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# Project memo

## Demonstration of benefits of voltage regulation options and the associated challenges

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**ABSTRACT**
This report presents the analysis of a case study of actual distribution network for its future distributed generation plans and the associated voltage quality challenges. After analysing the current and future state of the case network, a critical measurement assisted operation of HV/MV on load tap changer, OLTC (CMAO-OLTC) solution is proposed and studied for different combination of load and generation. The analysis demonstrated that CMAO-OLTC can limit the voltage level violations induced by new distributed generators if the occurrence of maximum voltage violation and minimum voltage violations are not happening at the same time.

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# 1 Introduction

With the increased integration of renewable generations in the distribution network, there will be emerging challenges for system operators. The challenges in general are related to feeder capacities, protection system and power quality [1]. In this study, much focus will be given to power quality related challenges and specifically voltage regulation. Within the DGNett project various state of the art power quality solutions has been evaluated and narrowed down to the most relevant and the less capital intensive solutions. In this report, however, the effectiveness of the proposed solutions will be evaluated and demonstrated using actual distribution networks with real imminent challenges associated with already planned integration of small hydro power plants.

In this section, the description of the case network is presented first and followed by brief remarks on the network data processing undertaken in this analysis. Section 2 discusses the standard power quality testing procedure with which the current and future performance of the case network is analysed. Sections 3 and 4 presents the voltage profiles in the current and future network scenarios respectively. The CMAO-OLTC method is introduced and simulation results are presented and analysed in Section 5. The last section, section 5, summarizes the main observations and recommendations as result of the case network analysis.

## 1.1 The Frøyset network

The Frøyset network has 613 nodes of which three are generating units. The network is looking forward to host five more small hydropower generators as shown in Table 1.There are four main feeders coming out of the primary substation MV side. The feeders are named: Åmdalsvik, Rambjør, Frøyset and Steine (see Fig. 1).The longest distance from primary substation node, which is also the node with the lowest voltage, is node 62 (7004 GRIMA). Node 62 is supplied by feeder Åmdalsvik. In cases of high production the highest voltage is associated with the Blådalselva generating unit (Node 515). It is supplied by the feeder named Rambjør (see Fig. 1). In Fig. 2, the voltage profiles for the nodes in the network using the data as it is extracted from the system are presented showing the maximum and minimum voltage nodes in a typical loading and generation conditions.

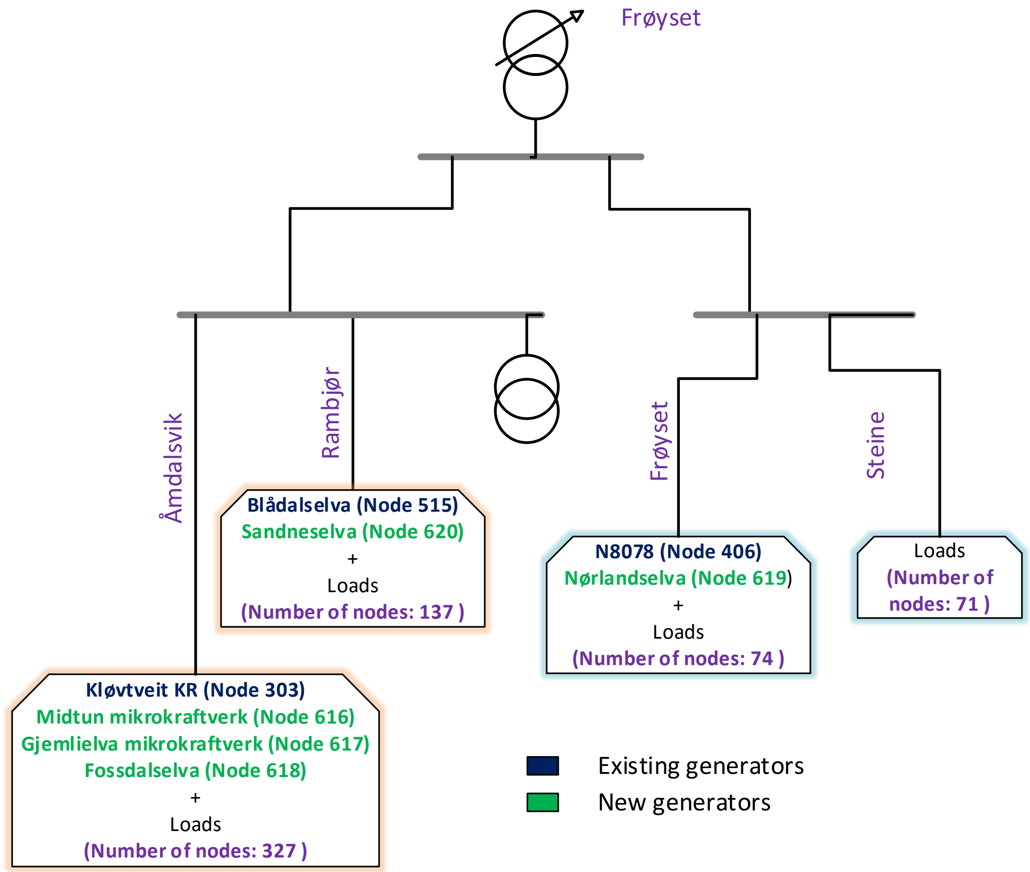


**Figure 1 Frøyset network sketch**

**Table 1 New and current generating units**

| Kraftverk | Rating, Pmax (kW) | New node number | Voltage regulation setting | |
|---|---|---|---|---|
| Midtun mikrokraftverk | 250 | 616 | 0.95 inductive | New generators |
| Gjemlielva mikrokraftverk | 99 | 617 | 0.95 inductive | |
| Fossdalselva | 2950 | 618 | 0.95 inductive | |
| Nørlandselva | 3500 | 619 | 0.95 inductive | |
| Sandneselva | 2300 | 620 | 0.95 inductive | |
| Blådalselva | 2500 | 515 | Constant 0.97 inductive | Current Generators |
| Svartdalen | 3300 | 406 | V=22.8: 0 MVAr<br>V<=21.6: +2 MVAr<br>22<=V : -2 MVAr | |
| Kløvtveit KR | 8900 | 303 | Constant 22 kV<br>-3.9 MVAr <= Q<=3.9 MVAr | |

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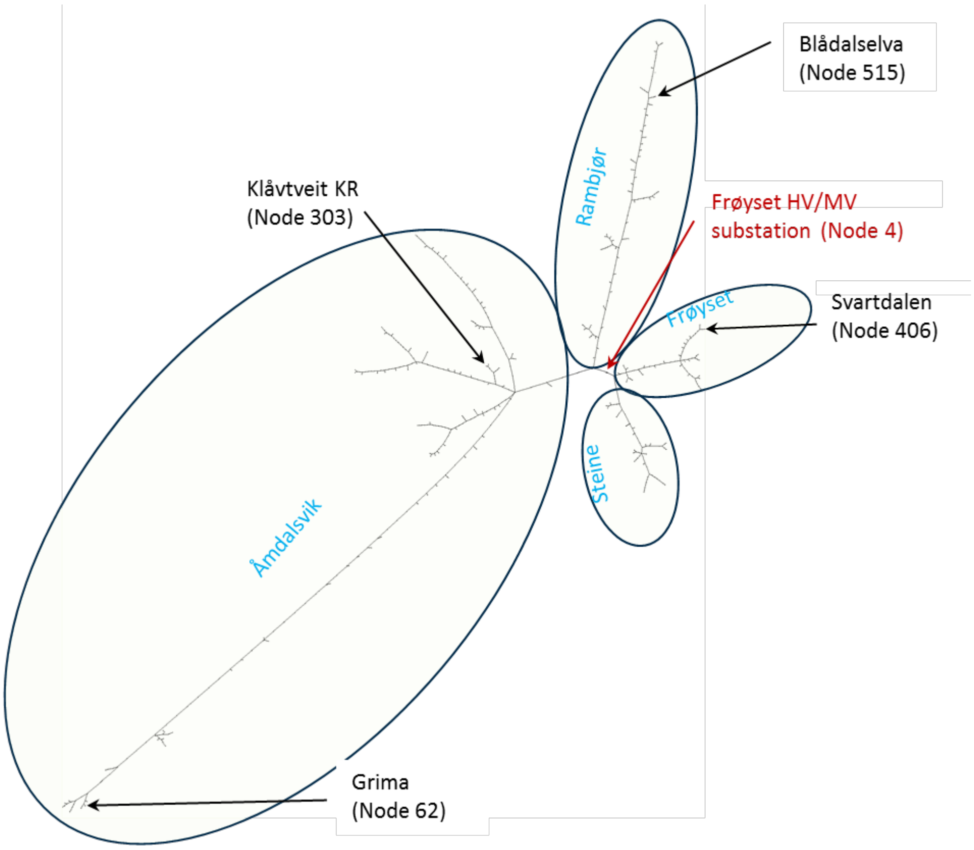
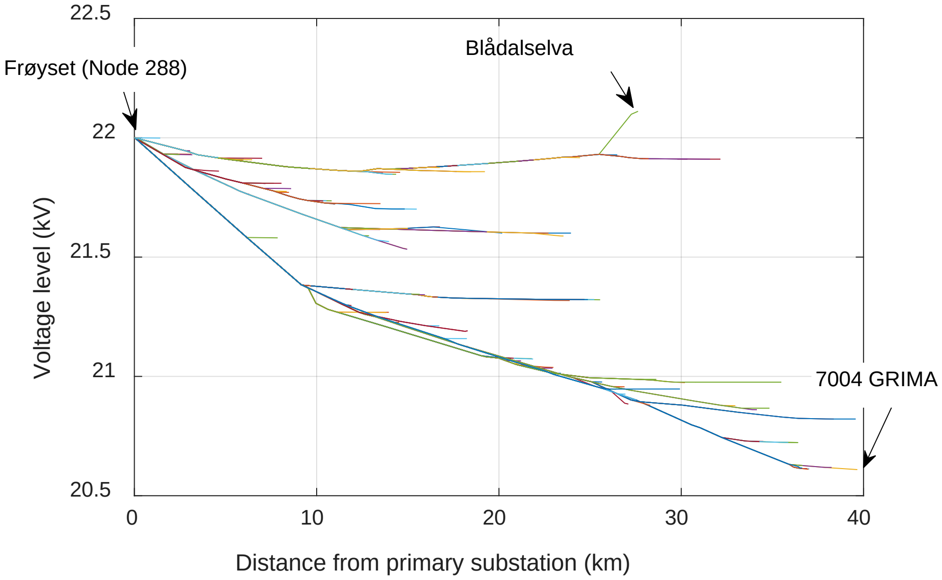



