Impact of smart grid technologies on the distribution network in Uganda: A case study

***Hassan Abouelgheit*[1*], *Luca Pizzimbone*[2], *Ashwini Danabal*[3]**

[1]*TRACTEBEL Engineering GmbH, Friedberger Strasse 173, 61118 Bad Vilbel, Germany*
[2] *ENGIE Impact Germany GmbH, Friedberger Strasse 173, 61118 Bad Vilbel, Germany*
[3]*Technical University of Munich, Boltzmannstrasse 15, 85748 Garching bei München*
**Hassan.Abouelgheit@tractebel.engie.com*

Keywords: SMART GRID, DISTRIBUTION NETWORKS, INTEGRATION OF RENEWABLE ENERGY, HOSTING CAPACITY, POWER QUALITY

Abstract

In light of rapidly growing energy demand, distribution network operators face significant challenges in maintaining a stable and secure grid. The focus of this study is investigating the integration of photovoltaic and battery energy storage systems and the most cost-effective options for grid reinforcement; evaluate what role, if any, smart grid components can take place of standard network reinforcement measures to bring the grid back into compliance. Low voltage distribution networks from remote villages in Uganda were selected as a case study. A techno-economic analysis showed that traditional grid reinforcement measures are the most cost effective. However, when new operational measures are introduced, only minor changes in the network structure are required to operate within the allowed limits. In this paper planning, operational measurements as well as integration of innovative technologies will be discussed and analyzed. Results show that using new technologies can increase the hosting capacity of renewable energy resources and hence reduce investing and operation costs.

Introduction

A smarter grid is a major factor in enabling the energy transition to a low-carbon energy system. Current research is focusing on each aspect of smart grids including planning, operation as well as smart grid components. While the main drivers for the implementation of smart grids in developed economies are based on governmental policies, environmental goals, integration of renewable energy resources and electric vehicles, the main drivers in emerging economies are reliability concerns, energy efficiency, increasing electricity demand and reduction of electricity theft [1]. In Uganda, about 90% of the total electricity generation is from hydropower plants. Although the solar radiation is high throughout the year, only 2% of total electricity generation is from photovoltaic (PV) sources [2]. According to the World Bank [3], in 2020 only 32% of the rural population in Uganda had access to electricity. The Rural Electrification Agency in Uganda aims to reach a 100% electrification rate by 2040 [4]. Increasing the rate of electrification technically means an increase in the electricity demand. In rural electrification, the energy through distribution feeders is travelling for relatively long distances which increases the voltage drop, injected reactive power and line losses [5]. To avoid transmitting electricity over long distances, distributed renewable energy resources could be installed near the consumption location to reduce losses and operation costs.

For this case study, a reference grid in rural area which consists of two villages was selected. Given the case of expected increase in demand smart grid technologies are stimulated to find the best techno-economic solution to overcome the effects rising electricity demand. It is assumed that demand increases annually in line with national system planning in Uganda and the grid reinforcement is carried out in 5-year cycles. Three scenarios were investigated. The base scenario year is 2020. The load demand forecast for the years 2025 and 2030 considered the increasing rate of electrification, increasing population, growing GDP and energy intensity.

Grid expansion measures

Electrical networks in Uganda are suffering from extremely high losses of 35% due to poorly maintained lines and overloading of transformers due to the increasing demand of electricity [4]. In such cases Distribution Network Operators (DNO) apply classical grid reinforcement measures which are based on worst-case scenario. While planning these measures the thermal load limits of the electrical equipment, the allowed voltage range and quality must be considered.

A. *Classical grid reinforcement:*

- Replacement of equipment with higher power ratings to avoid overloading which can cause thermal stress, mechanical damage, or reduction of lifetime.
- Replacement of cables with higher cross section areas to reduce the losses. Cables with higher cross section areas have less resistance and hence the voltage drop is reduced.
- Placement of capacitor banks to improve voltage quality.

B. *Grid reinforcement using flexibility:*

Flexibility solutions can be applied to delay classical grid reinforcement measures as the investment costs can be potentially high with a low utilization factor. Flexibility options used in this case study are as follows:

- Integration of distributed energy resources (mainly PV) where the reactive power is controlled using the PV-inverter.

