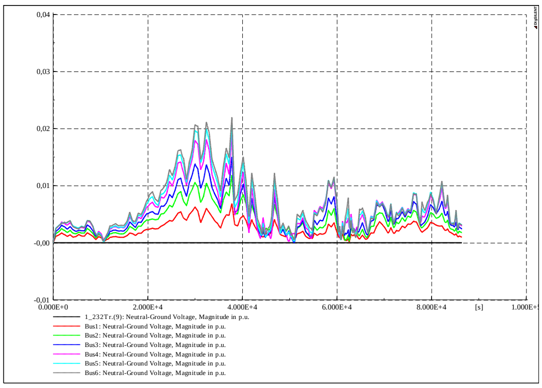




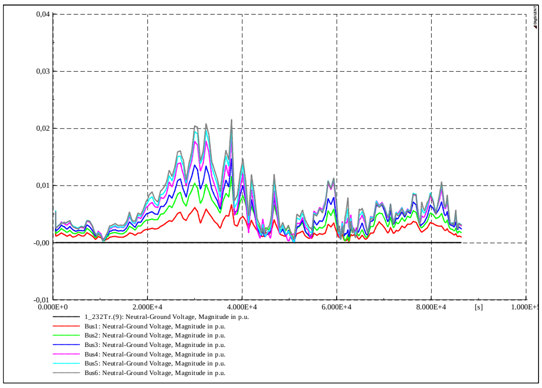
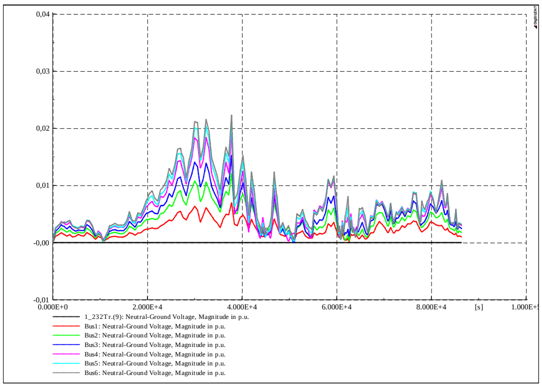
C. <u>Neutral-Ground Voltage</u>

- From base case to 3 phase: ➡ the same (peaks around 2%)



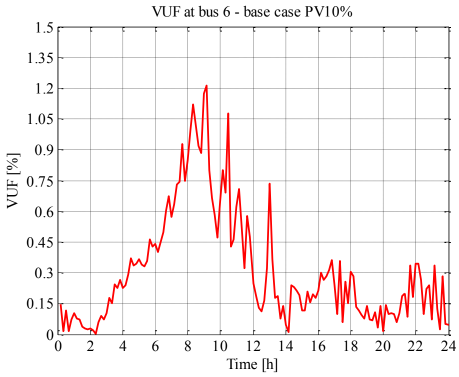


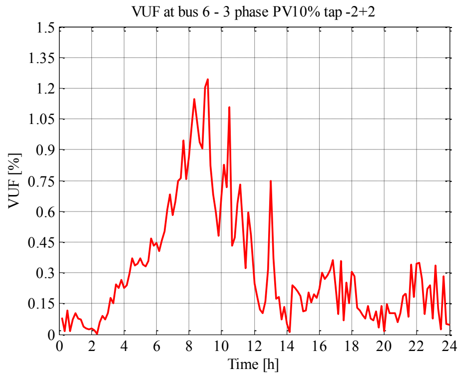
- From base case to 1 phase: ➡ the same (peaks around 2%)

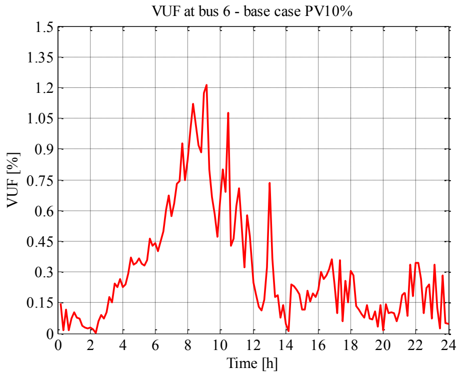
D. <u>Unbalance factor VUF at the worst bus: BUS 6</u>

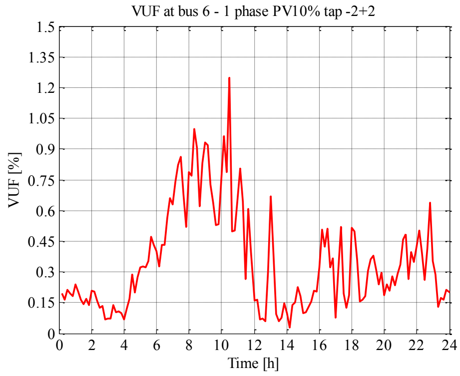
- From base case to 3 phase: ➡ the same





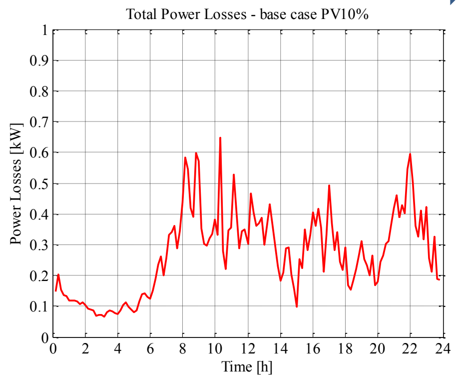
- From base case to 1 phase: ➡ just a bit lower

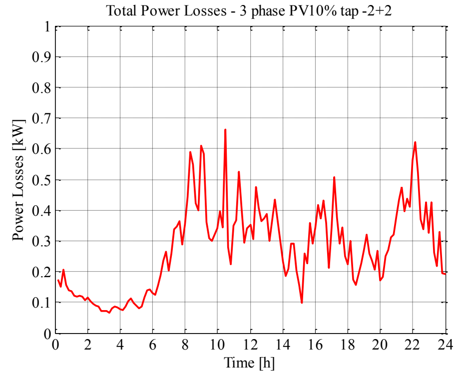




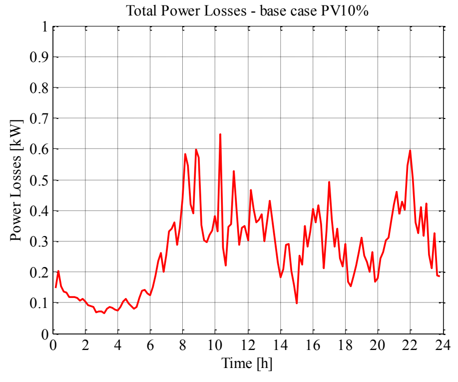
E. Total Power and Energy Losses

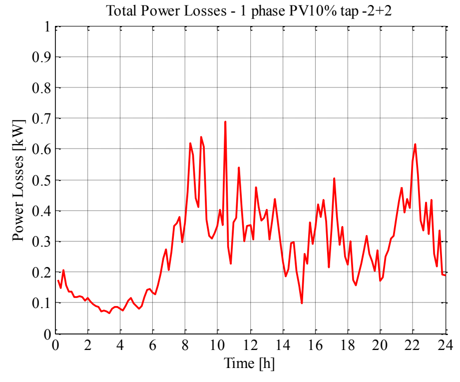
- From base case to 3 phase: the same





- From base case to 1 phase: just a bit higher

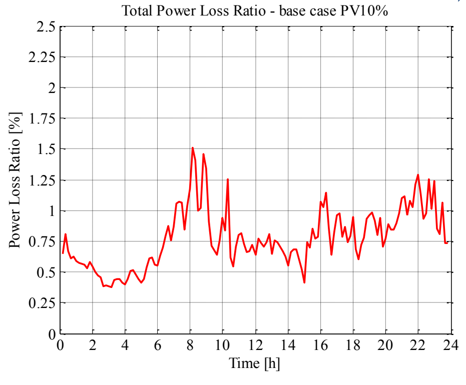


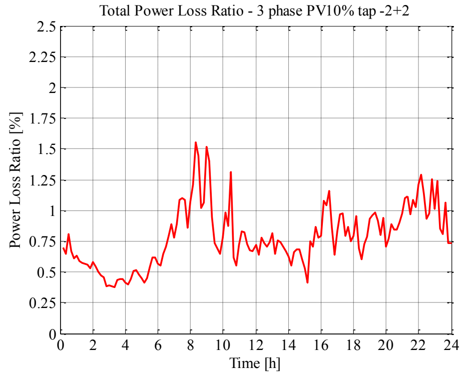


Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the transformer [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%, compared to base case]
Base Case	749,43	244,53	511,35	6,45	+0,00%
3 Phase	756,92	244,49	519,02	6,59	+2,18%
1 Phase	761,75	244,48	523,93	6,66	+3,33%

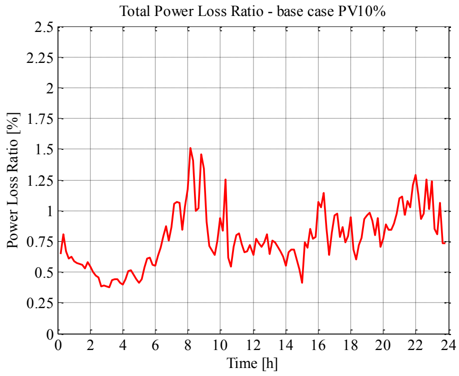
F. Total Power Loss Ratio

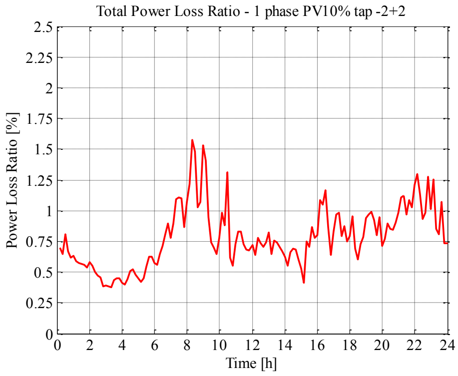
- From base case to 3 phase: just a bit higher





- From base case to 1 phase: ➡ just a bit higher

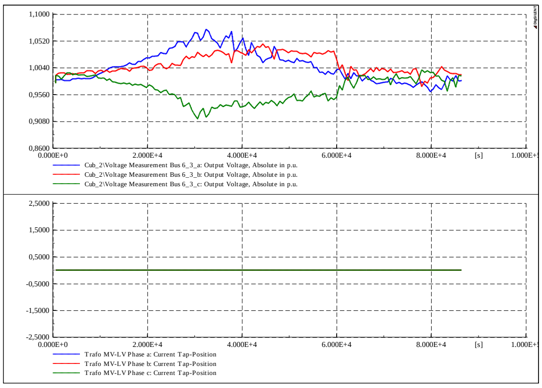


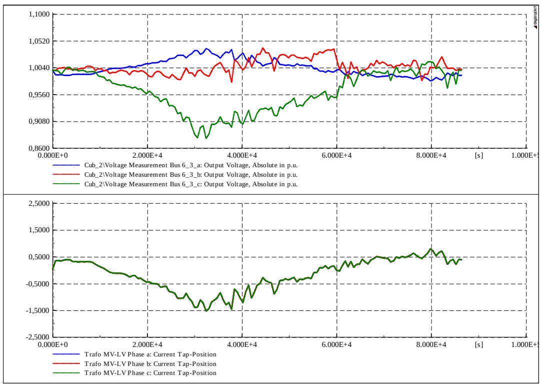


4.2.3 Results Comparison – PV 30%: 105kW PV split into phases a and b

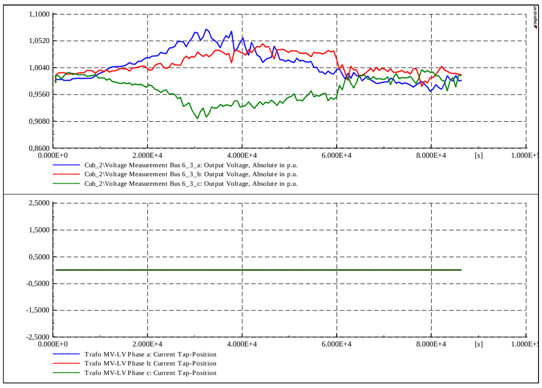
A. Voltage profile at the worst bus: BUS 6

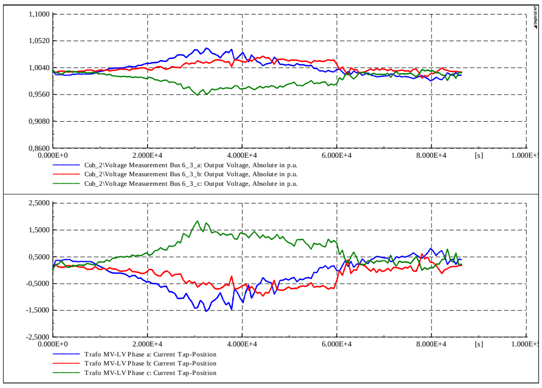
- From base case to 3 phase: ➡ phases a and b get better, phase c gets worse





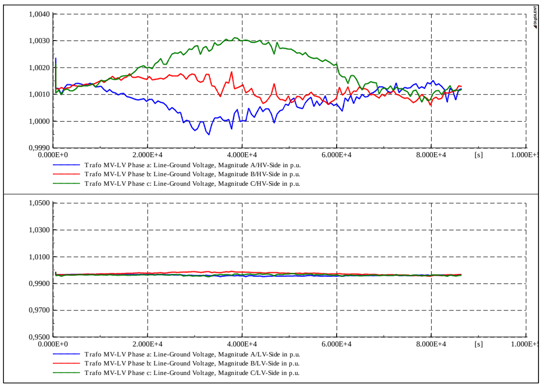
- From base case to 1 phase: ➡ the three phases get better

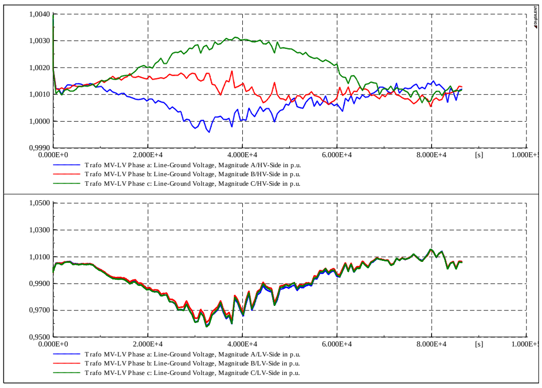




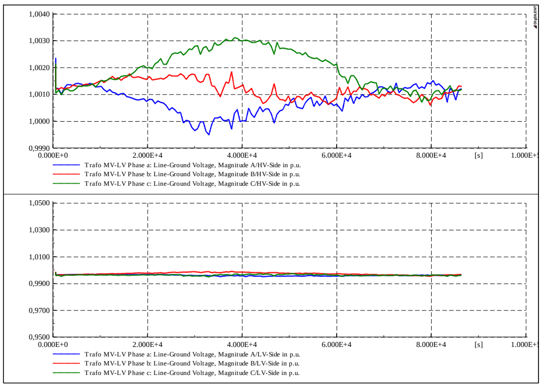
B. Voltage profile at the transformer level (LV side)