*(a) Single line diagram of the network*




*(b) Voltage profile of the Frøyset network at the time of extraction from the system*

**Figure 2 Preview of the Frøyset network**

## 1.2 Network data Processing

For purposes such as network visualization and voltage profile plotting, some assumptions are considered with certain procedures of data processing. These procedures will be briefly discussed in this section and their Matlab code will be provided in the appendix.

a. **Procedure to compute distances of branches**
   The three common line types in the network are FeAl25 (0.721 +j0.0395) Ω/km, FeAl95 (0.189+j0.353) Ω/km, and FeAl50 (0.359 + j0.373) Ω/km. hence an average value of 0.423 Ω/km is used to calculate the length of the branches. Nevertheless, these approximation of branch length has no impact on the voltage calculation as it was used solely for graphing purposes.

b. **Procedures to identify path to end nodes**
   A matlab function tracing the path between starting node (Primary substation) and target nodes (nodes which do not connect other nodes downstream) by using adjacency matrix. The Matlab routine for the process is presented Table A1 of the Appendix.

Other Matlab codes for network data processing and plotting procedures are presented in Tables A2-A4. The network file data in '.raw' format is converted to a case file for Matpower 6.0 with which the power flow analysis is conducted.

The generation buses, except for the generators at nodes 303 and 406, are treated as PQ-bus (not as PV-bus) as we are looking for their impact on voltage quality and as they have fixed power factor. Generator connected at node 303 (Kløvtveit) is modelled as a PV-bus with Q limit of 3.9 MVAr. Generator connected at node 406 (Svartdalen) is also modelled as a PV-bus with Q limit of 2 MVAr. The active power is set according to the testing procedure listed in Table 1 while the reactive power is set to value associated with 0.95 power factor for the new generators and 0.97 power factor for the generator connected at node 515 (Blådalselva). The powerflow is conducted with strict enforcement of the Q-limits. Hence, those two PV-bus modelled as generators (PV-bus) will be converted to PQ-bus if the Q-limit is reached.

## 2 Evaluation Strategy

The REN3006 protocol to assess the impact of the new generations on the voltage quality of the network is followed in this study. The REN3006 standard have clear guidelines in assessing the impacts as shown in Table 2 [2]. Based on the REN3006 test, there are two parameters to be calculated: the stationary voltage (SV) and the slow voltage variation (SSV). To stay within the limits specified in the Norwegian PQ Code, the following criteria need to be fulfilled [3].

- For stationary voltage (**SV**) changes the threshold value is set at 3%.
- For slow stationary voltage variations (**SSV**), the threshold set at 5%. (This value takes into account trinning of overlying transformation by 2%, so that in practice allowed 7% slow voltage variations at the connection point.)

$$\text{stationary voltage changes } (\mathbf{SV}) \ = \mathrm{LLHP} - \mathrm{LLLP} \text{ or } \mathrm{TLHP} - \mathrm{TLLP} \quad (1)$$

$$\text{slow stationary voltage variations } (\mathbf{SSV}) = \mathrm{LLHP} - \mathrm{TLLP} \quad (2)$$

**Table 2 REN3006 test**

| | Kriterier | Produksjon | Belastning |
|---|---|---|---|
| 1 | Lett Last - Lav Produksjon (LLLP) | 0% | Eks. 20% |
| 2 | Tung Last - Lav Produksjon (TLLP) | 0 % | 100% |
| 3 | Lett Last - Høy Produksjon (LLHP) | 100 % | Eks. 20% |
| 4 | Tung Last - Høy Produksjon (TLHP) | 100 % | 100% |
| 5 | Lett Last - Høy Produksjon (LLHP, tan φ = -0,33 ) | 100 % | Eks. 20% |
| 6 | Lett Last - Høy Produksjon (LLHP, tan φ = -0,48) | 100 % | Eks. 20% |
| 7 | Termisk grenselast lik beregning 3 (LLHP) | 100 % | Eks. 20% |
| 8 | Sensivitetsberegning – Reaktiv reserve” *LLHPRC*. | 100 % | Eks. 20% |

In the next sections, the REN3006 testing results will be presented for current and future network conditions and with different types of methods of voltage regulation.

## 3 Current network scenarios

In the existing network, there are only three generators at nodes 515, 406 and 303. Before conducting the standard test on the current network, the voltage regulation for the three generators is setup as it is shown in Table 1. The resulting voltage profiles at the three generators are presented in Figs 3 to 5.

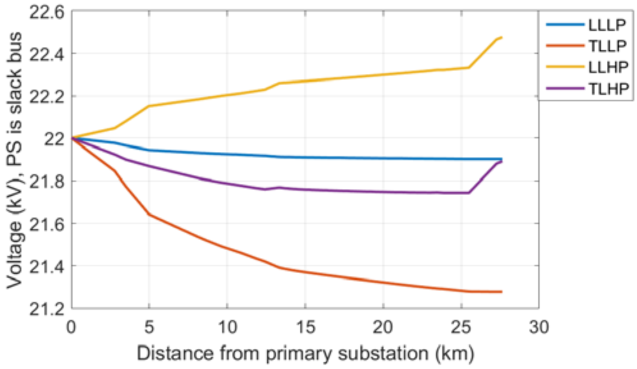



**Figure 3 Voltage profile for generator at Node 515, in the current network (Blådalselva (Node 515))**

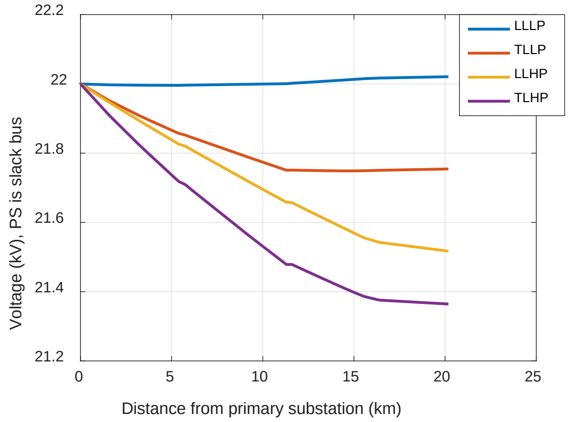



**Figure 4 Voltage profile for generator at Node 406, in the current network (Svartdalen (Node 406))**

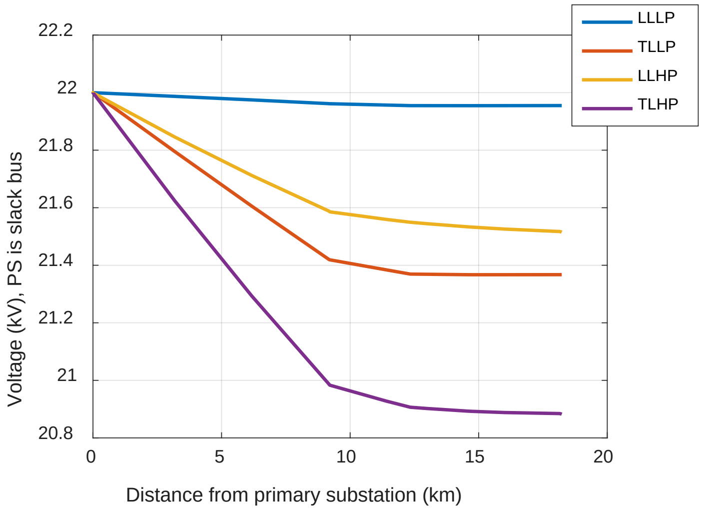



**Figure 5 Voltage profile for generator at Node 303, in the current network (Kløvtveit Kr (Node 303))**

**Table 3 Results for the current network**

| Name | SV | SSV | Vmax | Vmin |
|---|---|---|---|---|
| Blådalselva (Node 515) | 2.79 % | 5.45 % | 22.48 | 21.28 |
| Svartdalen (Node 406) | 2.29 % | 1.08 % | 22.02 | 21.36 |
| Kløvtveit Kr (Node 303) | 2.20 % | 0.82 % | 22.00 | 20.88 |

***As shown in Figs. 3-5 and Table 3, there is neither voltage limit violation nor violation of the SV and SSV (except for the exceedance by 0.45% over the 5% limit for Blådalselva) limits in the current situation.***

# 4 Future network scenarios

In the future network, there will be five more generators at nodes 616 to 620. The voltage profiles are calculated again for the new scenario where the five power plants are installed. A 0.95 pf is assumed for the new generators keeping the current generators' setting intact. The results are also calculated using a power-factor of one for future generators while keeping the existing generators setting intact. The difference between pf 1 and 0.95 will demonstrate the impact of the participation of the newly planned generators in voltage control through their reactive power capability.