Methodology

Figure 1 shows the methodology used in this work. The simulations are based on real network data from remote villages in Uganda. In each scenario, i.e. 2020, 2025 and 2030, a quasi-dynamic simulation is carried out using the corresponding forecasted data. The simulation results indicate the conditions of the reference network. For network violations, all affected equipment (lines, transformers, etc.) are allocated and the planning measures in section 1.1. are applied including capacity calculations of the new equipment. A new simulation is run, and the network conditions are investigated. For each scenario a techno-economic analysis is done, and the most cost-effective solutions is suggested as the optimal solution.

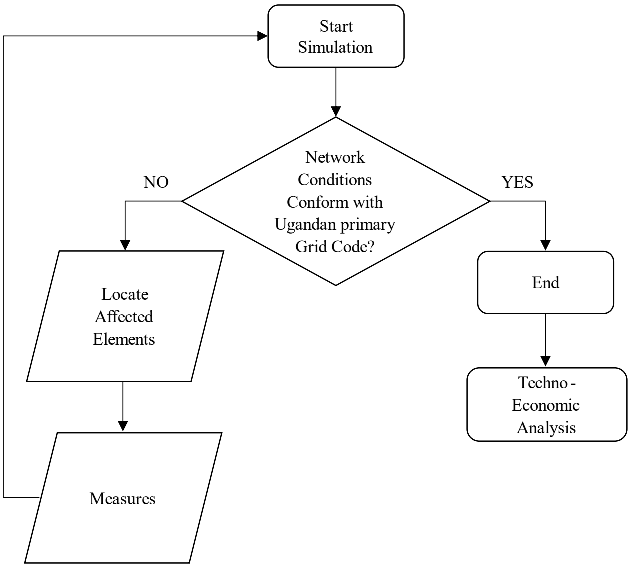

Figure 1: Methodology of the research

Table 1 shows the design and operation criteria of the network. According to the Uganda Electricity Primary Grid Code [6], the allowed voltage deviation in low voltage networks is ±6%. In normal operation conditions the transformers and power lines can be loaded up to 50% and 80% respectively.

Table 1: Design criteria of the network model

Criteria	**Value**
Voltage	±6%
Frequency	±0.5%
Loading of transformers[1]	70%
Loading of power lines	80%

SECTION I

Grid Model

The grid model consists of two low voltage (LV) distribution feeders connected to the medium voltage (MV) grid through two transformers rating 33/ 0.4 kV and 50 kVA each. The slack node is located on the HV side of the distribution transformer. Each distribution feeder supplies one remote village (village 1 and 2), and the maximum loading is 30 kVA. There are two lines (village 1: A & B, village 2: C & D) supplying the loads in each village due to the nature of villages in Africa with scattered houses over large areas, see Figure 2.

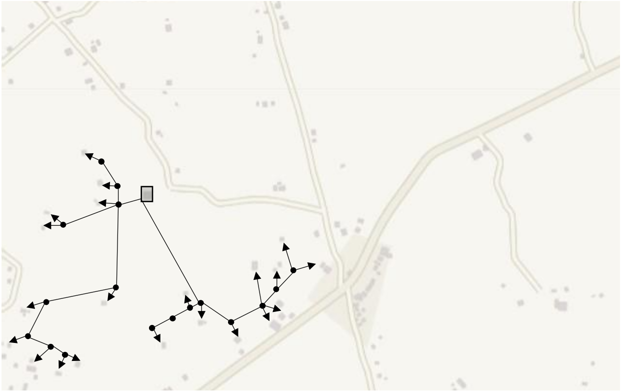

Figure 2: Distribution network in village 1

The total number of loads connected to villages 1 and 2 are 24 and 20 households, respectively. All the loads in the two villages are residentials, i.e., no commercial or industrial loads. To simplify the network model, residential loads next to each other are aggregated and represented as one single load. Line A has a total length of 0.57 km (35 mm^2) and line B has a total length of 1 km (35 mm^2).

A. Base scenario 2020:

The base scenario represents the original state of the grid, i.e., the grid has not undertaken any reinforcement. The voltage profiles of lines A&B in village 1 are shown in Figure 3. Although the results were taken during the peak time (@ 19:00 on 05.01.2020), the voltage profiles show no violations to the grid code.