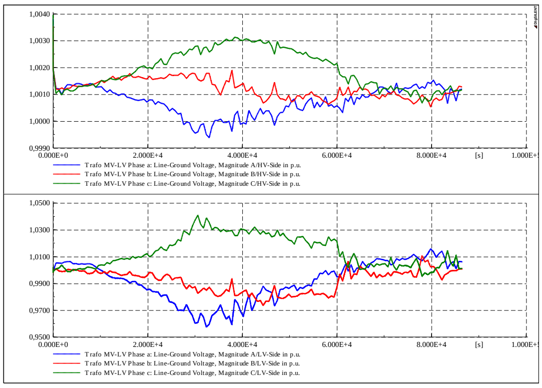
- From base case to 3 phase: ➡ the three phases get worse (-4%/+1,5%)





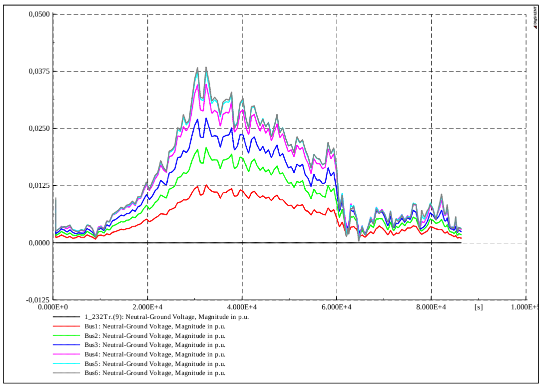
- From base case to 1 phase: ➡ the three phases get worse (-4%/+4%)

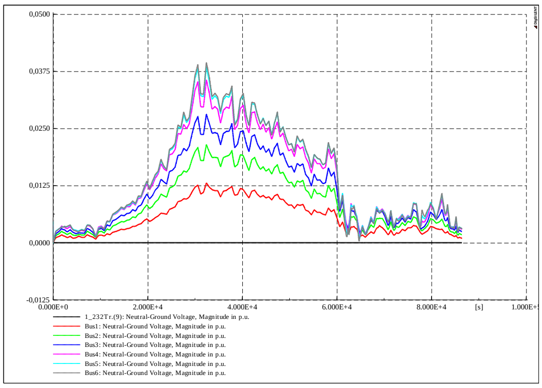




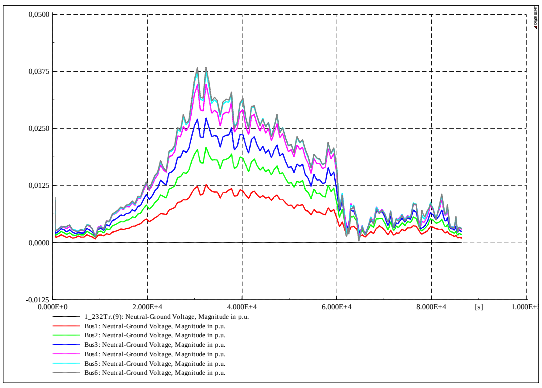
C. Neutral-Ground Voltage

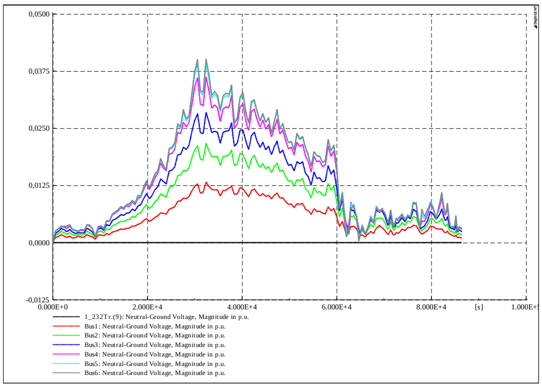
- From base case to 3 phase: ➡ the same (peaks around 3,75%)





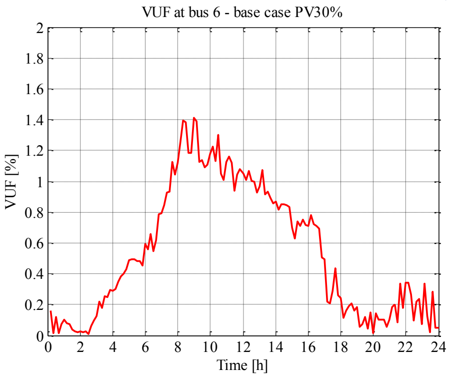
- From base case to 1 phase: ➡ the same (peaks around 3,75%)

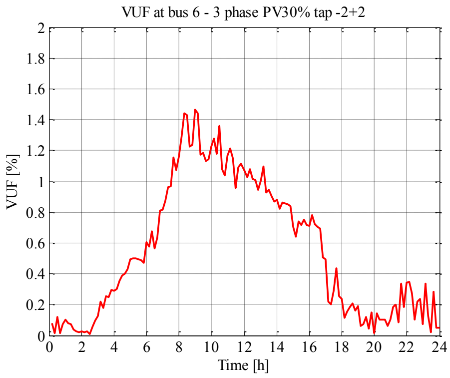




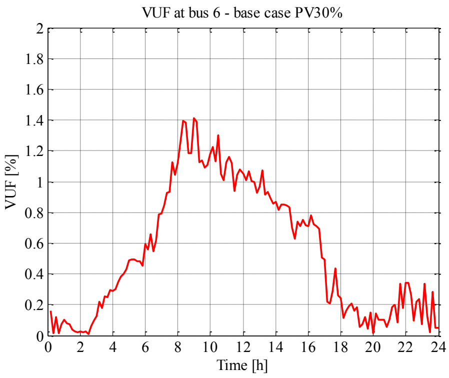
D. <u>Unbalance factor VUF at the worst bus: BUS 6</u>

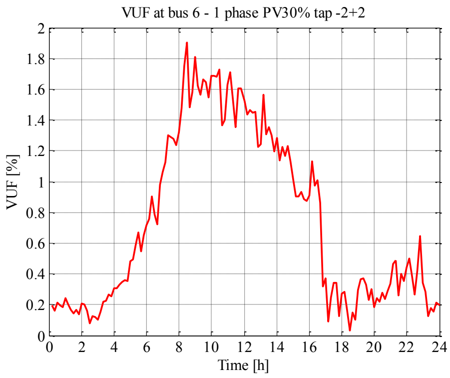
- From base case to 3 phase: ➡ gets just a bit higher





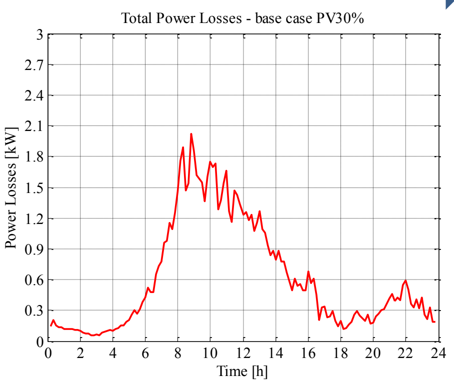
- From base case to 1 phase: ➡ gets higher

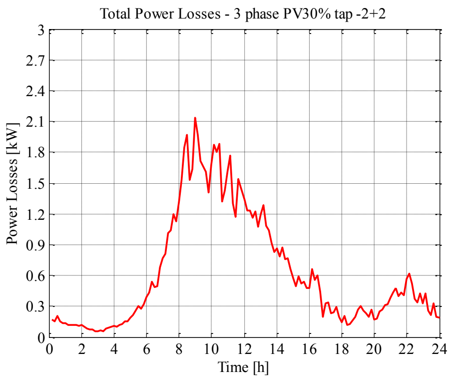




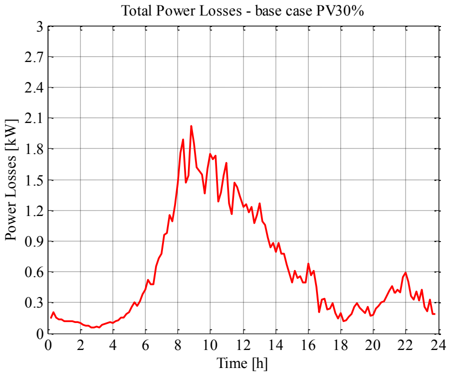
E. <u>Total Power and Energy Losses</u>

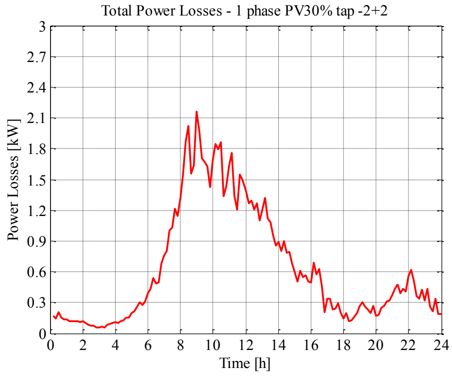
- From base case to 3 phase: ➡ just a bit higher





- From base case to 1 phase: just a bit higher

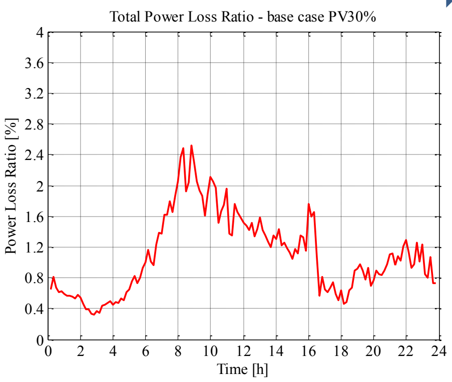


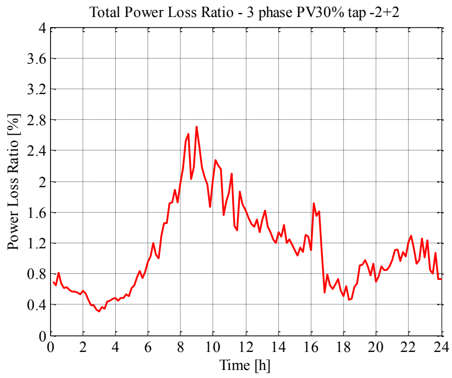


Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the transformer [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%, compared to base case]
Base Case	756,30	731,21	39,74	14,65	+0,00%
3 Phase	753,48	730,71	37,82	15,05	+2,73%
1 Phase	763,29	730,60	47,93	15,24	+4,01%

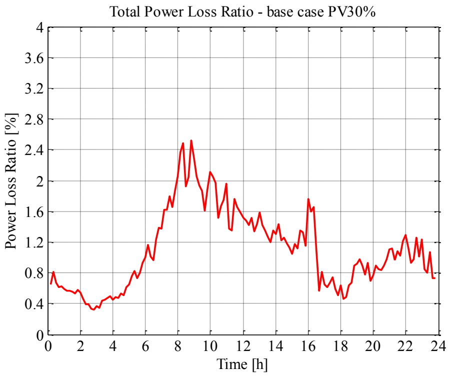
F. Total Power Loss Ratio

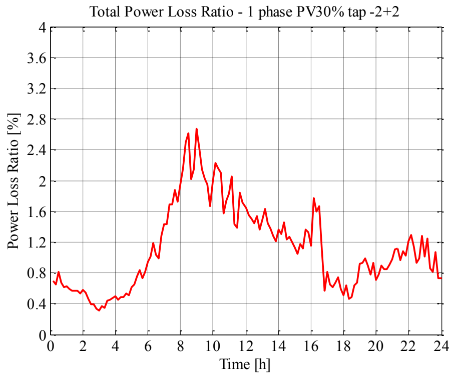
- From base case to 3 phase: just a bit higher





- From base case to 1 phase: just a bit higher

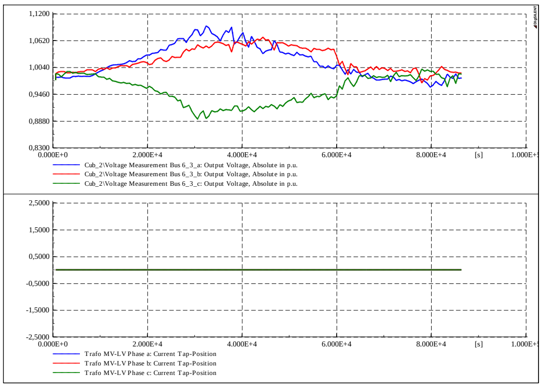


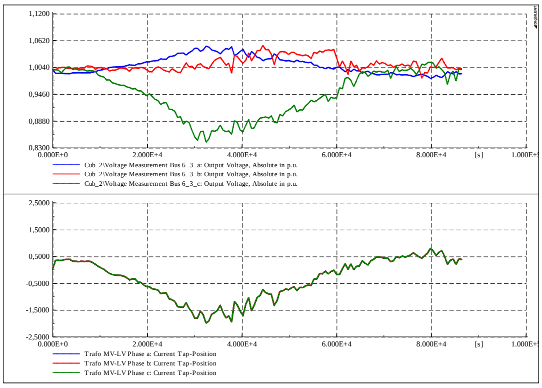


4.2.4 Results Comparison – PV 40%: 140kW PV split into phases a and b

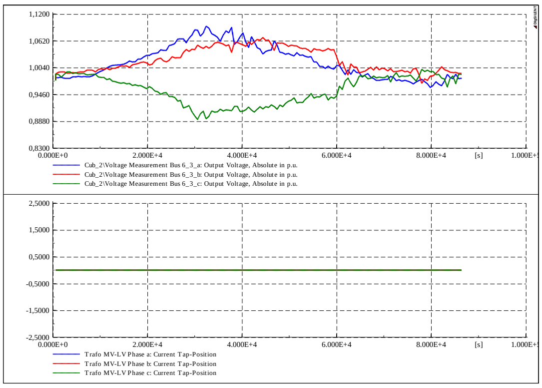
A. Voltage profile at the worst bus: BUS 6

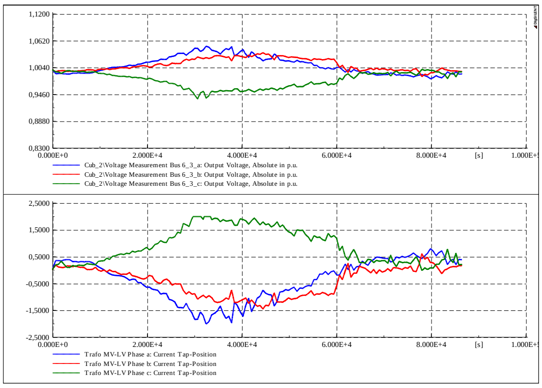
- From base case to 3 phase: phases a and b get better, phase c gets worse