Tables 4 and 5 show the profiles for the generating units with the pf of 1 and 0.95 conditions respectively. Table 6, however, show the voltage profiles of the entire network during the REN test. The REN test voltage profiles are also plotted for a pf case of 0.95 and are presented in the Appendix Table A5.

**Table 4 Results in the new network (New generator pf 1)**

| Name | Node | SV | SSV | Vmax | Vmin |
|---|---|---|---|---|---|
| Blådalselva (Node 515) | 515 | 4.99 % | 7.53 % | 22.93 | 21.28 |
| Svartdalen N8078 (Node 406) | 406 | 0.69 % | 1.06 % | 22.02 | 21.74 |
| Kløvtveit Kr (Node 303) | 303 | 1.26 % | 1.64 % | 22.00 | 21.28 |
| Midtun mikrokraftverk | 616 | 0.94 % | 1.78 % | 22.00 | 21.28 |
| Gjemlielva mikrokraftverk | 617 | 1.02 % | 2.08 % | 22.00 | 21.17 |
| Fossdalselva | 618 | 1.09 % | 1.81 % | 22.00 | 21.28 |
| Nørlandselva | 619 | 0.40 % | 1.08 % | 22.01 | 21.75 |
| Sandneselva | 620 | 3.92 % | 6.05 % | 22.72 | 21.39 |

**Table 5 Results in the new network (New generator pf 0.95)**

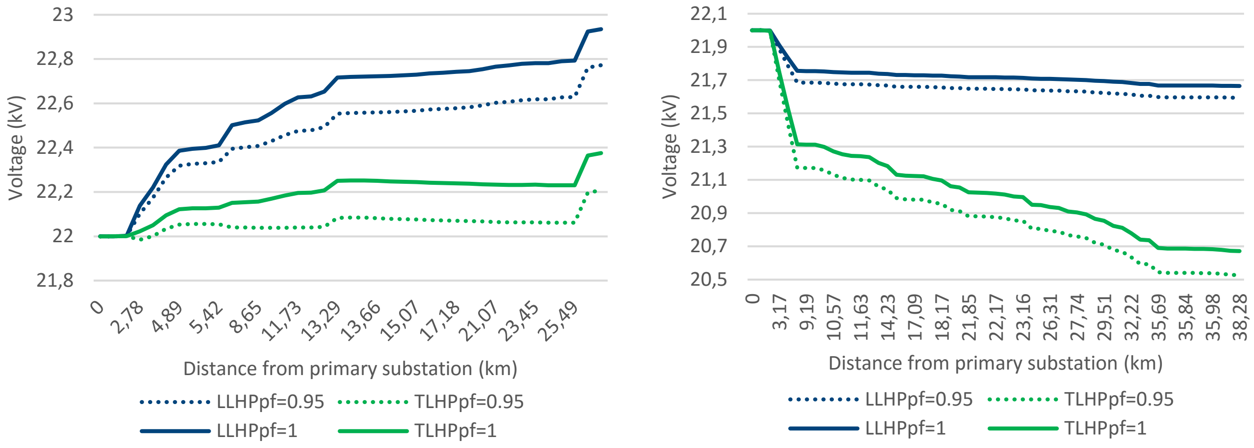
| Name | Node | SV | SSV | Vmax | Vmin |
|---|---|---|---|---|---|
| Blådalselva (Node 515) | 515 | 4.22 % | 6.79 % | 22.77 | 21.28 |
| Svartdalen N8078 (Node 406) | 406 | 1.22 % | 0.53 % | 22.02 | 21.62 |
| Kløvtveit Kr (Node 303) | 303 | 1.70 % | 1.23 % | 22.00 | 21.07 |
| Midtun mikrokraftverk | 616 | 1.26 % | 1.42 % | 22.00 | 21.14 |
| Gjemlielva mikrokraftverk | 617 | 1.43 % | 1.66 % | 22.00 | 20.98 |
| Fossdalselva | 618 | 1.60 % | 1.25 % | 22.00 | 21.08 |
| Nørlandselva | 619 | 0.76 % | 0.53 % | 22.01 | 21.69 |
| Sandneselva | 620 | 3.16 % | 5.31 % | 22.56 | 21.39 |

**Table 6 Comparison of $cos\,\varphi = 1$ and $cos\,\varphi = 0.95$ for the new generators**

| | | LLLP | TLLP | LLHP | TLHP |
|---|---|---|---|---|---|
| $\cos\varphi = 1$ | $V_{Max}$ | 22.04 | 22.00 | 22.93 | 22.38 |
| | MaxVoltNode | 465 | 286 | 514 | 514 |
| | $V_{Min}$ | 21.87 | 20.78 | 21.66 | 20.65 |
| | MinVoltNode | 62 | 62 | 62 | 62 |
| | $P_{fromGrid}$ (MW) | 2.95 | 15.08 | 4.13 | 16.36 |
| | $Q_{fromGrid}$ (MVAr) | -1.38 | 3.03 | -1.33 | 1.96 |
| | $P_{loss}$ (MW) | 0.02 | 0.46 | 0.60 | 1.14 |
| | $Q_{loss}$ (MVAr) | 0.09 | 2.10 | 2.15 | 4.79 |
| $\cos\varphi = 0.95$ | $V_{Max}$ | 22.04 | 22.00 | 22.77 | 22.21 |
| | MaxVoltNode | 465 | 286 | 514 | 514 |
| | $V_{Min}$ | 21.87 | 20.78 | 21.49 | 20.51 |
| | MinVoltNode | 62 | 62 | 618 | 62 |
| | $P_{fromGrid}$ (MW) | 2.95 | 15.08 | 4.15 | 16.38 |
| | $Q_{fromGrid}$ (MVAr) | -1.38 | 3.03 | 0.69 | 4.53 |
| | $P_{loss}$ (MW) | 0.02 | 0.46 | 0.63 | 1.17 |
| | $Q_{loss}$ (MVAr) | 0.09 | 2.10 | 2.23 | 4.87 |

The maximum voltage decrease by 0.7% and 0.76% in case of LLHP and TLHP respectively while the total loss increased by 3.81% and 1.72% in case of LLHP and TLHP respectively. In general, although the reactive power from generators contribute to the reduction of maximum voltages, the associated increase in loss is significant.

The light-load high-generation (LLHP) and the heavy-load high-generation (TLHP) voltage profiles are plotted for the highest voltage node (Node 515) and lowest voltage node (node 62) in Fig. 6. The reactive power contribution of the new generators reduces the highest voltage node from 4.25% overvoltage to 3.51% overvoltage while decreasing further the lowest voltage node from 1.52% to 1.84% below nominal voltage (as percentage of nominal voltage 22 kV). The reduction of maximum voltage in the network is usually accompanied with a reduction of the lowest voltage node as well. Hence, it is apparent that one has to monitor critical nodes especially if the primary substation OLTC is planned as mitigation to overvoltage created by the emerging new generator units. In the next section, a voltage regulation mechanism is evaluated involving primary substation OLTC assisted with critical node measurements.




(a) Blådalselva (Node 515)

(b) 7004 Grima (Node 62)

**Figure 6 Impact of participation of the new generators in voltage control at the highest voltage node (Node 515) and the lowest voltage node (Node 62) in the network.**

## 5 Critical measurement assisted operation of HV/MV OLTC (CMAO-OLTC)

Coordinated voltage control mechanisms can be designed in complexity ranging from primary substation OLTC with low voltage side measurement to distribution management system capable of deploying every available voltage supporting resources in the distribution system in real-time as shown in Fig. 7. Considering the practical usability of solutions in existing network with the eminent new generating units, we focused on a critical node measurement assisted voltage regulation using OLTCs at the primary substation. In this section, informed OLTC operation based on measurements at the highest and lowest voltage nodes (typical critical nodes) in the network is investigated as a solution to mitigate overvoltage problems associated with the integration of new generating units. The envisioned setup of the solution is sketched in Fig. 8.