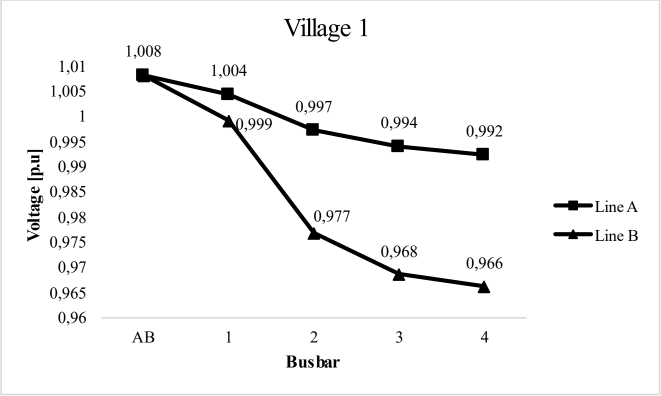

Figure 3: Voltage profiles of village 1, 2020

---

[1] Design requirement

The distribution transformer in village 1 is loaded with 48% and the lines are loaded between 2% to 15%.

Similarly in village 2, the voltage profiles in Figure 4 shows no violations of the grid code.

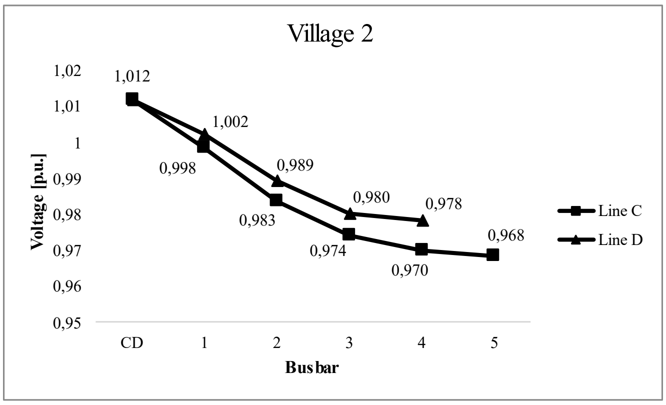

Figure 4: Voltage profiles of village 2, 2020

The distribution transformer in village 2 is loaded with 40% of its rated capacity and the lines with 2% to 10%.

The results show that no violations of the primary grid code and hence no countermeasures are needed in 2020.

B. Scenario 2025:

In 2025 the load demand increases by a factor 1.37 compared to the load demand of the base scenario 2020. The key drivers to increasing electricity demand are high population growth, rapidly increasing electrification rates and increasing GDP leading to rapidly increasing energy intensity. Figure 5 shows the voltage profiles in village 1. No voltage violations occur during 2025. The maximum voltage drop during the year is on 19.01.2025 with -6% on the power line B in village 1.

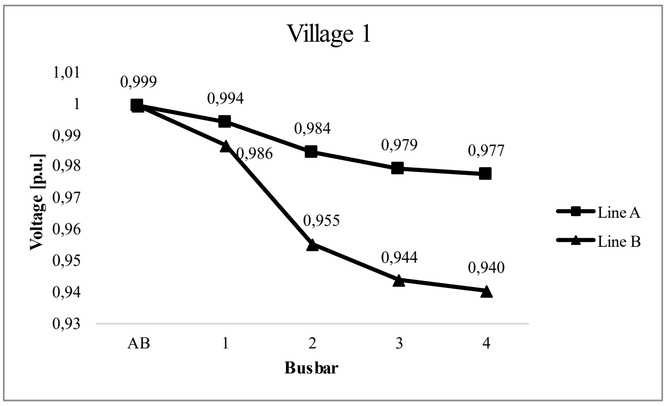

Figure 5: Voltage profiles for village 1, 2025

The transformer loading is at 67.8%. However, the maximum allowed operating capacity is 70%. The power lines are using less than 20% of the rated capacity.

Similarly, in village 2 the voltage profiles show no violations, see Figure 6.

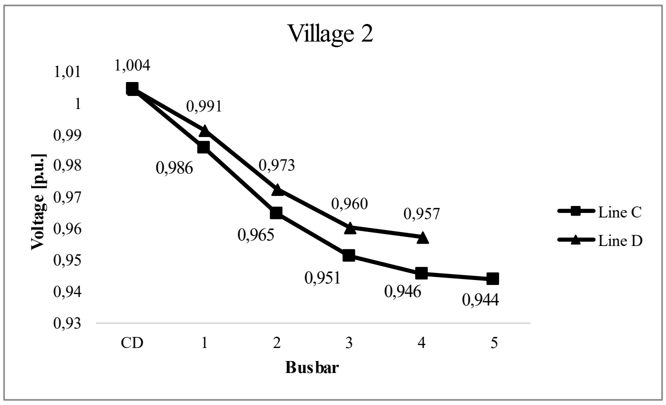

Figure 6: Voltage profiles of village 2

The transformer loading is 56.8% and for the power lines less than 17%.