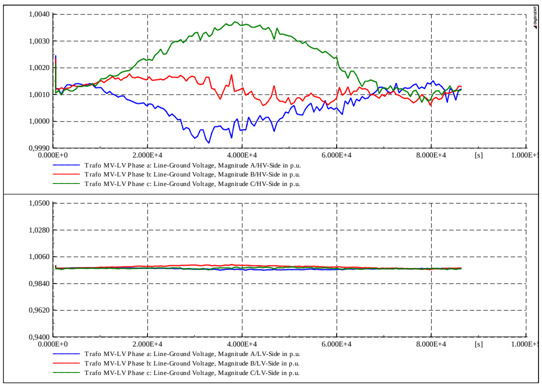
- From base case to 1 phase: ➡ the three phases get better

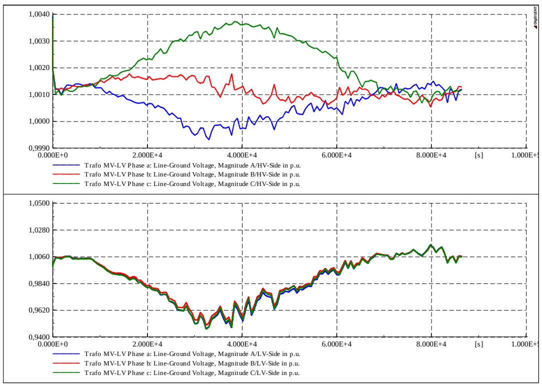




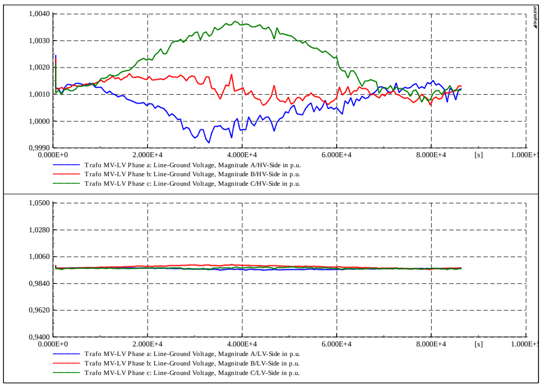
B. <u>Voltage profile at the transformer level (LV side)</u>

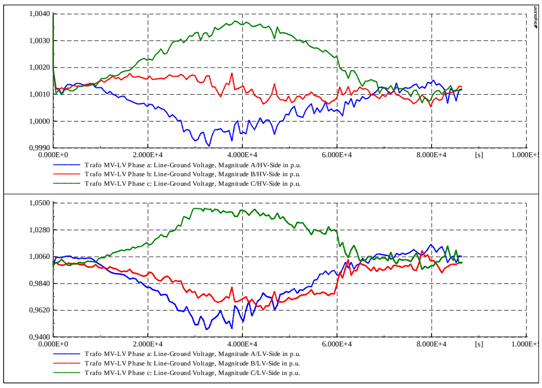
- From base case to 3 phase: ➡ the three phases get worse (-5%/+2%)





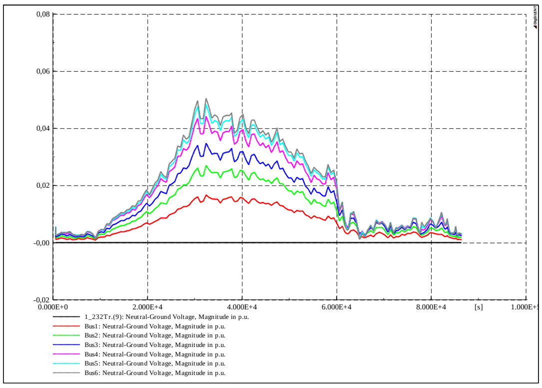
- From base case to 1 phase: ➡ the three phases get worse (-5%/+5%)

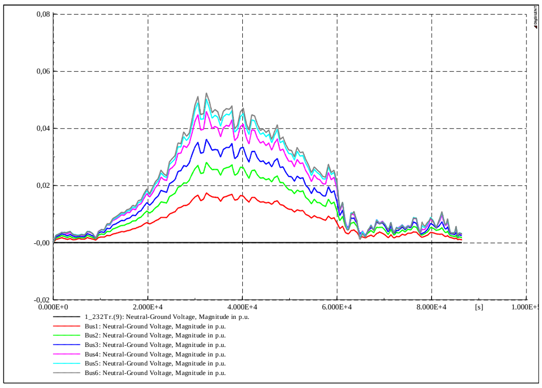




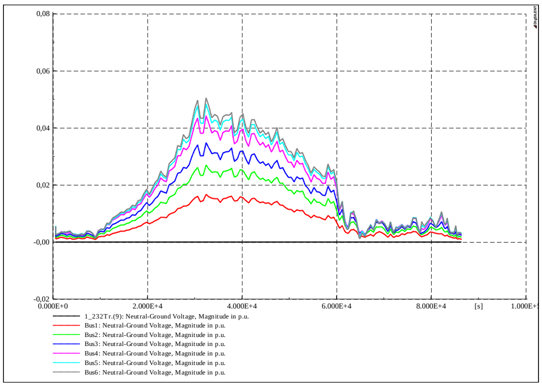
C. <u>Neutral-Ground Voltage</u>

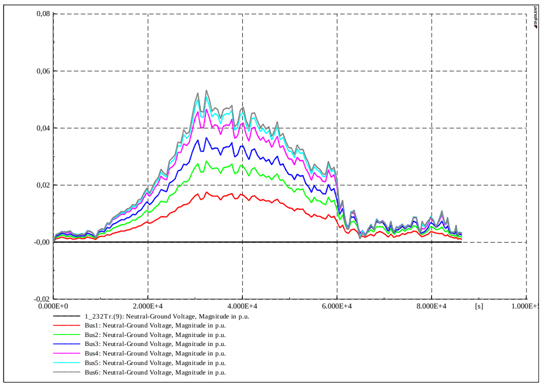
- From base case to 3 phase: → the same (peaks around +5%)





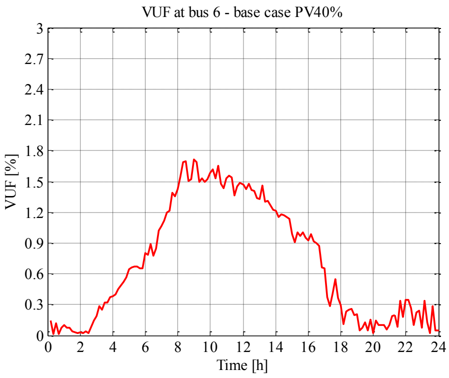
- From base case to 1 phase: → the same (peaks around +5%)

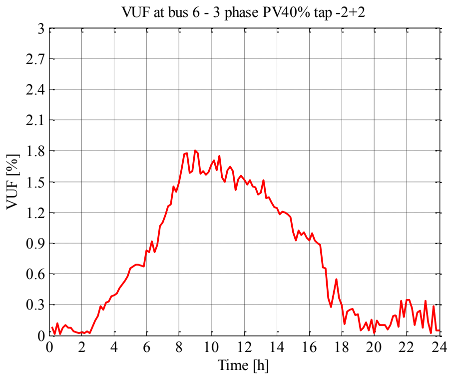




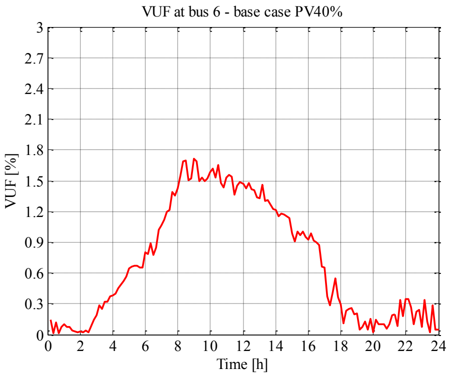
D. <u>Unbalance factor VUF at the worst bus: BUS 6</u>

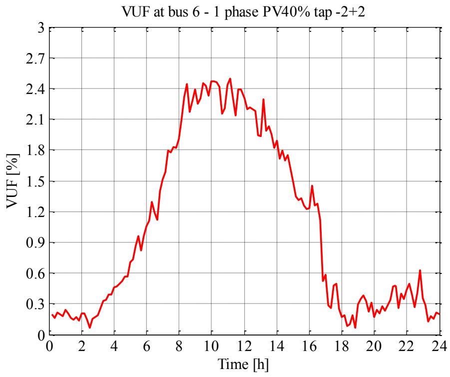
- From base case to 3 phase: → the same





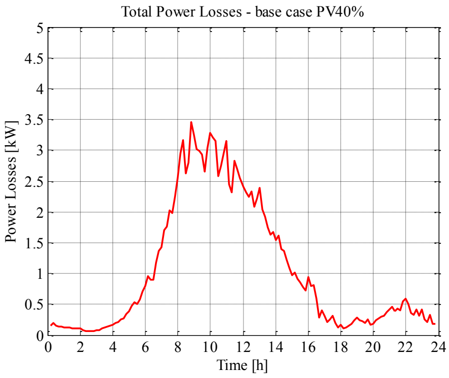
- From base case to 1 phase: gets higher (>2% !!!)

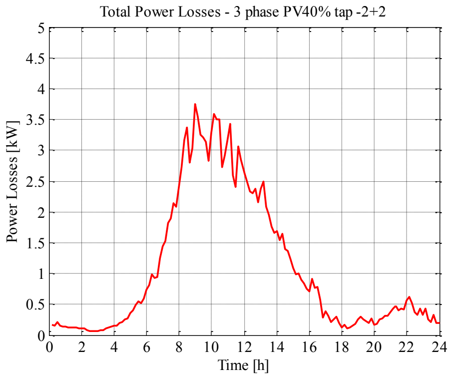




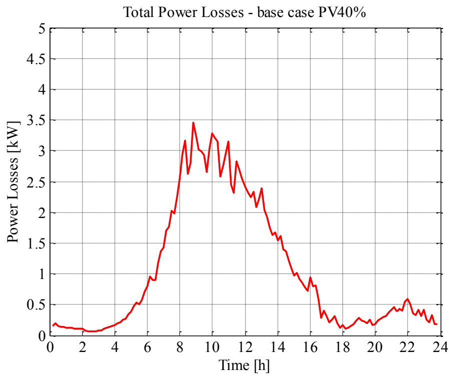
E. Total Power and Energy Losses

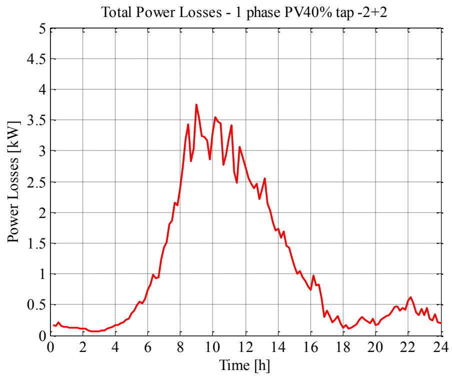
- From base case to 3 phase: get higher





- From base case to 1 phase: get higher, higher than the 3 phase case

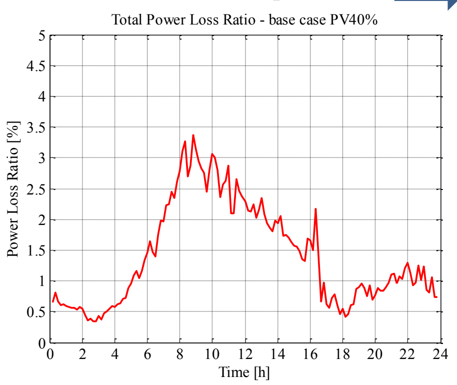


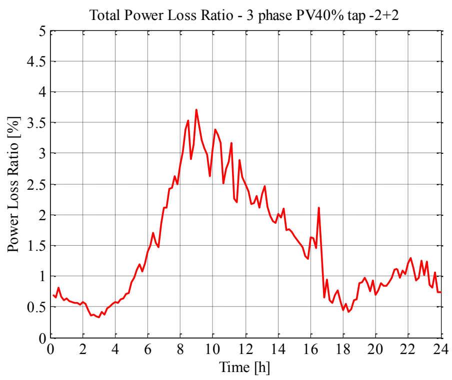


Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the transformer [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%, compared to base case]
Base Case	760,44	971,93	-186,77	24,72	+0,00%
3 Phase	749,57	971,02	-195,24	26,21	+6,01%
1 Phase	763,71	970,58	-180,62	26,25	+6,18%

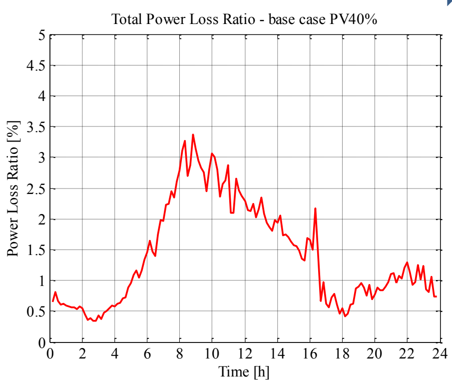
F. Total Power Loss Ratio

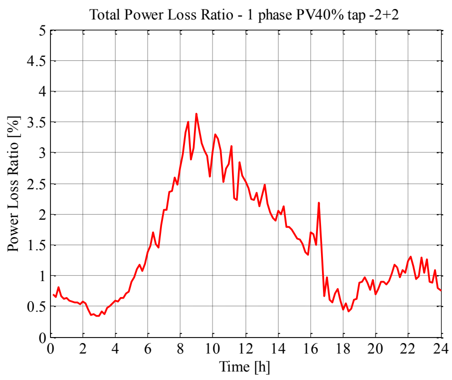
- From base case to 3 phase: ⇒ gets higher





- From base case to 1 phase: ⇒ gets higher





4.3 PV grid case with a less unbalanced connection

In order to evaluate the hosting capacity of the network in the cases characterized by different three phase PV connections, further simulations have been performed to consider a more realistic situation. The following less unbalanced distribution has been considered: 50% of the total PV power connected to phase a, 30% to phase b and 20% to phase c.

4.3.1 Overall results analysis

<u>40% Case with abc connections(Simulation results are presented in section 4.3.2)</u>

It is noticed that in all scenarios the phase-neutral voltages at the worst bus (bus 5) are within the acceptable range (-10%/+10% of the nominal value). Losses and VUF are acceptable as well.

No OLTC results:

- phase-neutral voltages at the final bus stay within the range -4%/+7%;
- phase-neutral voltages at the transformer level keep close at the nominal values;
- neutral-ground voltages are around 2.5% of the nominal phase to ground voltage (230V);
- VUF under 1.1%;
- amount of energy losses is 11.61kWh;
- maximal power loss ratio is about 1.7%.

1 Phase OLTC results:

- phase-neutral voltages at the final bus stay within the range -2%/+4%;
- phase-neutral voltages at the transformer level stay within the range -4%/+2%;
- neutral-ground voltages are under 2.5% of the nominal phase to ground voltage (230V);
- VUF is under 1.3%;
- amount of energy losses is about 12.22kWh, which means around +5.29% compared to the base case;
- maximal power loss ratio of about 1.8%.