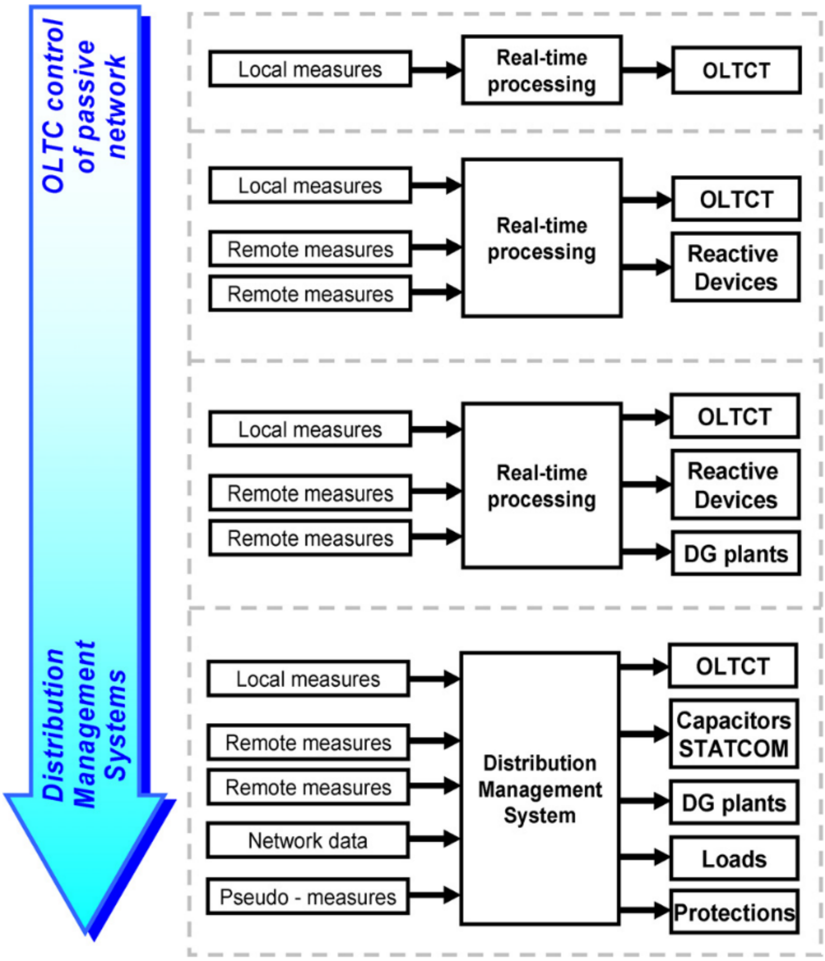



**Figure 7 Schematic diagrams of different integration levels in the active management of distribution networks [4]**

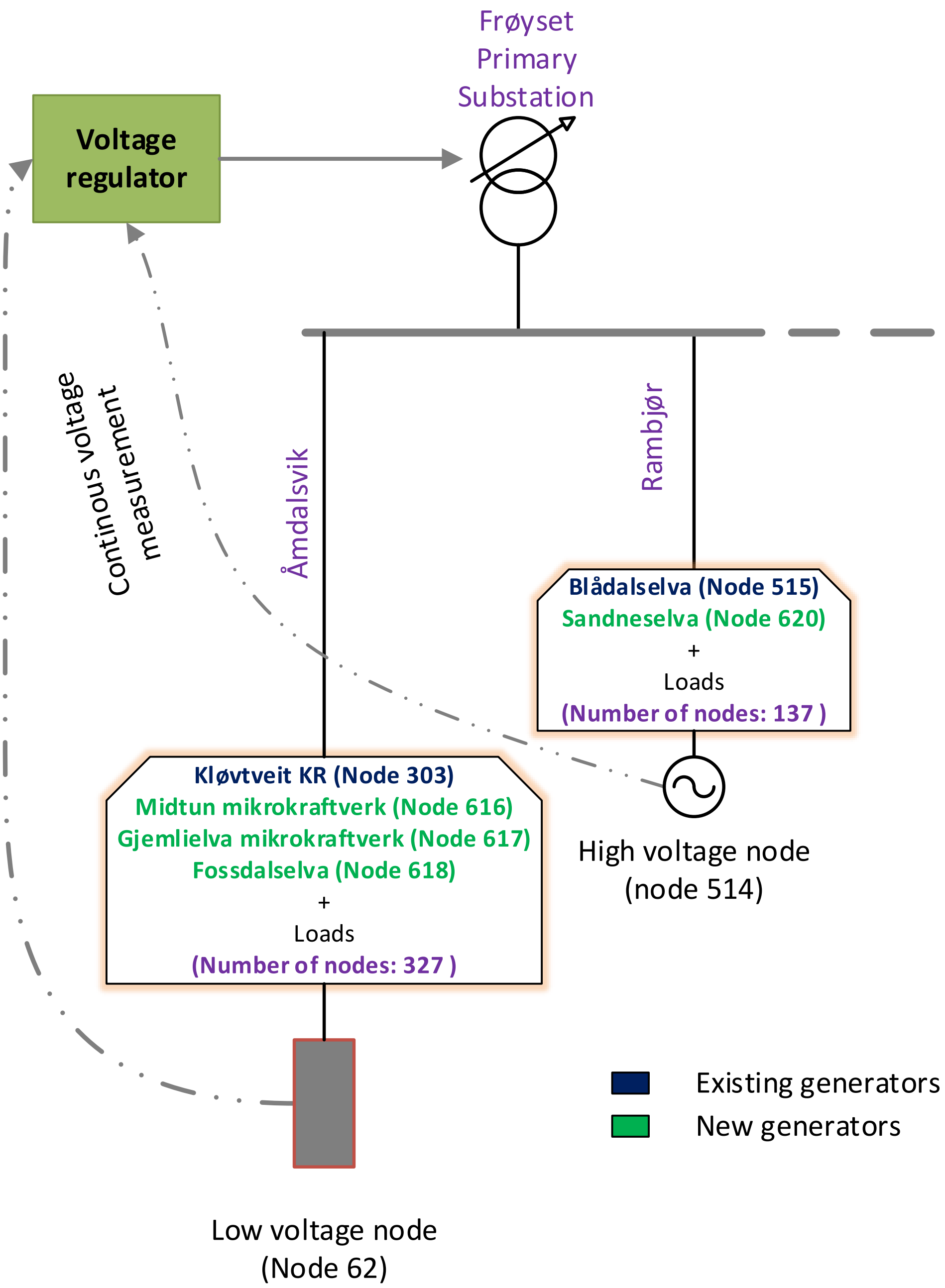
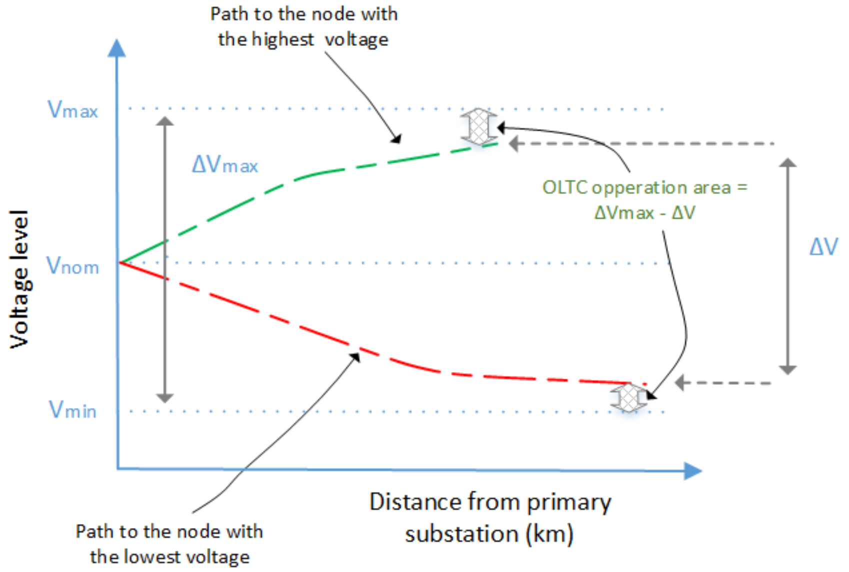



**Figure 8  Informed OLTC operation scheme at primary substation**

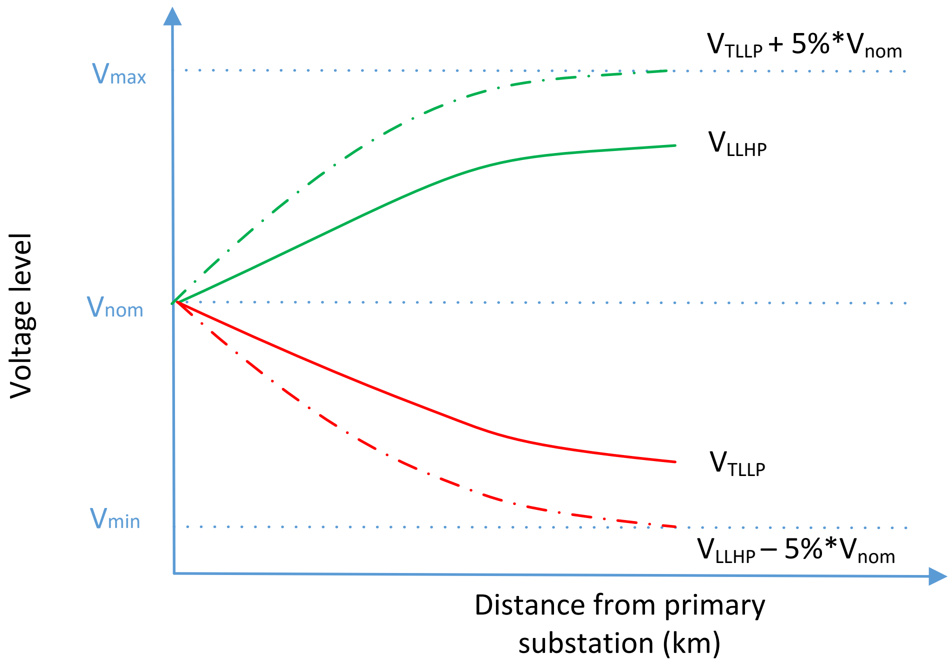
The primary substation assisted with remote measurements can be essential when the main feeders from the primary substation are unbalanced. In the Frøyset network shown in Fig. 1, one can see the low voltage node is connected to the feeder supplying 327 nodes while the high voltage node is connected to the feeder that is supplying 137 nodes.

For the OLTC to be useful in keeping the voltage within the limit by creating opportunity for new generators to communicate, the gap between the maximum and minimum voltage and worst-case conditions should be low. In addition, to conduct justified operation of OLTCs at the HV/MV substation as a solution, one has to consider the following three main principles [5].