The 2025 scenario shows that the grid operates near the maximum allowed limits for the transformers as well as for voltage quality. Therefore, countermeasures must be taken in the years between 2025 and 2030.

C. Scenario 2030:

The forecasted load demand continues to increase by a factor 2 compared to the base scenario 2020. This rapid increase in demand is due to the electrification plan of the Ugandan government to connect 100% of the rural areas to the national grid.

As shown in the voltage curves in Figure 7, the busbars are experiencing violations during the peak times in addition to violations of grid code operating during different periods of the day.

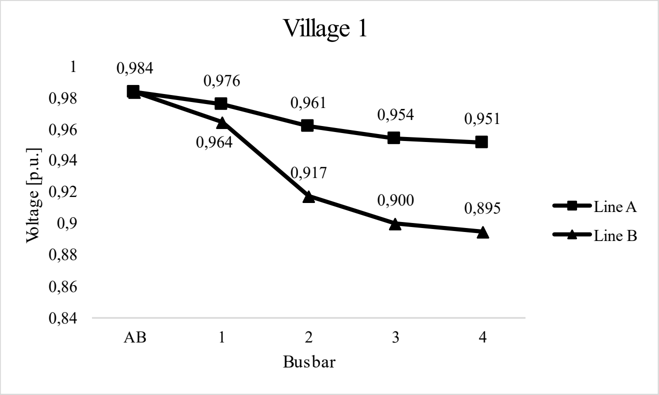

Figure 7: Voltage profiles for village 1, 2030

Additionally, the transformer experience 90.5% loading several times per day.

Voltage curves from village 2 show multiple violations several times a day.

To avoid voltage violations and overloading of power transformers, grid reinforcement measures are taken. Following the methodology in Figure 1 different grid reinforcement measures were simulated and analysed in Table

2. In both options, 2 and 3, the network model shows no violations of the primary grid code of Uganda.

Table 2: Simulation results of classical grid reinforcement, 2030

Option	Measures	Simulation results	
		Voltage violations	Transformer overloading
1	Replacement of the existing transformer with a higher capacity transformer of 100 kVA.	Yes	No
2	Replacement of existing transformer with a higher capacity transformer 100 kVA, upgrading existing cables with cables of higher cross section area from 35 mm^2 to 50 mm^2.	No	No
3	Replacement of existing transformer with a higher capacity transformer 100 kVA, using capacitor banks on different locations in the grid.	No	No

The investment costs for options 2 and 3 were estimated with 18.167 k€ and 16.098 k€ respectively. Although, option 3 provides a more economical solution, voltage violations occurred when rooftop PV systems installed on the houses. As a result, option 2 is implemented in the reference network as it considered further grid expansions by integrating renewable energy resources without experiencing any violations.

SECTION II

Integration of renewable energy resources in LV grids

As seen in SECTION I the voltage profiles of a traditional power network are monotonously decreasing along the distribution feeder due to the voltage drop over distance. In LV distribution networks with renewable energy resources, this is no longer the case [7]. Voltages can rise above the defined maximum limits, in locations where renewable energy resources are installed, causing overvoltage and damages to household devices, see Figure 8. This problem often limits the expansion of renewable energy in distribution networks.

On the other hand, installing renewable energy resources in in distribution networks of rural areas plays a vital role in reducing power losses, voltage drops and injected reactive power to compensate the voltage drop.

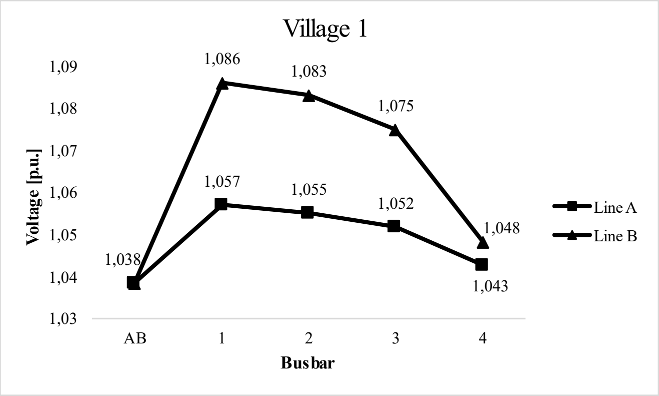

Figure 8: Overvoltage in village 1

The voltage profiles in Figure 8 show the non-monotonic profile of the voltage at the busbars of village 1, with an overvoltage condition, experienced when PV systems of total 22 kW$_p$ are installed on the rooftop of 50% of the households. The impact of distributed PV generation on bus voltage can be mitigated by applying a *global control strategy* which provides an optimal management of the PV system [8].