The amount of the energy absorbed by the loads, injected by the PVs and the transformer and the corresponding energy loss, can be read in the following table, which contains values of the three study cases:

Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the trafo [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%, compared to base case]
Base Case	759.78	981.99	-210.60	11.61	+0.00%
3 Phase	760.07	981.97	-209.68	12.22	+5.29%
1 Phase	764.90	981.84	-204.78	12.16	+4.77%

<u>50-60-70% Cases (Simulation results are presented in sections 4.3.3-4.3.4-4.3.5)</u>

The 50% and 60% cases, which refer respectively to PV power connections of 175 and 210 kW, show that the PV hosting capacity could be higher than 140kW if 1 phase tap action is performed. However, a higher PV power penetration could not be considered acceptable although considering 1-phase OLTC operation: this is because the 70% case leads to VUF peak value which is higher than 2%. The results of the 70% case with 1-phase OLTC are summarized as follows:

- phase-neutral voltages at the final bus within the range -2.5%/+8.8%;
- phase-neutral voltages at the transformer level within the range -5%/+2%;
- neutral-ground voltages under 4% of the nominal phase to ground voltage (230V);
- VUF peak around 2.05%;
- amount of energy losses of about 41.72kWh, which means around +9.50% compared to the base case (38.10kWh);
- maximal power loss ratio of about 3.8%.

The amount of the energy absorbed by the loads, injected by the PVs and the transformer and the corresponding energy loss, can be read in the following tables, which contain values of the three study cases respectively in the four scenarios 50%, 60% and 70%:

PV 50% : 175kW PV connected to phases a, b and c

Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the trafo [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%. compared to base case]
Base Case	766.62	1224.70	-436.63	21.45	+0.00%
3 Phase	752.51	1224.48	-448.38	23.59	+9.98%
1 Phase	765.86	1224.08	-434.89	23.33	+8.76%

PV 60% : 205kW PV connected to phases a, b and c

Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the trafo [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%. compared to base case]
Base Case	769.70	1468.77	-670.66	28.41	+0.00%
3 Phase	751.97	1468.50	-684.89	31.64	+11.37%
1 Phase	767.24	1467.91	-669.63	31.04	+9.26%

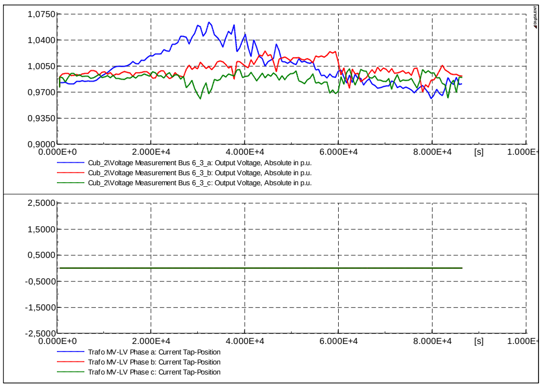
PV 70% : 245kW PV connected to phases a, b and c

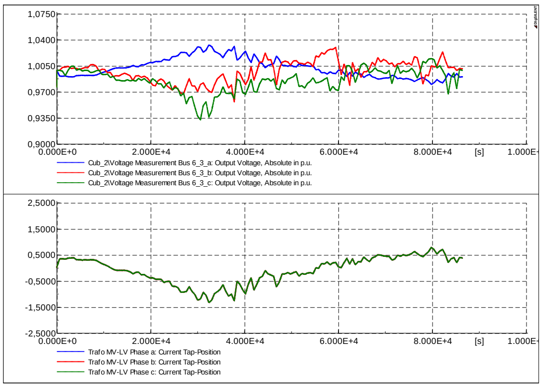
Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the trafo [kWh]	Energy Loss [kWh]	Energy Loss Ratio [%]	Energy Loss Deviation [%, compared to base case]
Base Case	774.76	1714.48	-901.62	38.10	2.22%	+0.00%
3 Phase	751.56	1714.29	-919.65	43.08	2.51%	+13.07%
1 Phase	769.12	1713.54	-902.70	41.72	2.43%	+9.50%

4.3.2 Results Comparison – PV 40%: 140kW PV connected to phases a, b and c

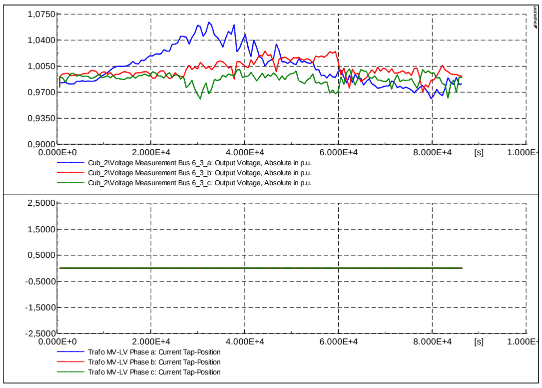
A. <u>Voltage profile at the worst bus: BUS 6</u>

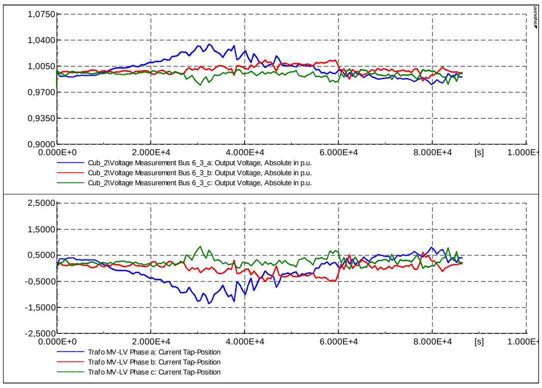
- From base case to 3 phase: ➡ phases a and b get better, phase c gets worse





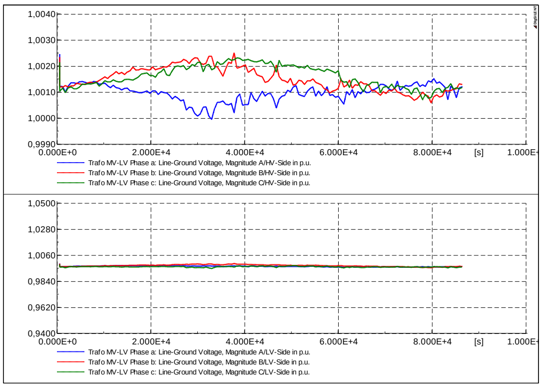
- From base case to 1 phase: ➡ the three phases get better

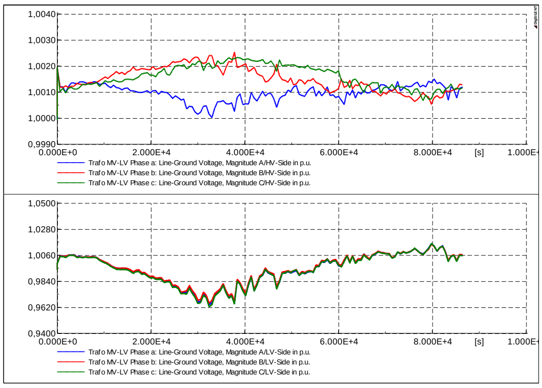




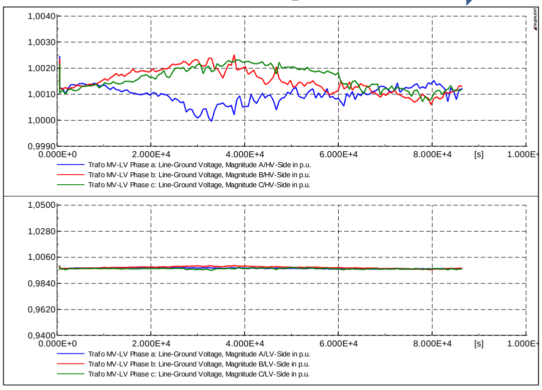
B. <u>Voltage profile at the transformer level (LV side)</u>

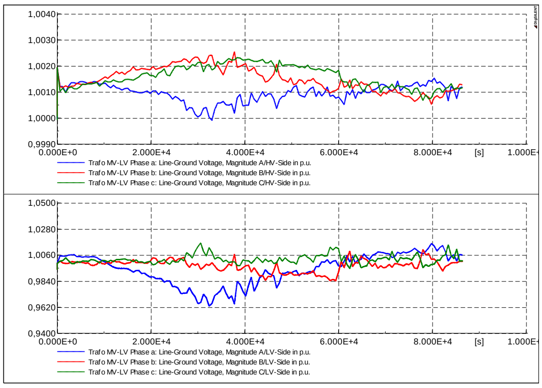
- From base case to 3 phase: ➡ the three phases get worse (peaks around -4%/+2%)





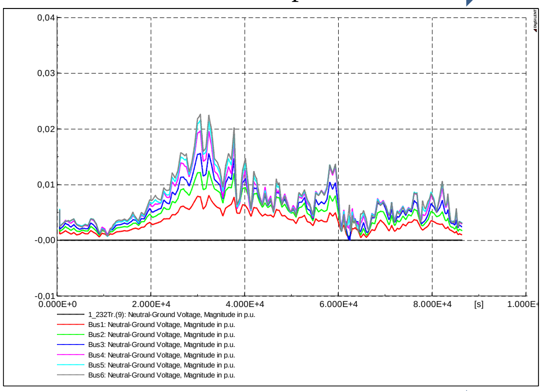
- From base case to 1 phase: the three phases get worse (peaks around -4%/+2%)

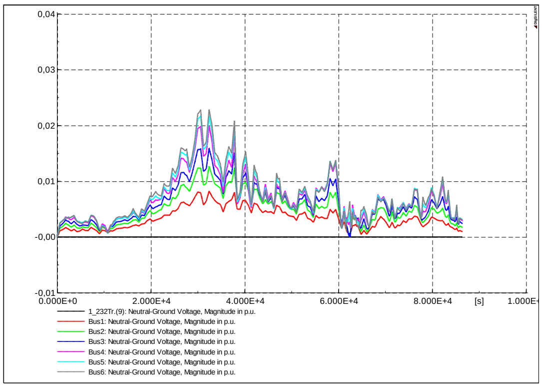




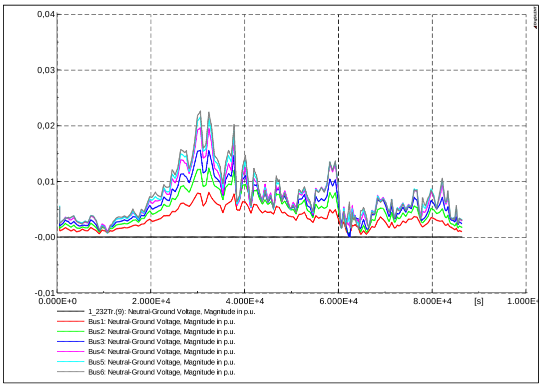
C. Neutral-Ground Voltage

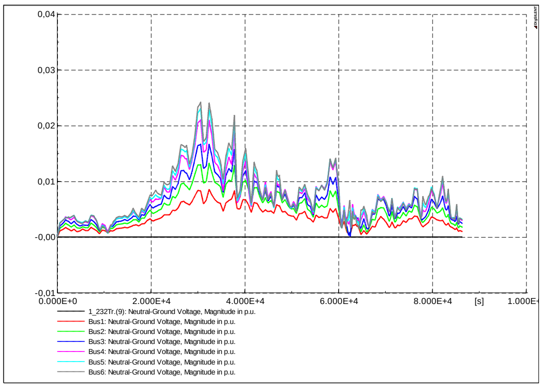
- From base case to 3 phase: the same (peaks around +2.5%)





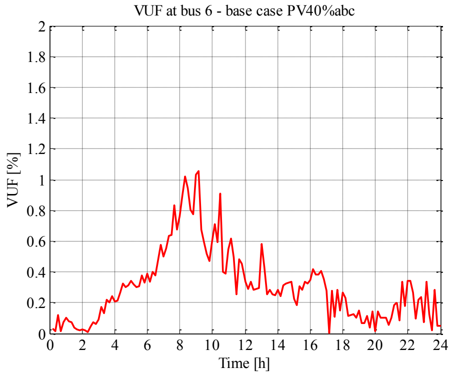
- From base case to 1 phase: the same (peaks around +2.5%)

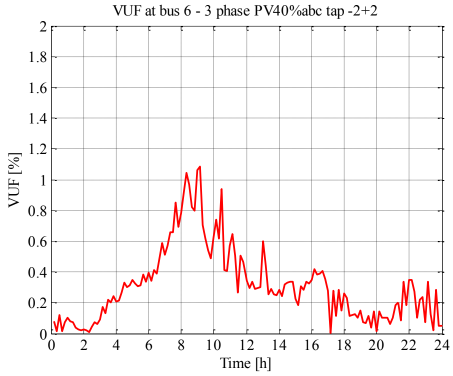




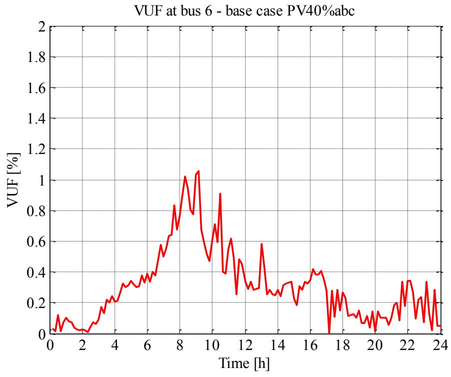
D. Unbalance factor VUF at the worst bus: BUS 6

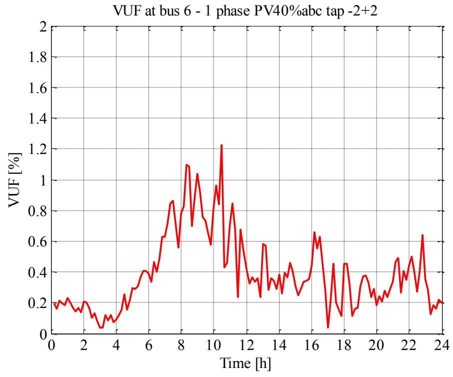
- From base case to 3 phase: → the same





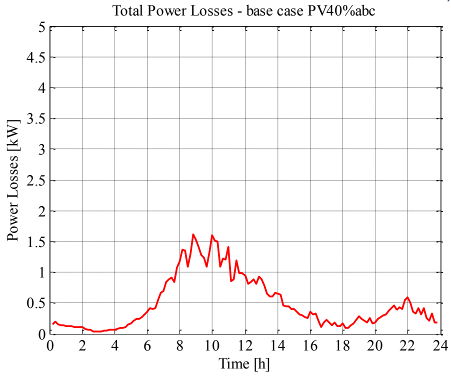
- From base case to 1 phase: → gets higher