1. The voltage level may only be changed if the new level does not violate any voltage limit (see Fig. 9).
2. The voltage level may only be changed if the new level has a positive impact on the network.
3. The voltage level may only be changed if there is a certain time gap since the last change.




*(a)*




*(b)*

**Figure 9 Voltage band showing the operation range for OLTC (a) and (b) the voltage range calculation for each node.**

The goal of the utilization of the OLTC in the network is to limit the slow stationary voltage variation (SSV) under 5% for every node in the network. The equation for SSV is presented in (2). In order to set the maximum and minimum voltage limits at each node of the test network, a method is developed in which the stationary voltage variation limit (i.e. 5%) is translated into absolute maximum and minimum limits. The equations for the voltage limits are presented in (3) and (4).

$$V_{\max\_\lim}(N) = V_{TLLP}(N) + 5\% * V_N \quad (3)$$
$$V_{\min\_\lim}(N) = V_{LLHP}(N) - 5\% * V_N \quad (4)$$

Where $V_{TLLP}(N)$ is the voltage at node $N$ for high load low generation condition, $V_{LLHP}$ is the voltage at node N for low load high generation condition. Consequently, $V_{\max\_\lim}(N)$ and $V_{\min\_\lim}(N)$ are the absolute maximum and minimum voltage respectively for node N where the voltage at the node should not violate in the case of OLTC operation to mitigate the SSV conditions on the critical nodes. Hence, using the equations in (3) to (4), maximum and minimum voltage limits are calculated for each of the nodes in the test network (see Fig. 9). The limits make sure that the stationary voltage variation limits at each of the nodes in the network will stay below the 5% limit.

**Table 7 Example OLTC with 8 steps of each 1.5%**

| *Steps* | Variation | Secondary voltage |
|---|---|---|
| | 6% | 23.32 |
| | 4.5 % | 22.99 |
| | 3 % | 22.66 |
| | 1.5 % | 22.33 |
| | 0.00 % | 22.00 |
| | -1.5 % | 21.67 |
| | -3% | 21.34 |
| | -4.5 % | 21.01 |
| | -6 % | 20.68 |

For the OLTC at the HV/MV substation as shown in Fig. 8 is assumed to have 8 steps of each 1.5% of the nominal voltage which is 22 kV (See Table 7). The OLTC operation workflow is illustrated in Fig. 10. In order to assess the effectiveness of OLTCs, different scenarios of load and generation combinations are evaluated in the next section using the work flow illustrated in fig. 10.

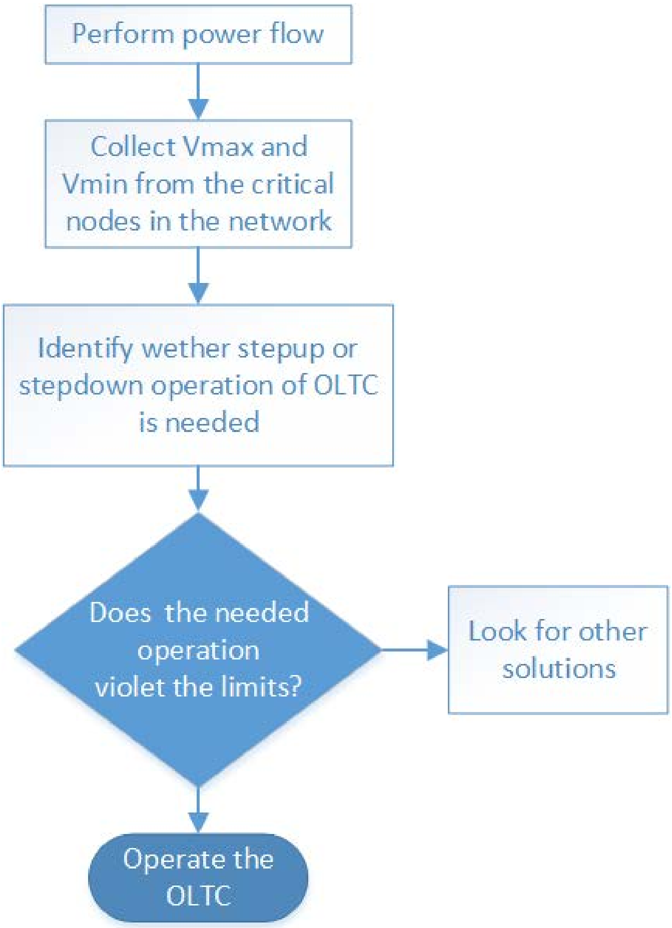



**Figure 10 OLTC operation steps**

## 5.1 Case simulations

After setting the rule of operation for the OLTC, we conducted simulations of different combinations of load and generation levels to see potential problems and to check if OLTC at HV/MV substation can help in mitigating the problems. Primarily though, the TLLP and HLLP cases are computed to check the number and location of SSV limit violations in the network. In the simulations, the levels of all generations and nodes in the network are raised or lowered at the same time.

As shown in Table 8, the highest SSV limit violation occurred at node 514 which is connected to generating node at 515 with 6.79%. Hence, a reduction of the highest voltage by 1.79 would correct the violation at the node. And this can be achieved by stepping down of the OLTC by one step (i.e 1.5%). Nevertheless, one has to be careful of other SSV violations induced by this operation.

The voltage conditions of each and every node in the Frøyset network for voltage violations under all possible combinations of load and generations are also simulated. The number of nodes violating either their respective upper or lower voltage limits are presented in Fig. 11 for the different combinations of load and generation levels.

**Table 8 List of all nodes that violated the 5% SSV limit (in red are generation nodes and in yellow are those nodes next to generating node on the same feeder)**

| Node | SSV (%) | Node | SSV (%) | Node | SSV (%) | Node | SSV (%) | Node | SSV (%) | Node | SSV (%) | Node | SSV (%) | Node | SSV (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **514** | 6.79 % | 486 | 6.20 % | 532 | 6.18 % | 527 | 6.12 % | 74 | 6.04 % | 79 | 6.03 % | 82 | 5.99 % | 510 | 5.86 % |
| **494** | 6.74 % | 483 | 6.20 % | 531 | 6.16 % | 62 | 6.06 % | 310 | 6.04 % | 522 | 6.02 % | 524 | 5.99 % | 106 | 5.79 % |
| **512** | 6.21 % | 476 | 6.20 % | 493 | 6.14 % | 76 | 6.06 % | 309 | 6.04 % | 83 | 6.02 % | 110 | 5.98 % | 105 | 5.78 % |
| **506** | 6.21 % | 475 | 6.20 % | 492 | 6.14 % | 75 | 6.06 % | 78 | 6.04 % | 525 | 6.02 % | 111 | 5.98 % | 537 | 5.74 % |
| **489** | 6.21 % | 521 | 6.20 % | 491 | 6.14 % | 69 | 6.05 % | 63 | 6.04 % | 66 | 6.01 % | 109 | 5.98 % | 536 | 5.74 % |
| **513** | 6.21 % | 520 | 6.20 % | 490 | 6.14 % | 77 | 6.05 % | 308 | 6.04 % | 67 | 6.01 % | 108 | 5.98 % | 509 | 5.74 % |
| **505** | 6.21 % | 519 | 6.20 % | 529 | 6.14 % | 70 | 6.05 % | 64 | 6.03 % | 80 | 6.01 % | 107 | 5.97 % | 90 | 5.71 % |
| **501** | 6.21 % | 535 | 6.20 % | 528 | 6.13 % | 71 | 6.05 % | 518 | 6.03 % | 68 | 5.99 % | 523 | 5.92 % | 93 | 5.71 % |
| **488** | 6.21 % | 534 | 6.19 % | 517 | 6.12 % | 72 | 6.05 % | 65 | 6.03 % | 81 | 5.99 % | 511 | 5.92 % | 91 | 5.71 % |
| **487** | 6.21 % | 533 | 6.18 % | 516 | 6.12 % | 73 | 6.04 % | 526 | 6.03 % | 84 | 5.99 % | 530 | 5.86 % | 92 | 5.71 % |

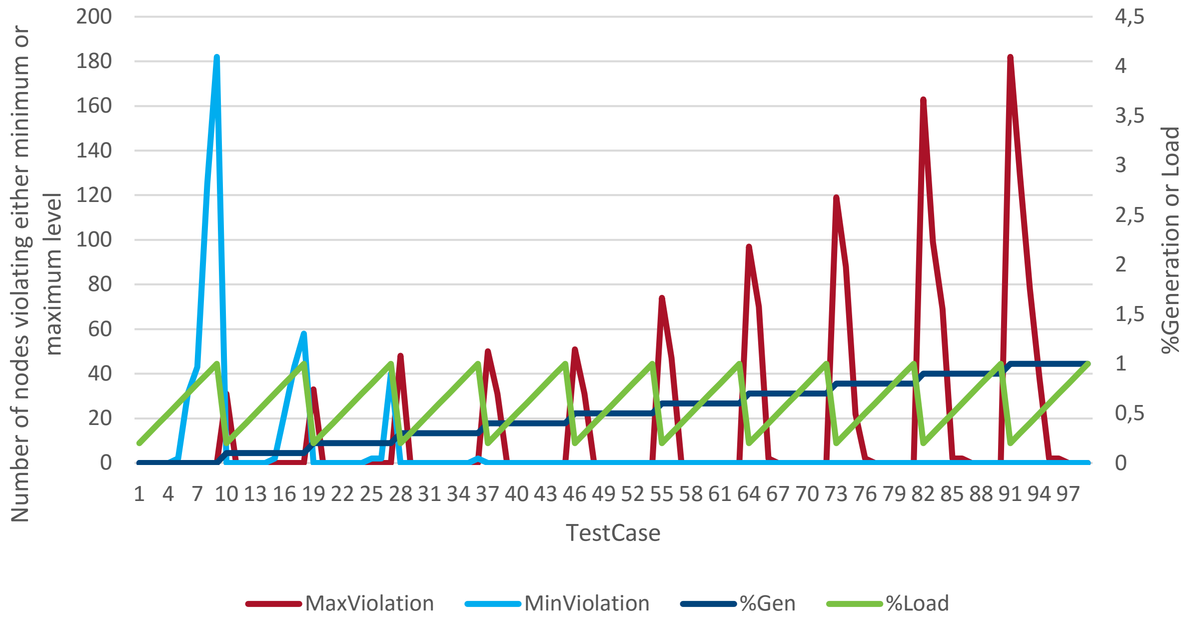



**Figure 11 Number of nodes violating their respective maximum or minimum level under various combinations of load and generation: Before CMAO-OLTC is applied.**

***Observations:***

- With the existing conditions (no smart OLTC utilization), 1562 upper voltage violations and 554 lower voltage violations at nodes in the network are counted.
- The highest voltage experienced is 22.77 Volt and it correlates with 100% generation and 20% loading and it is associated with node 514 which is connected before the Blådelselva generator node (515).
- In none of the above combinations of generations and loads exist nodes violating their respective maximum voltage and minimum voltage at the same time.

***Demonstrative cases selected from the different load and generation combinations in Fig. 11 are investigated.***

***Case#1: 100% generation and 20% loading condition***
Before the utilization of OLTC the number of nodes violating their respective maximum voltage were 181. After stepping down the OLTC at the HV/MV substation by two step (i.e. -3%), the number of nodes violating their upper limit are reduced to zero. As described in the previous sections the upper and lower voltage limits of each of the nodes are set so that the voltage variations of each of the nodes in the network are within the 5% limit.

***Case#2: 100% load and 0% generation***
In this case, about 79 nodes violated their respective minimum voltage violation. The lowest voltage is about 20.776 kV and was experienced at Node 62 which is also the longest node.
With stepping up of the OLTC at HV/MV substation by two step (+3%) all nodes violating their minimum voltage limits are lifted up to their normal voltage zone without violating the highest voltage limits of the other nodes.

***Case#3: 20% load and 10% generation***
This is a high voltage condition associated with very low load and very low generation. The phenomena looks-like the Ferranti effect. Hence, these specific conditions shall be mitigated with the mechanisms in place for the Ferranti effect overvoltage minimization.

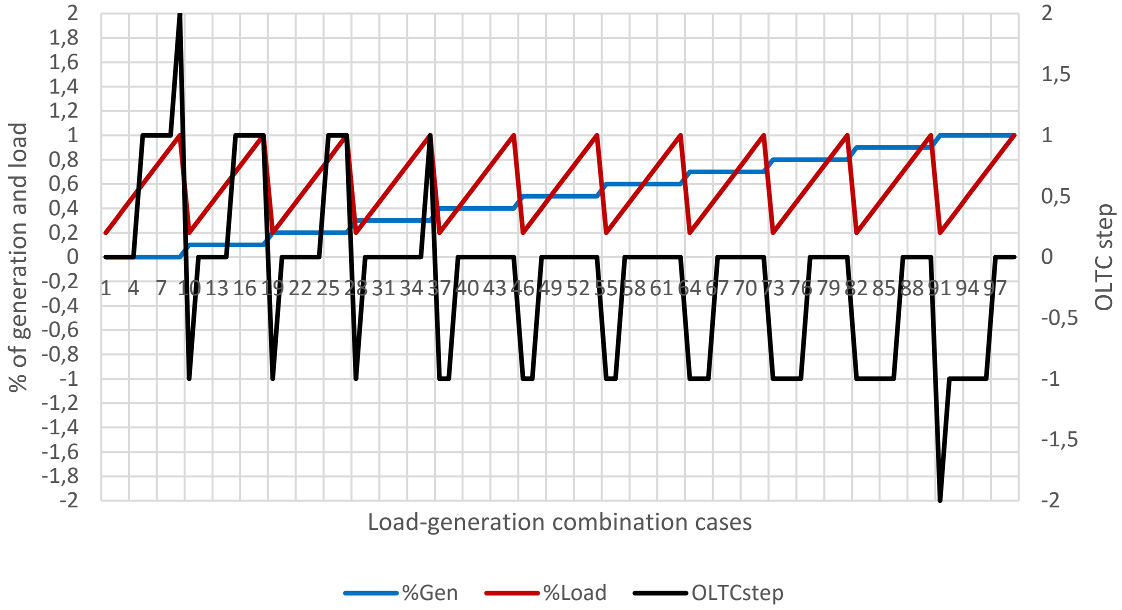



**Figure 12 After CMAO-OLTC is applied, all over voltage and under voltage violations are eliminated.**

The over voltages experienced at nodes 494 and 514 are the most persistent in most of the generation-load combinations. Hence, in addition to the OLTC at HV/MV substation, local solutions can be helpful to keep the voltage within limits for the two nodes adjacent to the Blådalselva generator. See the placement of the nodes in Fig. 13. Nevertheless, by utilizing OLTC assisted by remote voltage measurements the SSV at the node 514 can be reduced to 3.15% from 6.79%.


**Figure 13  The order of the nodes near the generator Blådalselva**

## 5.2 Critical measurement nodes

The conventional operation of OLTCs use the secondary side voltage measurement as a reference [6]. However, this operation could inhibit the potential benefit OLTCs can offer in hosting additional DGs. As discussed in the previous section, an alternative approach could be the use certain measurements from certain critical nodes in the LV side of the distribution network. Unless these measurements are minimized to the very critical ones, the increasing measurements in the LV network could have drawback by inducing excessive operation of OLTCs. The critical locations are usually where large voltage swings or a large unbalance is expected such as end of a feeder, near large loads or DG units.  Accordingly, for the Frøyset network, the critical nodes where measurement is useful for secure and reliable operation of OLTC are identified as shown in Table 9. The nodes in Table 9 are nodes where the maximum or the minimum voltage is experienced resulting in an increased voltage band and consequently minimizing the range at which OLTC can be utilized (see Fig. 9). These critical nodes in the Frøyset network are identified after running simulations of different combinations of load and generation to identify the worst case scenarios as shown Figs 11 and 12.

These critical nodes are among the nodes presented in Table 8 and they are also observed in the case studies in the previous section. They are characterized by high SSV and situated in critical entanglement with other nodes. These nodes in general are those which are connected near to generators and those connected at the end of very long or heavily loaded feeder. As shown in Table 8 most nodes on the same long feeder or same generator connecting feeder will have close SSV (%) values. Nevertheless, to narrow down the number of the critical nodes, nodes connected at the end of heavily loaded or end of long feeder and nodes connected adjacent to the generator node are selected as critical nodes. And hence, for the Frøyset network the critical nodes are listed in Table 9. There are also a third group of nodes which are at the end of a feeder and in the neighbourhood of the generator.

**Table 9  List of critical nodes**

| Nodes | Common feature | Critical measurement reduction mechanism |
|---|---|---|
| **514** | Adjacent to generator node | Nodes adjacent to big generators in the network shall be measured |
| **512, 489, 488, 493, 517, 518, 522,523,530,537** | In the neighbourhood of generator nodes and are at the end of feeder | A node in the neighbourhood of big generator and connected to at the end of feeder supplying heavy load shall be selected. |
| **62, 76, 70, 310, 64, 66, 90, 93** | They are at the end of heavily loaded or very long feeder. | The node at the end of a long feeder supplying heavy load shall be selected. |

## 5.3 Simulation of selected events

Certain occurrences of load and generation combination on different feeders might result in reduced capability of OLTC. Our simulations in the previous sections increases or decreases load and generation by identical factor for all nodes in the network. However, practically it is possible to have a scenario, for example, where there is low load on the feeder connecting high generation DG and another feeder with heavy load while both feeders are supplied from similar primary substation. Two such feeders in the Frøyset network are the Åmdalsvik and the Rambjør feeders where Åmdalsvik supply the longest feeder and Rambjør feeder connects two generators.