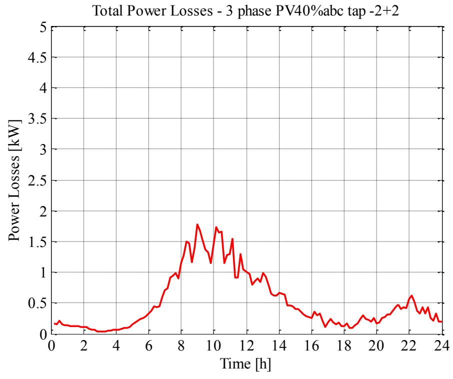




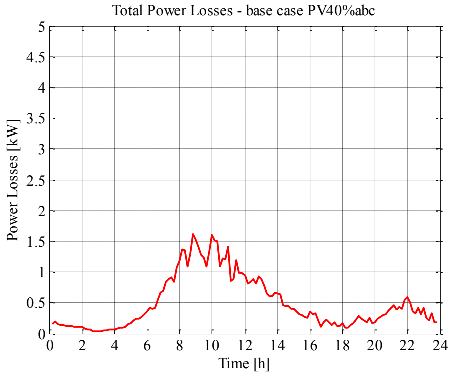
E. Total Power and Energy Losses

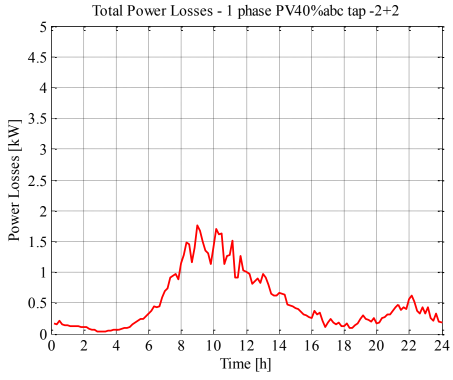
- From base case to 3 phase: → get higher





- From base case to 1 phase: → get higher



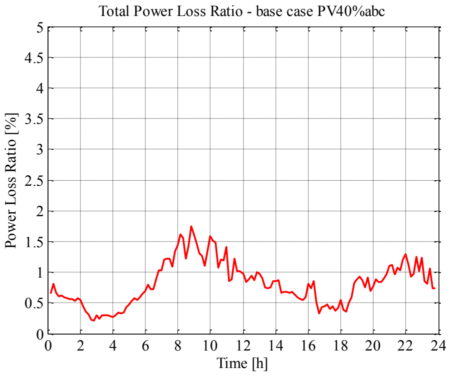


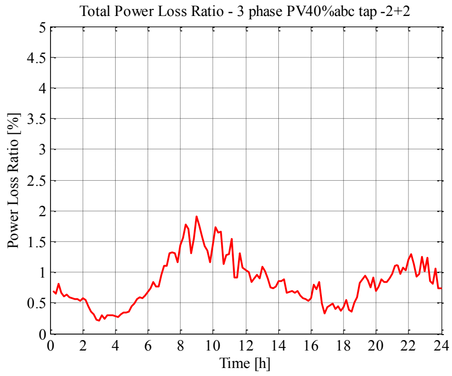
Total Energy Losses

Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the trafo [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%, compared to base case]
Base Case	759.78	981.99	-210.60	11.61	+0.00%
3 Phase	760.07	981.97	-209.68	12.22	+5.29%
1 Phase	764.90	981.84	-204.78	12.16	+4.77%

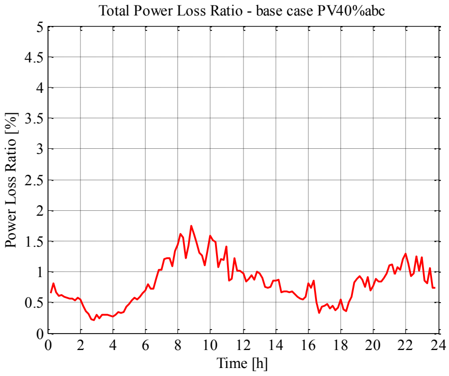
F. Total Power Loss Ratio

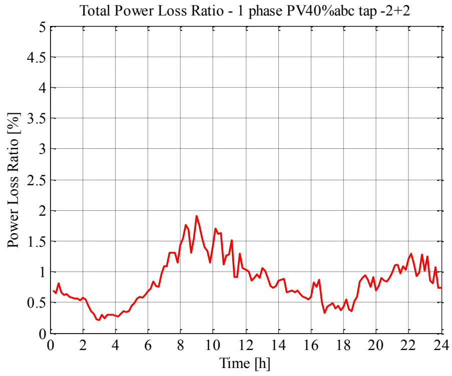
- From base case to 3 phase: ➡ gets higher





- From base case to 1 phase: ➡ gets higher

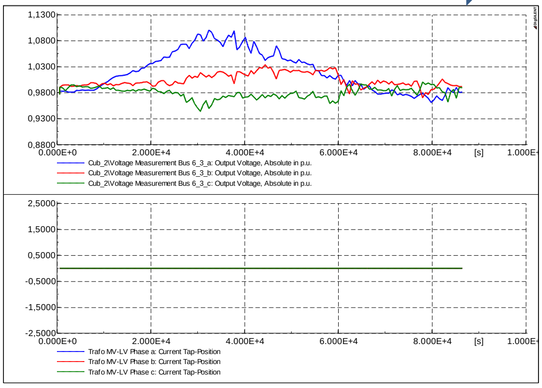


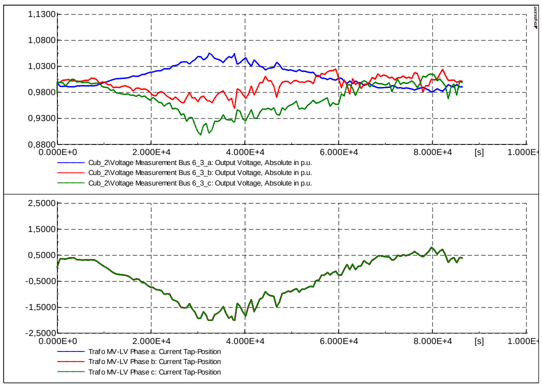


4.3.3 Results Comparison – PV 50%: 175kW PV connected to phases a, b and c

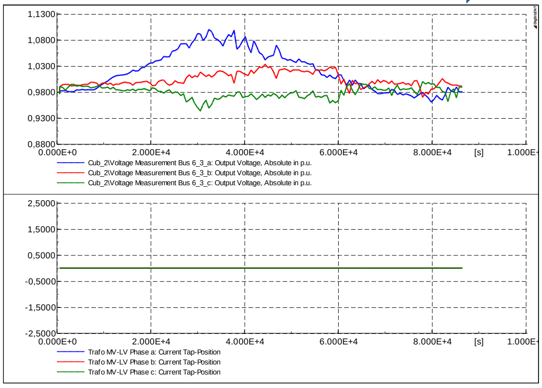
A. Voltage profile at the worst bus: BUS 6

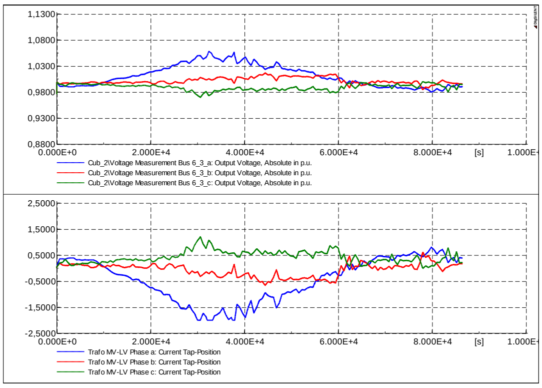
- From base case to 3 phase: ➡ phases a and b get better, phase c gets worse





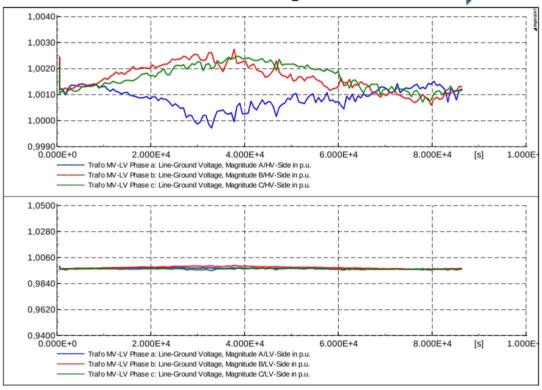
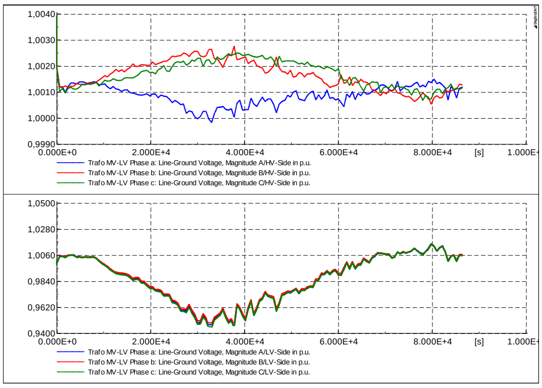
- From base case to 1 phase: → the three phases get better



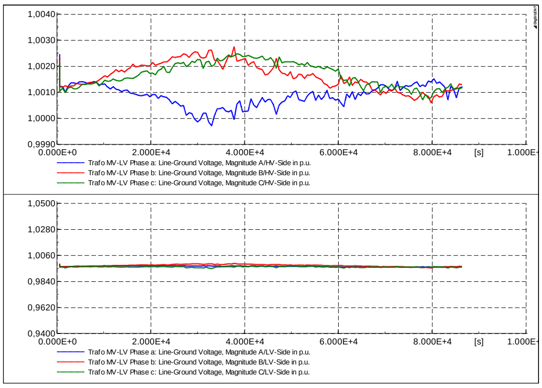
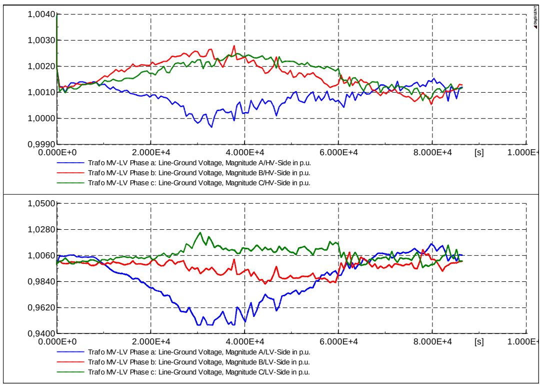


B. <u>Voltage profile at the transformer level (LV side)</u>

- From base case to 3 phase: → the three phases get worse (peaks around -5%/+2%)

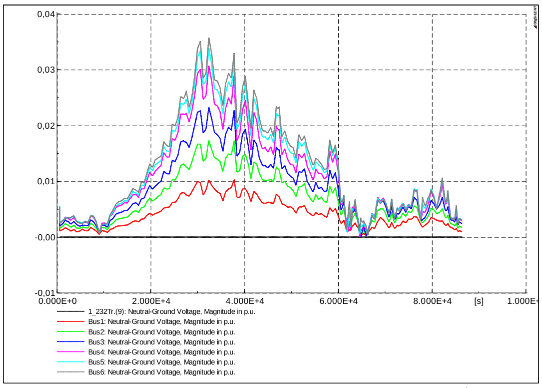



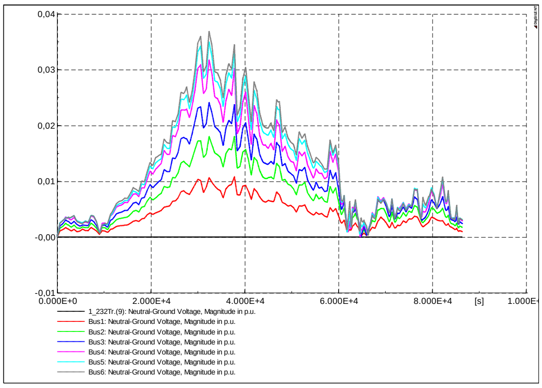
- From base case to 1 phase: → the three phases get worse (peaks around -5%/+2.5%)

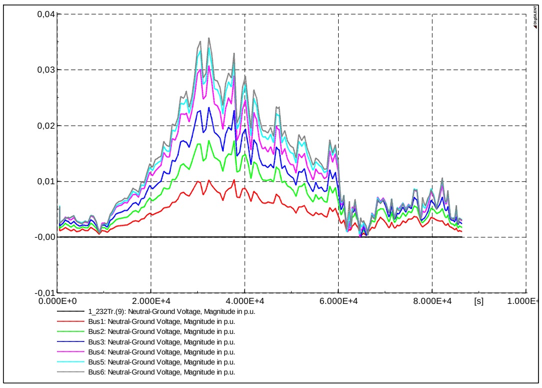
C. <u>Neutral-Ground Voltage</u>

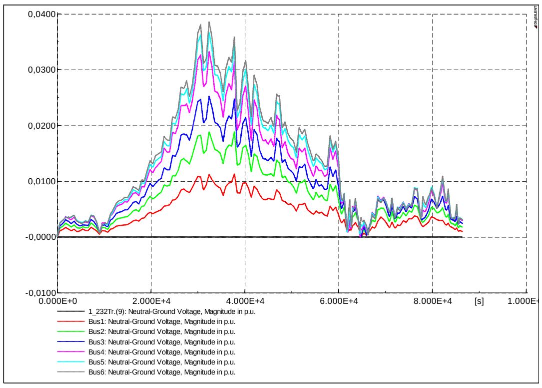
- From base case to 3 phase: → the same (peaks around +3.5%)





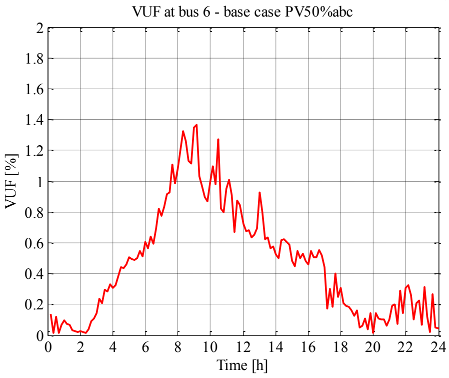
- From base case to 1 phase: ➡ the same (peaks around +3.5%)

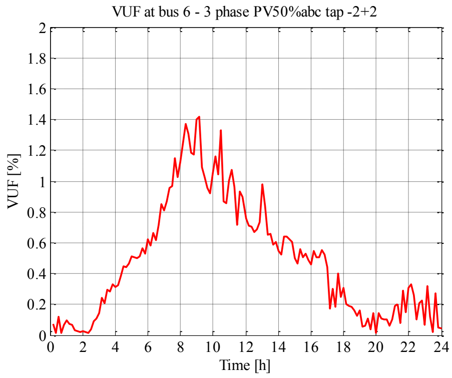




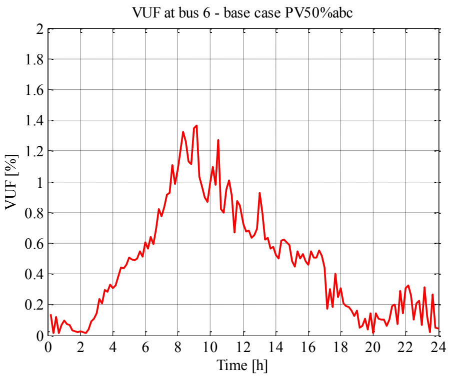
D. Unbalance factor VUF at the worst bus: BUS 6

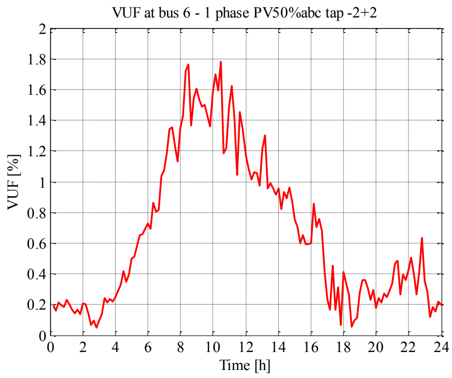
- From base case to 3 phase: ➡ the same





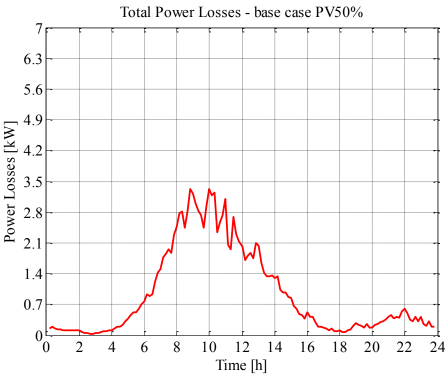
- From base case to 1 phase: ➡ gets higher

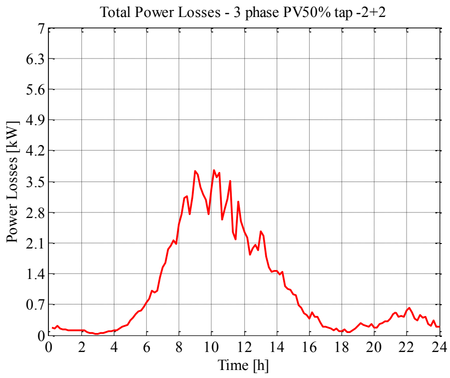




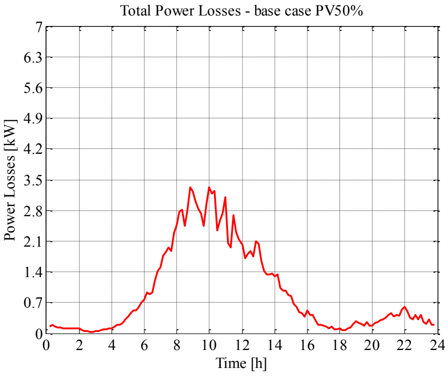
E. Total Power and Energy Losses

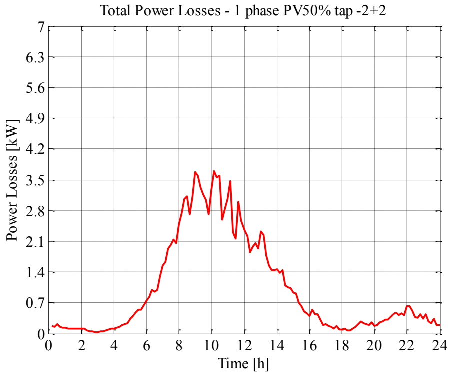
- From base case to 3 phase: → get higher





- From base case to 1 phase: → get higher

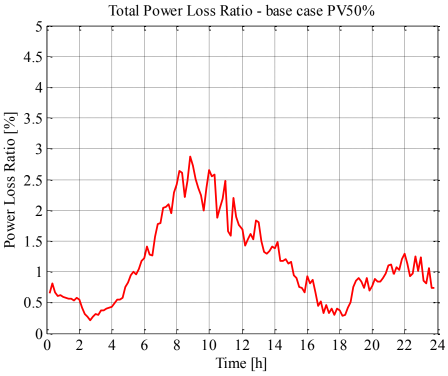


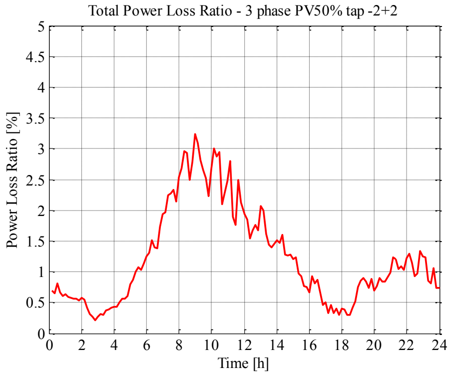


Case	**Total Energy absorbed by loads [kWh]**	**Total Energy injected by PV [kWh]**	**Energy through the trafo [kWh]**	**Energy Loss [kWh]**	**Energy Loss Deviation [%, compared to base case]**
Base Case	766.62	1224.70	-436.63	21.45	+0.00%
3 Phase	752.51	1224.48	-448.38	23.59	+9.98%
1 Phase	765.86	1224.08	-434.89	23.33	+8.76%

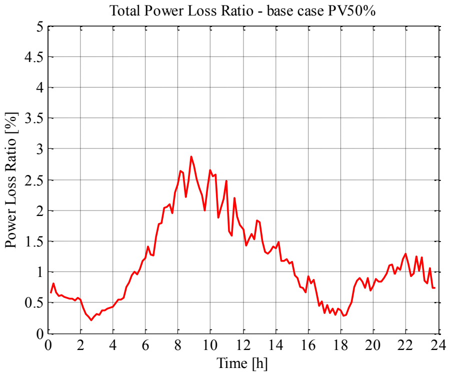
F. Total Power Loss Ratio

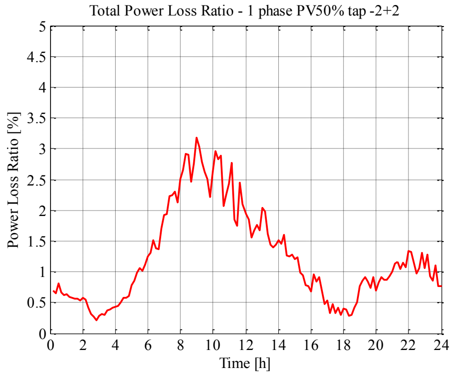
- From base case to 3 phase: → gets higher





- From base case to 1 phase: ➡ gets higher

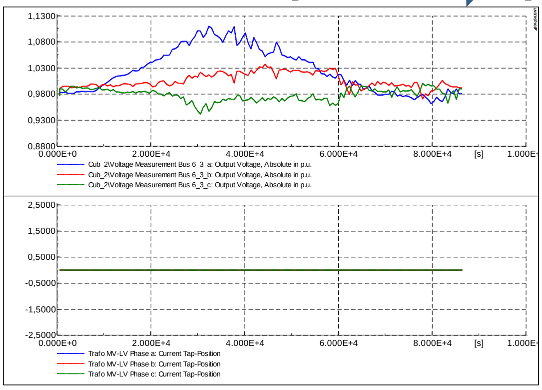


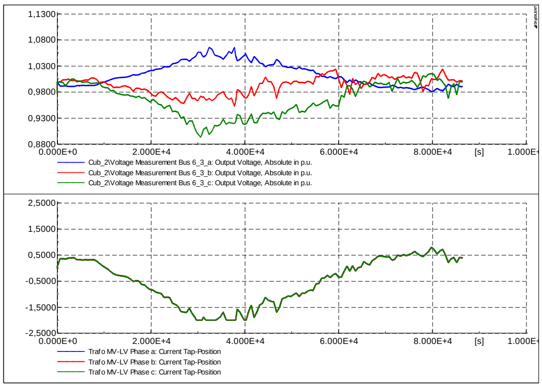


4.3.4 Results Comparison – PV 60%: 210kW PV connected to phases a, b and c

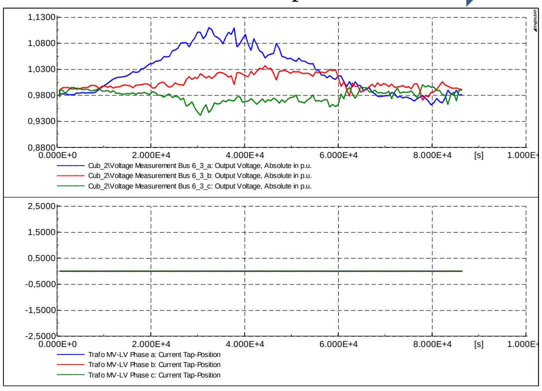
A. Voltage profile at the worst bus: BUS 6

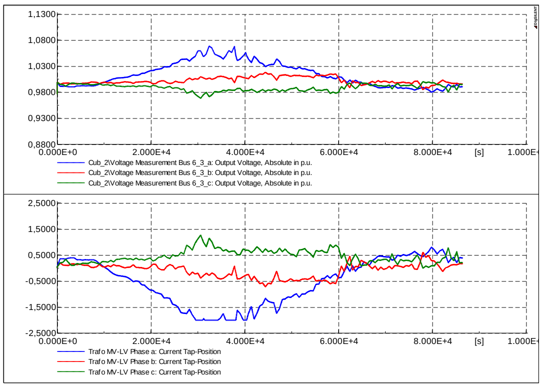
- From base case to 3 phase: ➡ phases a and b get better, phase c gets worse





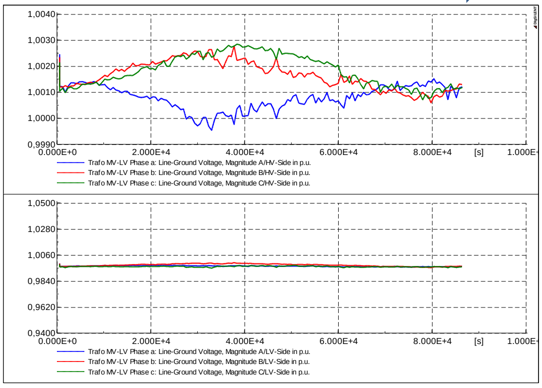
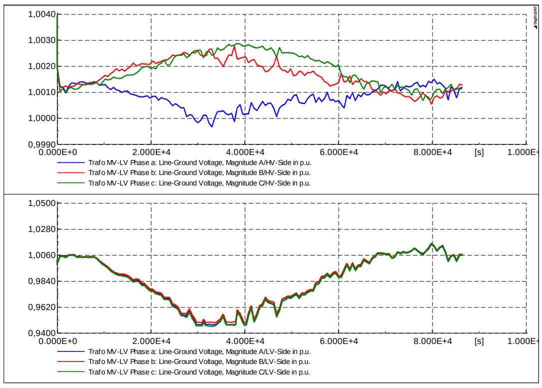
- From base case to 1 phase: ➡ the three phases get better



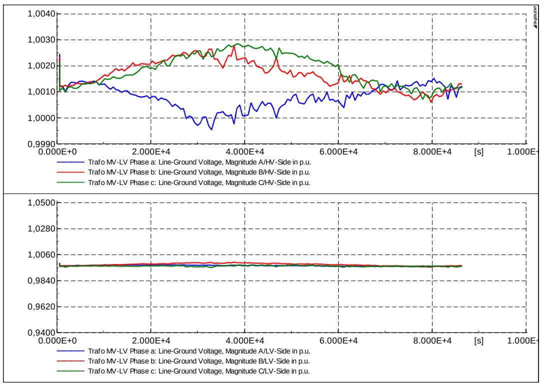
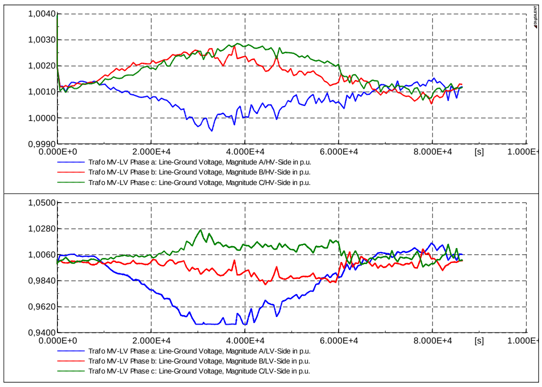


B. Voltage profile at the transformer level (LV side)

- From base case to 3 phase: ➡ the three phases get worse (peaks around -5%/+2%)

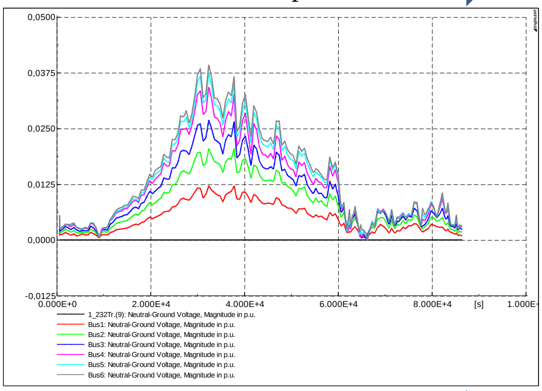
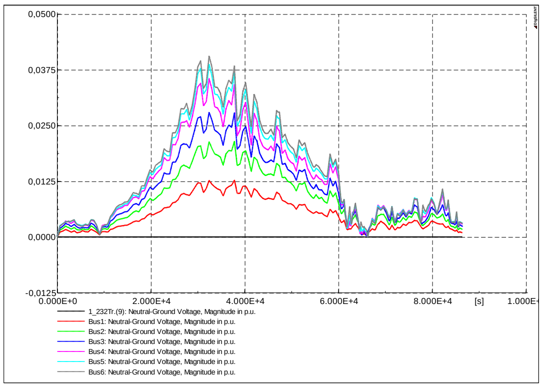



- From base case to 1 phase: ➡ the three phases get worse (peaks around -5%/+2.8%)

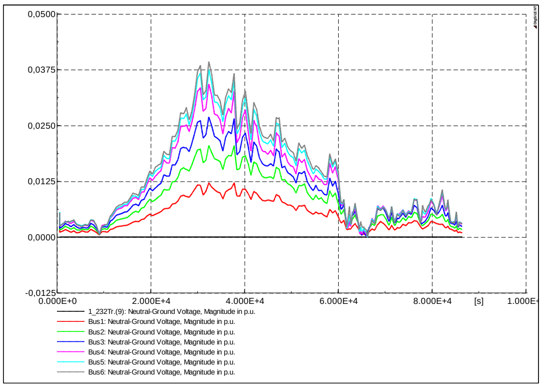
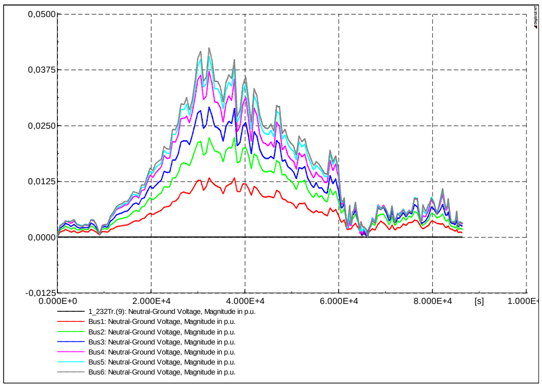



C. Neutral-Ground Voltage

- From base case to 3 phase: ➡ the same (peaks around +4%)