**Table 10 Simulation of events on Åmdalsvik and Rambjør feeders (All the other loads and generators connected to the other two feeders are kept to have maximum load and maximum generation)**

| Event Num. | Events | |
|---|---|---|
| | **Feeder Åmdalsvik** | **Feeder Rambjør** |
| 1 | New generators are not connected (Existing generators with total output) | |
| 2 | All new generators are connected (with total output) | |
| 3 | 100% load and 0% generation | 20% load and 100% generation |
| 4 | 20% load and 100% generation | 100% load and 0% generation |
| 5 | 100% load and 0% generation | 100% load and 100% generation |
| 6 | 100% load and 100% generation | 100% load and 0% generation |

**Table 11 Simulation results for selected events**

| | *t(s)* | *Event: 1* | *Event: 2* | *Event: 3* | *Event: 4* | *Event: 5* | *Event: 6* |
|---|---|---|---|---|---|---|---|
| ***Before*** | ***Vmax*** | *22.09 (Node#405)* | *22.35 (Node#405)* | *22.77 (Node#514)* | *22.35 (Node#405)* | *22.35 (Node#403)* | *22.3562 (Node#403)* |
| | ***Vmin*** | *21.23 (Node#62)* | *21.26 (Node#62)* | *20.77 (Node#62)* | *21.26 (Node#512)* | *20.77 (Node#62)* | *21.2609 (Node#510)* |
| | ***MaxViolationNumber*** | *0* | *0* | *80* | *102* | *0* | *0* |
| | ***MinViolationNumber*** | *0* | *0* | *102* | *80* | *102* | *80* |
| | ***OLTC action*** | *No* | *No* | *NA* | *NA* | *NA* | *Up +1.5%* |
| ***After*** | ***Vmax*** | *22.09 (Node#405)* | *22.35 (Node#405)* | *22.77* | *22.35* | *22.3562* | *23.02 (Node#405)* |
| | ***Vmin*** | *21.23 (Node#62)* | *21.26 (Node#62)* | *20.77* | *21.26* | *20.77 (Node#62)* | *21.7439 (Node#62)* |
| | ***MaxViolationNumber*** | *0* | *0* | *80* | *102* | *0* | *15* |
| | ***MinViolationNumber*** | *0* | *0* | *102* | *80* | *102* | *0* |

OLTC at primary substation cannot be used in situations where violations of maximum voltage limits and minimum voltage limits occur at the same time in the network. If load and generation scenarios leading to these events are believed to be imminent then one has to install local voltage regulating solutions at the selected critical nodes.

# 6 Summary

In this work:

- The possible voltage quality problems associated with planned DG connections are demonstrated using a real MV distribution network.
- A method to set a rule for operation of OLTC is devised using the stationary voltage variation limits of the individual nodes in the network.
- The benefits of critical measurement assisted operation of OLTC at the HV/MV substation is demonstrated in the test network.
- The selection procedure for critical nodes is discussed and demonstrated using the test network.

Critical measurement assisted operation of OLTC (CMAO-OLTC) has significant potential in enabling the integration of new DGs by alleviating the possible power quality problems. If the method is tested for all possible load-generation combinations in the network by simulation, the implementation phase only requires monitoring the critical nodes and the nodes susceptible to under and over voltage problems to decide the control of the HV/MV OLTC.

Before deploying CMAO-OLTCs and relying on them to connect new DGs, a distribution system operator has to study the critical nodes in the specific network in consideration. Besides, although the method presented in this proposal is generally replicable one has to customize the OLTC operation rules considering the load- generation dynamics in the considered area. Also, the deployment of the OLTC with distributed measurement can be useful if local voltage regulation solutions are developed for some critical nodes which persistently inhibiting the operation of OLTCs. In addition, building new HV/MV substations will inevitability become necessity as the load density increases, as the local generation integration intensifies and as the alternative solutions become costly. In the Frøyset network that we utilized in this study, for example, a new HV/MV substation is planned to be built feeding the branch connecting the generator at Kløvtveit. This kind of solutions will lower the variability of the voltage at the generating nodes.

## 7 References

[1] E. Tønne, K. Sand, J. A. Foosnæs and R. Paulsen, “Integration of Distributed Generation into MV Distribution Grid in Norway-The Namsskogan case,” in *CIRED Workshop*, Lisbon, 29-30 May 2012.

[2] Rasjonell Elektrisk Nettvirksomhet (REN), “Kraftproduksjon - Råd om Nettanalyse (NR 3006 – VER 1.2 / 2011),” REN, 2011.

[3] Norwegian Water Resources and Energy Directorate, “Regulations relating to the quality of supply in the Norwegian power system,” Ministry of Petroleum and Energy, 2004.

[4] F. Bignucolo, R. Caldon and P. V., “Radial MV networks voltage regulation with distribution management system coordinated controller,” *Electric Power Systems Research, 78(4)*, pp. 634-645, 2008.

[5] P. Esslinger and R. Witzmann, “Regulated distribution transformers in low-voltage networks with a high degree of distributed generation.,” in *In Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on*, 2012.

[6] L. Gevaert, T. Vandoorn, C. Deckmyn, J. Van de Vyver and L. Vandevelde, “ OLTC selection and switching reduction in multiple-feeder LV distribution networks.,” in *In Renewable Energy Research and Applications (ICRERA), 2015 International Conference on* , 2015.

[7] EN Standard 50160, “Voltage characteristics of public distribution systems,” 2010.

## Appendix

*Table A1. Procedures to identify path to end nodes*

```
% List of unique buses (UB)
% List of connected or branch nodes (BB)
% List of branch nodes in one vector and ascending order B =
% reshape(BB,2*length(BB),1);
%%Number of buses
NN = 289;

%%Adjuscent matrix
nMat = zeros(NN,NN);
for i =1:NN
    DT = BB(find(BB(:,1)==UB(i)),2);
    LG = length(find(BB(:,1)==UB(i)));
    if LG ~=0
        for t = 1:LG
            nMat(i, find(UB==DT(t))) = 1;
        end
    end
    DTb = BB(find(BB(:,2)==UB(i)),2);
    LGb = length(find(BB(:,2)==UB(i)));
    if LGb ~=0
        for t = 1:LGb
            nMat( find(UB==DTb(t)),i) = 1;
        end
    end

end
for i = 1:NN
    for j= 1:NN
        if nMat(i,j) ==1 || nMat(j,i)==1
        nMat(i,j)= 1;
        nMat(j,i)= 1;
    end
    end
    nMat(i,i)= 0;
end

%%Find end nodes
 ct = 1;
 ENDS = zeros(NN,1);
 for i =1:NN
     if length(find(B==UB(i)))==1
         ENDS(ct)= UB(i);
         ct = ct+1;
     end
 end
 ENDS(ENDS==0)=[];

 %%Find PATH
 PATH = zeros(300,300);
for i = 1:length(ENDS)
```

```
pat = pathbetweennodes(nMat, find(UB==280), find(UB==ENDS(i)));
pt = pat{1};
np = zeros(1,length(pt));
for k=1:length(pt)
    np(k)=UB(pt(k));
end
PATH(i,1:length(np))=np;
end
```

***Table A2. Procedure to calculate the distance from the primary substation for the nodes on each path in the network***

```
%NP: number of paths
%NB: The largest number of nodes on a single path
%ND: Number of unique buses
%LengCord: Length coordinate of each node on each path according  to its
%distance from the primary substation
NP = 93;
NB = 47;
ND = 289;
LengCord= zeros(NP,NB);
  yc = 1;
for u = 1:NP

   p = PATH_sam(u,:);
   p(find(p==0))=[];
lengp = zeros(length(p),1);
for i = 2:length(p)
    for k = 1:ND
        if  (NodeLENG_sam(k,1)==p(i-1) && NodeLENG_sam(k,2)==p(i))||
(NodeLENG_sam(k,1)==p(i) && NodeLENG_sam(k,2)==p(i-1))
             lengp(i)= lengp(i-1)+NodeLENG_sam(k,3);
        end
    end
end
LengCord(u, 1:length(p)) = lengp;
end
```

***Table A3. Procedure for conversion of one base system to another for the pu values of resistance, reactance and succeptance***

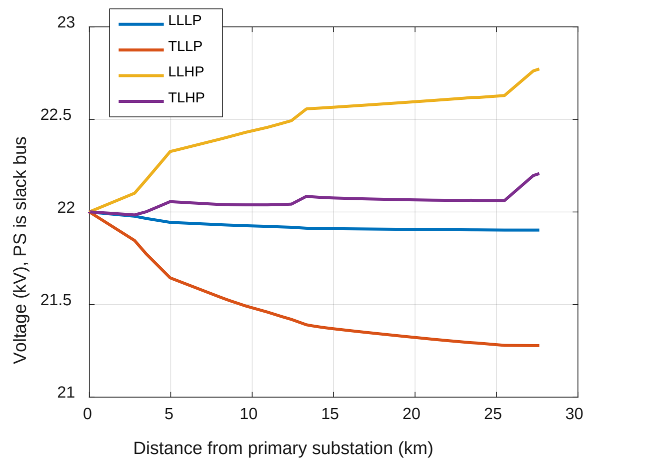
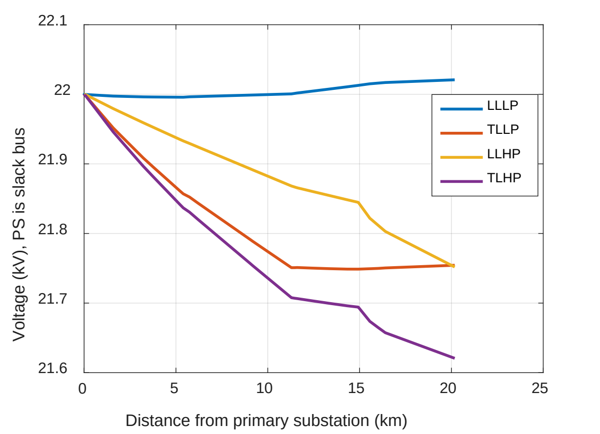
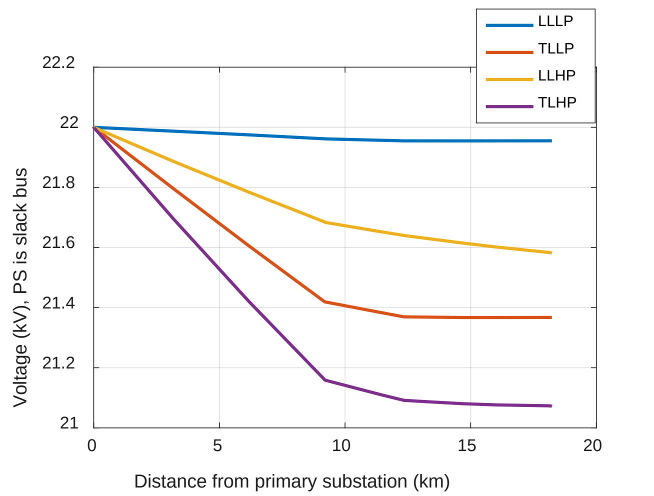
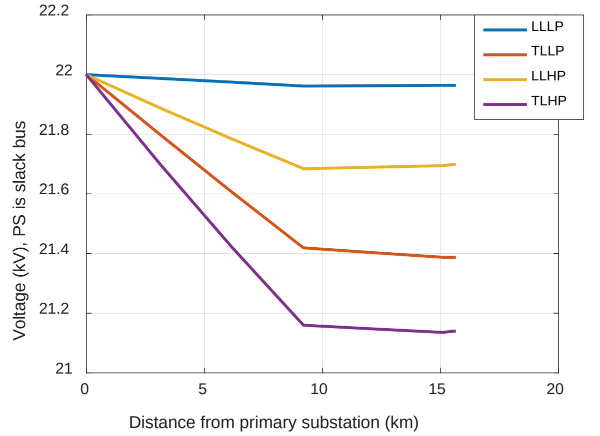
```
%Conversion from voltage base system 1 to 2
for i = 1:293
    SAM_ntk.branch(i,3) =
SAM_ntk.branch(i,3)*Vbase_sam_1(find(SAM_ntk.bus(:,1)==SAM_ntk.branch(i,2)))^2
/Vbase_sam_2(find(SAM_ntk.bus(:,1)==SAM_ntk.branch(i,2)))^2;
    SAM_ntk.branch(i,4) =
SAM_ntk.branch(i,4)*Vbase_sam_1(find(SAM_ntk.bus(:,1)==SAM_ntk.branch(i,2)))^2
/Vbase_sam_2(find(SAM_ntk.bus(:,1)==SAM_ntk.branch(i,2)))^2;
    SAM_ntk.branch(i,5) =
SAM_ntk.branch(i,5)*Vbase_sam_2(find(SAM_ntk.bus(:,1)==SAM_ntk.branch(i,2)))^2
/Vbase_sam_1(find(SAM_ntk.bus(:,1)==SAM_ntk.branch(i,2)))^2;
end
```

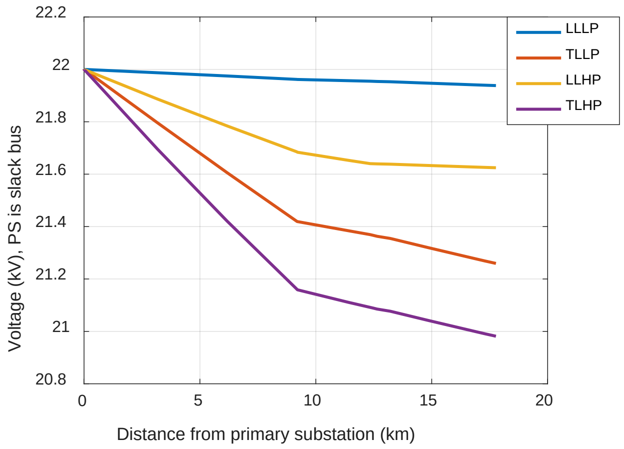
*Table A4. Procedure to run and plot REN test.*

```
clear
figure

load('ntkDAT.mat')

z=1;

GENnode = NDnPATH(z,1);
GENnodePath = NDnPATH(z,2);

for u = 1:4 %The four REN test formats LLLP, TLLP, LLHP, TLHP

load('ntkDAT.mat')

NDpath = PATH_sam(GENnodePath,:)';  %Identify the pathe number on which the
generator node is connected to
NDpath(NDpath==0)=[]; %Cleaning the node path data
NDlength = Path_Length_Sam(GENnodePath,1:length(NDpath))'; %COmputing the node
length starting from the primary substation to the generator node

LongPath = PATH_sam(17,:)';
LongPath(LongPath==0)=[];
LongLength = Path_Length_Sam(17,1:length(LongPath))';

SAM_ntk.bus(:,3:4) = SAM_ntk.bus(:,3:4).*ProLod(u,2);%Active (3) and reactive
(4) load (setting the values for P and Q of load based on the selected REN
test)

 for m = 1:15
     if m<9
   SAM_ntk.gen(SAM_ntk.gen(:,1)==NDnPATH(m,1),2) = GenLim(m)*ProLod(u,1);
     else
   SAM_ntk.gen(SAM_ntk.gen(:,1)==NDnPATH(m,1),2) = GenLim(m)*ProLod(u,1);
     end
 end

 mpopt = mpoption('pf.enforce_q_lims', 1, 'out.all', 0);  %Matpower power flow
with enforced Q limits
 LFans = runpf(SAM_ntk,mpopt); %i.e when the Q limit is reached it captures
the Qlimit and changes the node from PV-bus to PQ-bus

 Volt_SAM_Prof(:,2) = LFans.bus(:,8);

NDs(:,1) = NDpath;
NDs(:,2) = NDlength;
for i = 1: length(NDpath)
NDs(i,3) =
Volt_SAM_Prof(find(Volt_SAM_Prof(:,1)==NDs(i,1)),2)*Vbase_sam(find(Volt_SAM_Pr
of(:,1)==NDs(i,1))); %Converting the voltage value from pu to actual value
end

STORE{z}(u,:) = NDs(1:end-1,3)';
```

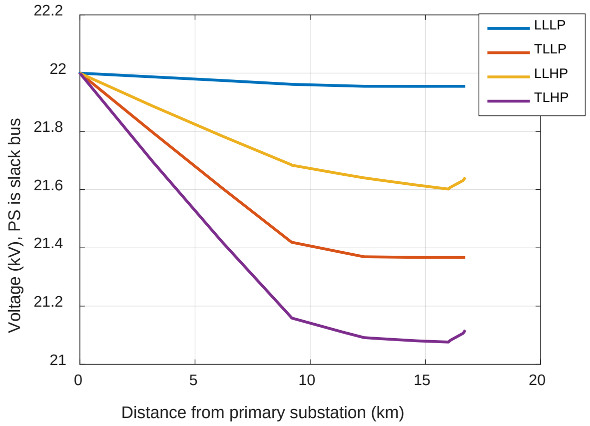
```
LEN{z} = NDs(1:end-1,2);

plot(NDs(1:end-1,2),NDs(1:end-1,3),'LineWidth',2);
hold on
end

xlabel('Distance from primary substation (km)') % x-axis label
ylabel('Voltage (kV), PS is slack bus') % y-axis label
legend('LLLP','TLLP','LLHP','TLHP')
set(gca,'fontsize',14)
grid on
```

***Table A5. Voltage profile for generators after REN test with new generators are set with pf 0.95.***

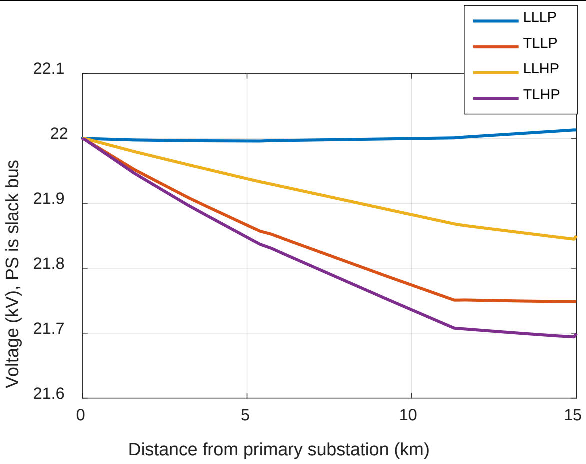
| | |
|---|---|
|  **B1:** *Voltage profile for generator at Node 515, in the future network (BLÅDALSELVA (Node 515))* |  **B2:** *Voltage profile for generator at Node 406, in the future network (Node 406 (N8078))* |
|  **B3:** *Voltage profile for generator at Node 303, in the future network (KLØVTVEIT KR)* |  **B4:** *Voltage profile for generator at Node 616, in the future network (250 kW Midtun mikrokraftverk)* |



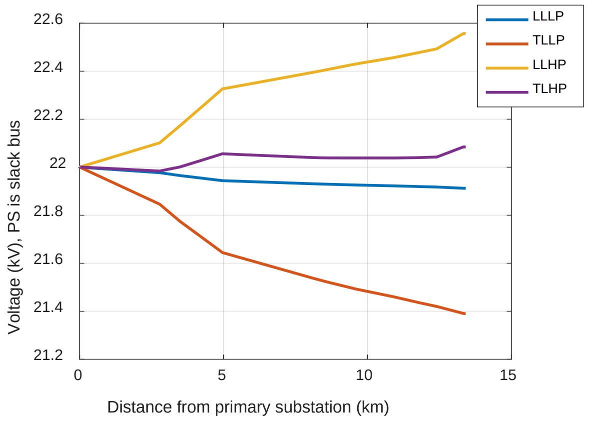

***B5:*** *Voltage profile for generator at Node 617, in the future network (99 kW Gjemlielva mikrokraftverk)*




***B6:*** *Voltage profile for generator at Node 618, in the future network (2950 kW Fossdalselva)*




***B7:*** *Voltage profile for generator at Node 619, in the future network (3500kW Nørlandselva)*




***B8:*** *Voltage profile for generator at Node 620, in the future network (2300 kW Sandneselva)*

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