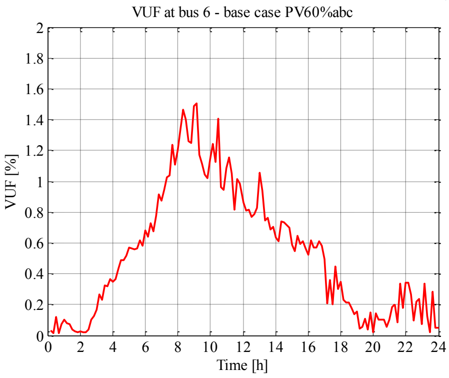



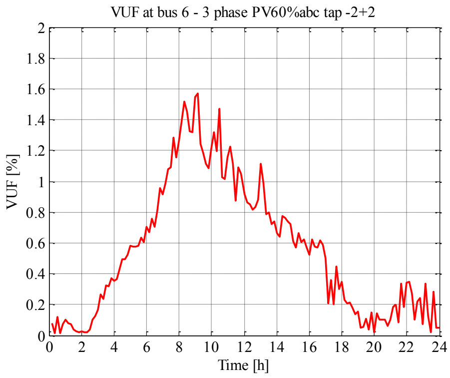
- From base case to 1 phase: ➡ the same (peaks around +4%)

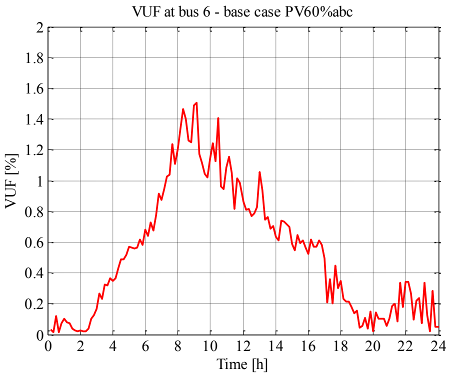
D. <u>Unbalance factor VUF at the worst bus: BUS 6</u>

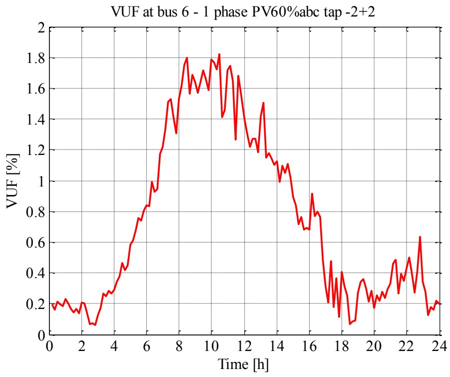
- From base case to 3 phase: ➡ the same





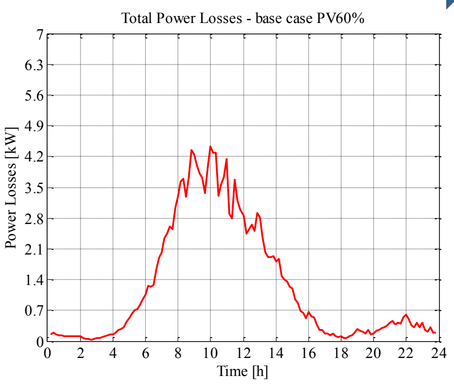
- From base case to 1 phase: ➡ gets higher

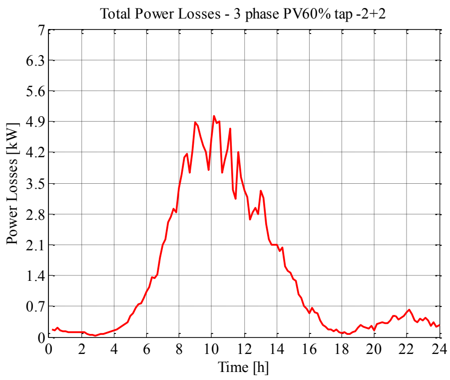




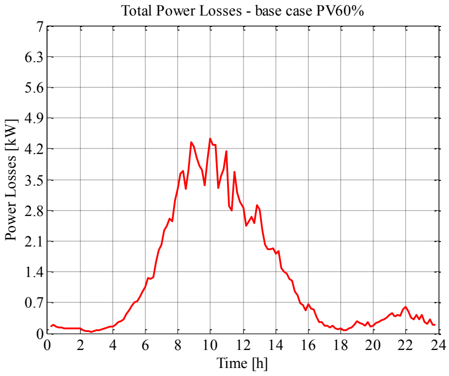
E. <u>Total Power and Energy Losses</u>

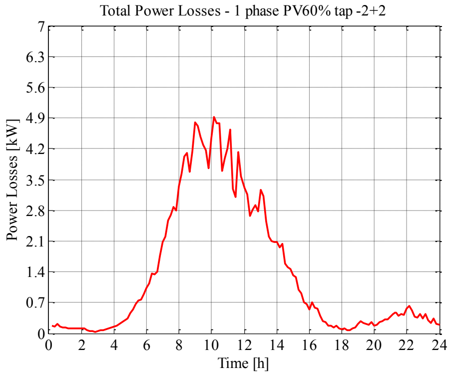
- From base case to 3 phase: ➡ get higher





- From base case to 1 phase: ➡ get higher

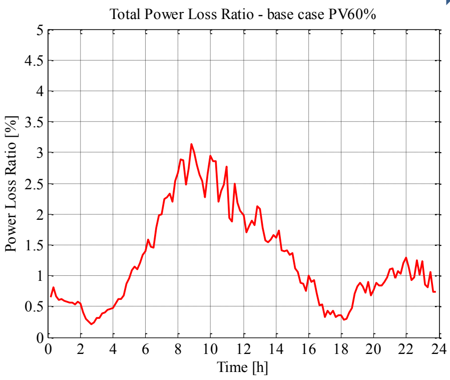


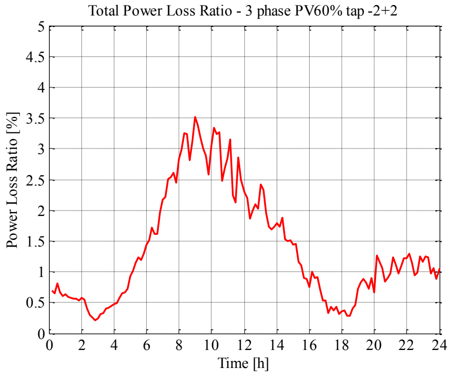


Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the trafo [kWh]	Energy Loss [kWh]	Energy Loss Deviation [%, compared to base case]
Base Case	769.70	1468.77	-670.66	28.41	+0.00%
3 Phase	751.97	1468.50	-684.89	31.64	+11.37%
1 Phase	767.24	1467.91	-669.63	31.04	+9.26%

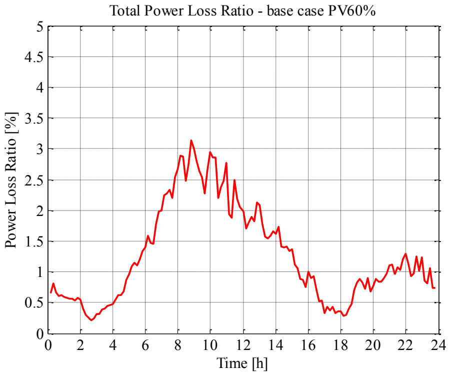
F. Total Power Loss Ratio

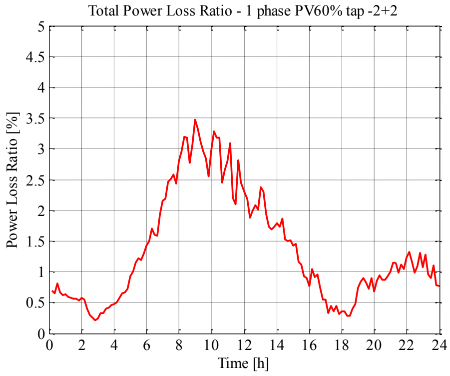
- From base case to 3 phase: ➡ gets higher





- From base case to 1 phase: ➡ gets higher

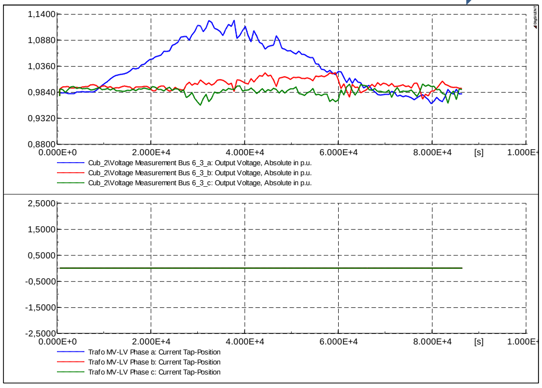


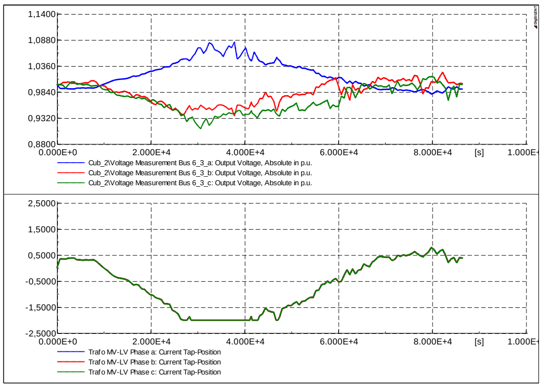


4.3.5 Results Comparison – PV 70%: 245kW PV connected to phases a, b and c

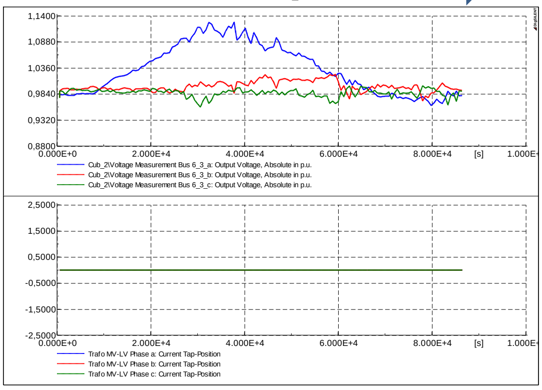
A. Voltage profile at the worst bus: BUS 6

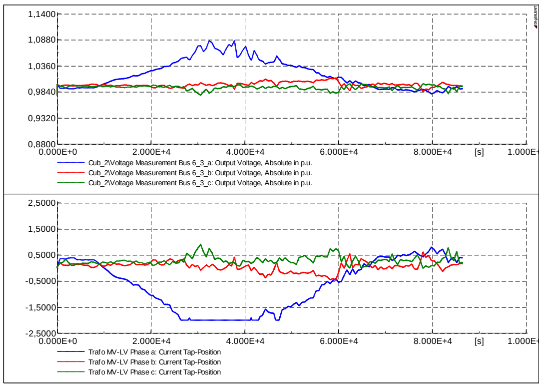
- From base case to 3 phase: ➡ phases a and b get better, phase c gets worse





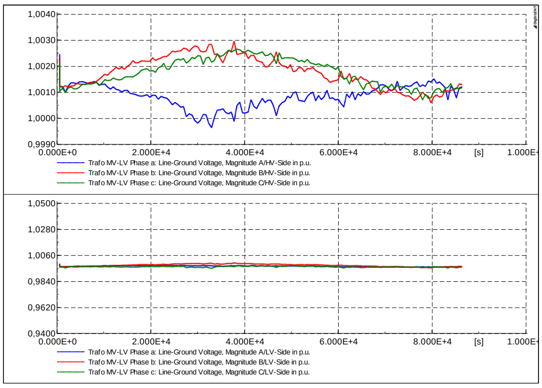
- From base case to 1 phase: ➡ the three phases get better

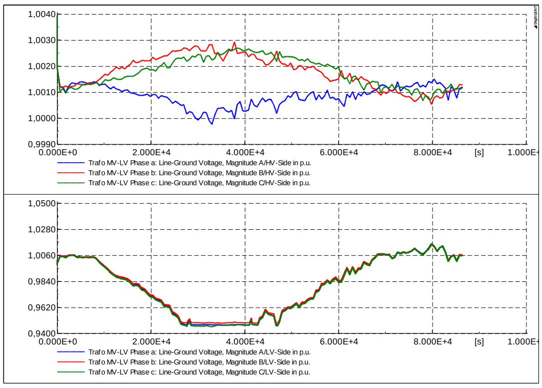




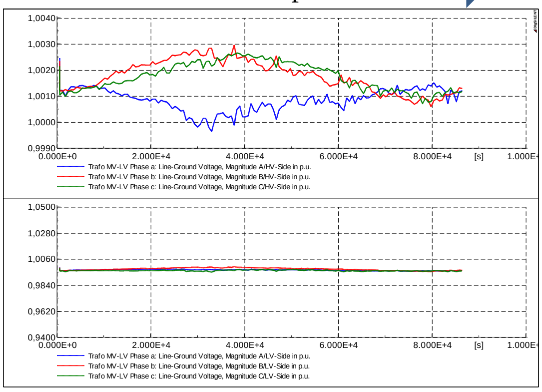
B. <u>Voltage profile at the transformer level (LV side)</u>

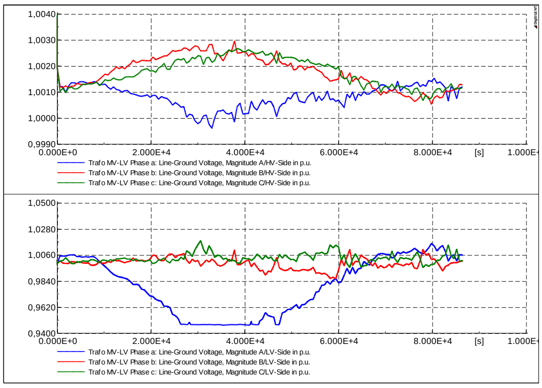
- From base case to 3 phase: ➡ the three phases get worse (peaks around -5%/+2%)





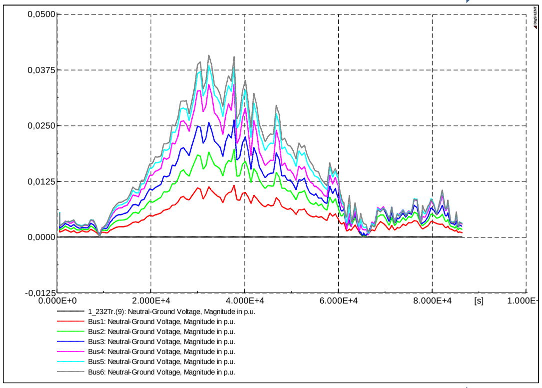
- From base case to 1 phase: ➡ the three phases get worse (peaks around -5%/+2%)

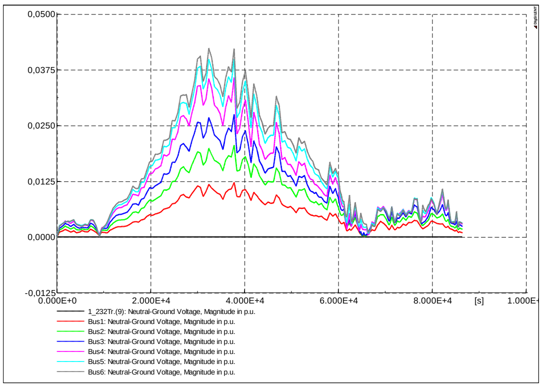




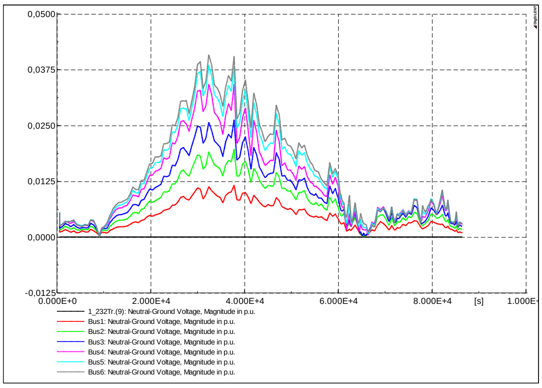
C. Neutral-Ground Voltage

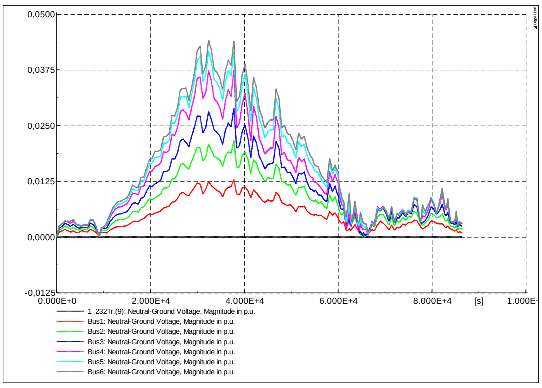
- From base case to 3 phase: ➡ the same (peaks around +4%)





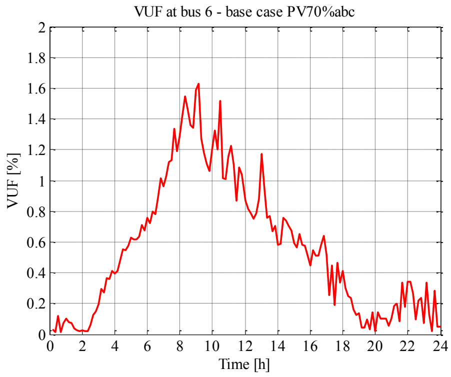
- From base case to 1 phase: ➡ the same (peaks around +4%)

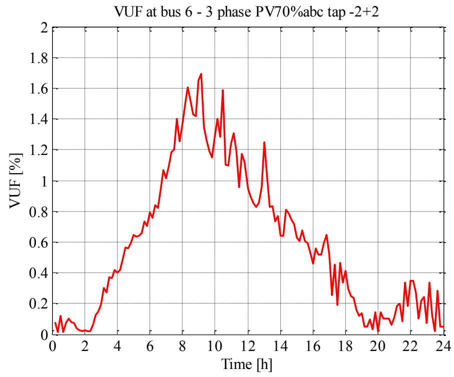




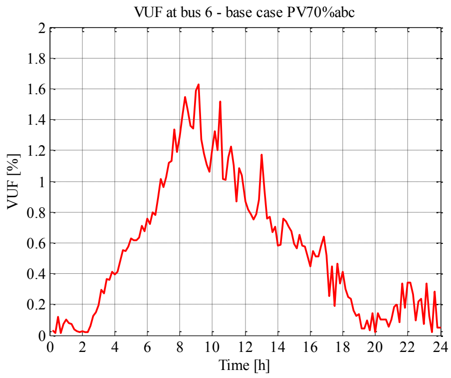
D. Unbalance factor VUF at the worst bus: BUS 6

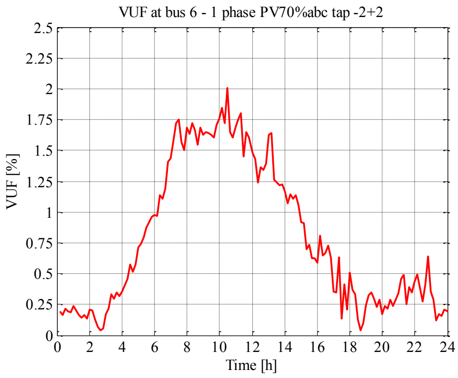
- From base case to 3 phase: ➡ the same





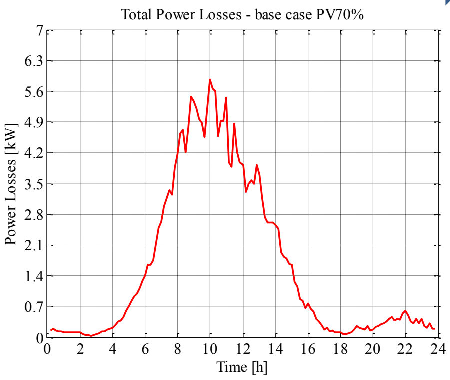
- From base case to 1 phase: ➡ gets higher

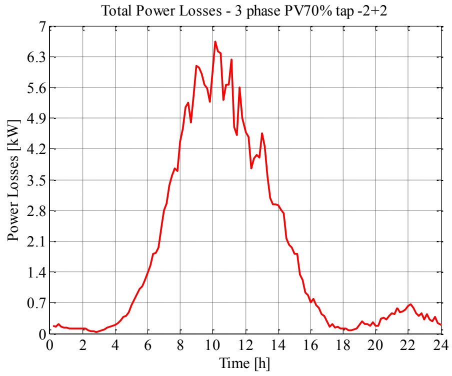




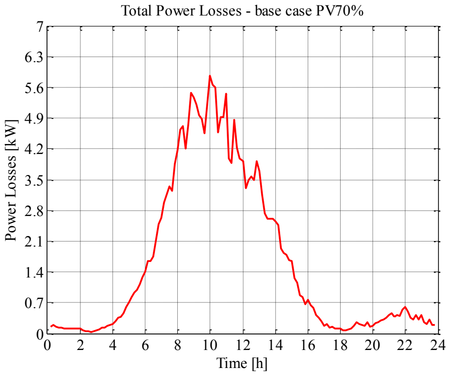
E. Total Power and Energy Losses

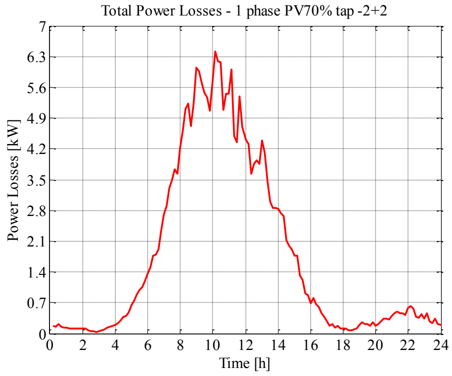
- From base case to 3 phase: ➡ get higher





- From base case to 1 phase: ➡ get higher

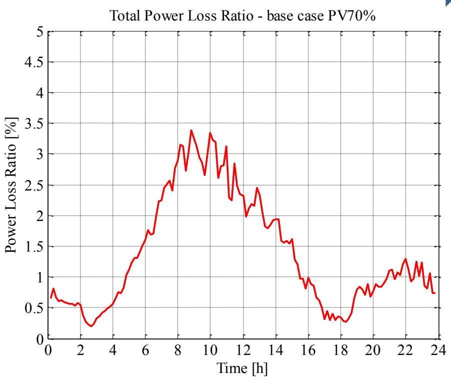


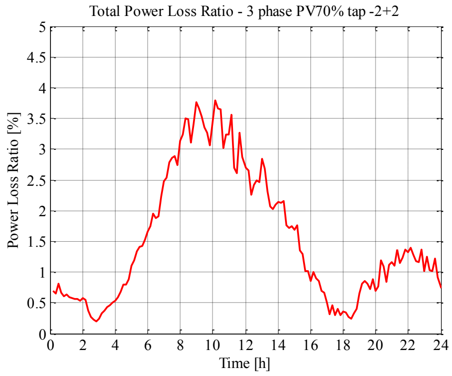


Case	Total Energy absorbed by loads [kWh]	Total Energy injected by PV [kWh]	Energy through the trafo [kWh]	Energy Loss [kWh]	Energy Loss Ratio [%]	Energy Loss Deviation [%, compared to base case]
Base Case	774.76	1714.48	-901.62	38.10	2.22%	+0.00%
3 Phase	751.56	1714.29	-919.65	43.08	2.51%	+13.07%
1 Phase	769.12	1713.54	-902.70	41.72	2.43%	+9.50%

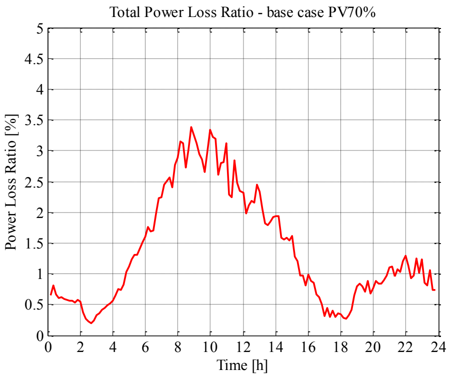
F. Total Power Loss Ratio

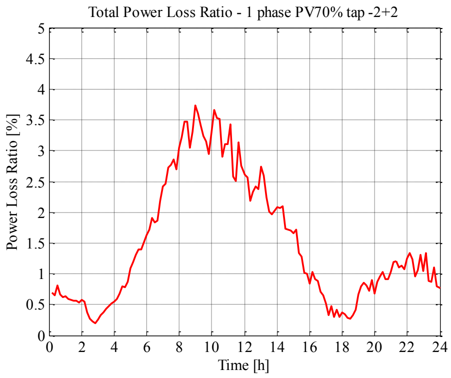
- From base case to 3 phase: ➡ gets higher





- From base case to 1 phase: ➡ gets higher


Total Power Loss Ratio - base case PV70%
Power Loss Ratio [%]
Time [h]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14
16
18
20
22
24


Total Power Loss Ratio - 1 phase PV70% tap -2+2
Power Loss Ratio [%]
Time [h]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
14
16
18
20
22
24

5 CONCLUSION

From the analysis of the results obtained applying different levels of PV penetration, it is deduced that the maximal PV hosting capacity of the network (considering the unbalanced connection to phases a and b, without power injection into phase c) is 30%, i.e. the situation of 105kW of PV connected to phases a and b.

The analyzed cases are summarized in the following tables:

PV 10% : 35kW PV installed at phase a

Case	Voltages (an, bn, cn) at bus 6	VUF at bus 6	Neutral potential	Total losses [kWh]
Base Case	within -5%/+5%	max: 1.2%	Peaks around 2%	6.45
3 Phase	within -7%/+3%	max: 1.3%	Peaks around 2%	6.59
1 Phase	within -2.5%/+2.5%	max: 1.3%	Peaks around 2%	6.66

PV 30% : 105kW PV installed split into phases a and b

Case	Voltages (an, bn, cn) at bus 6	VUF at bus 6	Neutral potential	Total energy losses
Base Case	within -8%/+8%	max: 1.4%	Peaks around 3.75%	14.65
3 Phase	within -12%/+4%	max: 1.5%	Peaks around 3.75%	15.05
1 Phase	within -5%/+4%	max: 1.9%	Peaks around 3.75%	15.24

PV 40% : 140kW PV installed split into phases a and b

Case	Voltages (an, bn, cn) at bus 6	VUF at bus 6	Neutral potential	Total energy losses
Base Case	within -10.1%/+10%	max: 1.7%	Peaks around 5%	24.72
3 Phase	within -15%/+5%	max: 1.8%	Peaks around 5%	26.21
1 Phase	within -6.5%/+5%	max: 2.5%	Peaks around 5%	26.25

PV 50% : 175kW PV installed split into phases a and b

Case	Voltages (an, bn, cn) at bus 6	VUF at bus 6	Neutral potential	Total energy losses
Base Case	within -13%/+15%	max: 2.05%	Peaks around 6%	40.30
3 Phase	within -17%/+9%	max: 2.2%	Peaks around 6%	43.98
1 Phase	within -8%/+9%	max: 2.9%	Peaks around 6%	43.75

Furthermore, the PV hosting capacity is higher than 105kW if the PV connections are distributed on the three phases with a more realistic degree of unbalance. With the less unbalanced configuration the worst bus became bus 5. Due to this, the phase-neutral voltages as well as the VUF have been considered referring to bus 5 instead of bus 6. It has been decided to repeat the 40% case – 140kW – and from this case on, increasing the amount of PV power. The 40% scenario is now acceptable both without and with tapping action. The 50% and 60% cases – respectively 175 and 210 kW – showed that the PV hosting capacity could be higher than 140kW only if 1 phase OLTC is performed. The simulation results are summarized as follows:

PV 40% : 140kW PV connected to phases a, b and c

Case	Voltages (an, bn, cn) at bus 5	VUF at bus 5	Neutral Potential	Total losses [kWh]
Base Case	within -4%/+7.5%	max: 1%	Peaks around 2.5%	11.61
3 Phase	within -6.5%/+4%	max: 1%	Peaks around 2.5%	12.22
1 Phase	within -2%/+4%	max: 1.3%	Peaks around 2.5%	12.16

PV 50% : 175kW PV connected to phases a, b and c

Case	Voltages (an, bn, cn) at bus 5	VUF at bus 5	Neutral Potential	Total losses [kWh]
Base Case	within -6%/+11%	max: 1.4%	Peaks around 3.75%	21.45
3 Phase	within -11%/+6.5%	max: 1.4%	Peaks around 3.75%	23.59
1 Phase	within -3%/+5%	max: 1.8%	Peaks around 3.75%	23.33

PV 60% : 210kW PV connected to phases a, b and c

Case	Voltages (an, bn, cn) at bus 5	VUF at bus 5	Neutral Potential	Total losses [kWh]
Base Case	within -6%/+11%	max: 1.5%	Peaks around 4%	28.41
3 Phase	within -11%/+7%	max: 1.5%	Peaks around 4%	31.64
1 Phase	within -3%/+7%	max: 1.9%	Peaks around 4%	31.04

PV 70% : 245kW PV connected to phases a, b and c

Case	Voltages (an, bn, cn) at bus 6	VUF at bus 6	Neutral Potential	Total losses [kWh]
Base Case	within -4%/+13%	max: 1.6%	Peaks around 4%	38.10
3 Phase	within -10.1%/+8.8%	max: 1.6%	Peaks around 4%	43.08
1 Phase	within -2.5%/+8.8%	max: 2.05%	Peaks around 4%	41.72

From the above table, it can be concluded that with less unbalanced PV power injection, the hosting capacity increased compared to previous very unbalanced connection case,growing from 105 kW to 210 kW.

In the end, it should be noted that any reactive power injection from the PV plants has yet to be considered, probably resulting in a further improvement in the hosting capacity, beyond the found limit of 210 kW if the PVs could inject inductive-capacitive reactive power, following a voltage and active power dependence law: Q=f(V,P).

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