In recent years new innovative technologies were developed to control and optimize the operation of renewable energy resources in LV grids, e.g., smart transformers, distributed energy resources management systems (DERMS), D-STATCOM, etc.

This section provides results of using a combination of smart transformers and Phasor Measurement Unit (PMU) to optimize the voltage distribution among the nodes of the feeders and consequently increase the hosting capacity of renewable energies in LV grids. The analysis was conducted considering the following assumptions:

1. Transformer devices with voltage control capabilities are analysed and compared to conventional transformers equipped with off-load-tap-changers, typically used in LV distribution system. Due to the need of adjusting the voltage several times in a day, the use of power electronics (i.e., smart transformers) would represent a suitable technology.
2. Traditionally, transformers equipped with automatic tap changer control the voltage to a fix set point. In the proposed methods, the set point of the voltage controller is dynamically adjusted by an optimized algorithm based on PMU measurements. PMUs can be installed in each node or for more convenience on a subset of nodes, where max and min voltage amplitudes are expected.
3. The optimal voltage set point is calculated to 'centre' the minimum and maximum voltages along the 1.0 p.u. value, in a symmetrical way, so that the thresholds of maximum and minimum values are reached for a higher amount of renewable energies penetration.

To prove the effectiveness of the proposed method, three cases are compared:

a. **Base Case:** traditional transformer with Off-Load-Tap-Changer and PVs operating at unit power factor (zero reactive power).
b. **Base Case with PV voltage control:** traditional transformer with Off-Load-Tap-Changer, and PV controlling the voltage at local nodes (reactive power capability is considered equivalent to a power factor of 0.95 leading/lagging)
c. **Smart Transformer Case and constant Q PVs:** Smart transformer controlling dynamically the voltage at the transformer terminals through the optimal algorithm. PVs are operating at unit power factor.
d. **Smart Transformer Case with PV voltage control:** Smart transformer controlling dynamically the voltage at the transformer terminals through the optimal algorithm, and PVs controlling the voltage at local nodes.

In all the above cases, PVs are installed in half of the nodes of the LV feeders (randomly selected) and the injected power uniformly increased until either maximum equipment loading, or voltage constraints are reached. In this section (Section II), voltage constraints have been raised to ±10% for all simulated cases, which seems to be a reasonable range, considering the new use of the feeders. However, the principles of the proposed smart voltage control would apply also for the actual limits of ± 6%.

In Figure 9, the time series of the minimum and maximum voltage for the case with traditional feeder design, with conventional transformers and no voltage control from tap changer and VRE is presented. The maximum voltage constraints are reached at the time of maximum PV power injection and the hosting capacity resulted to be 85.70 kW.

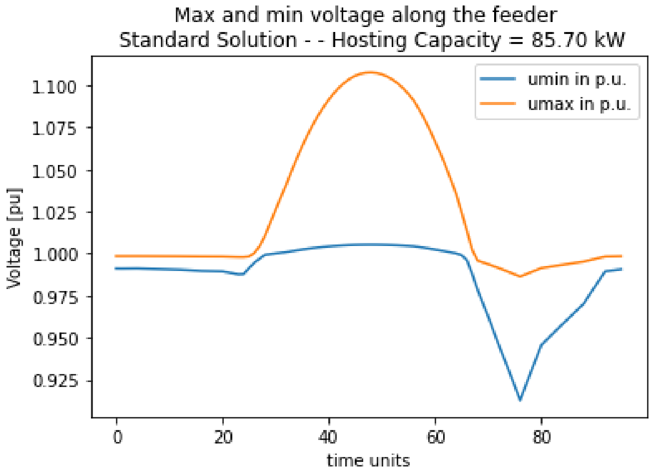

Figure 9: Maximum and minimum voltage at Village 2, Case a

When conventional transformers are replaced by smart transformers based on power electronics and the voltage is actively controlled on the base of the PMU measurements, the new voltage profile allow a higher penetration of renewables.

In Figure 10, the time series results for the maximum and minimum voltage are shown for the smart transformer solution (Case d). In this case, the hosting capacity is greatly increased to a value of 171.4 kW.

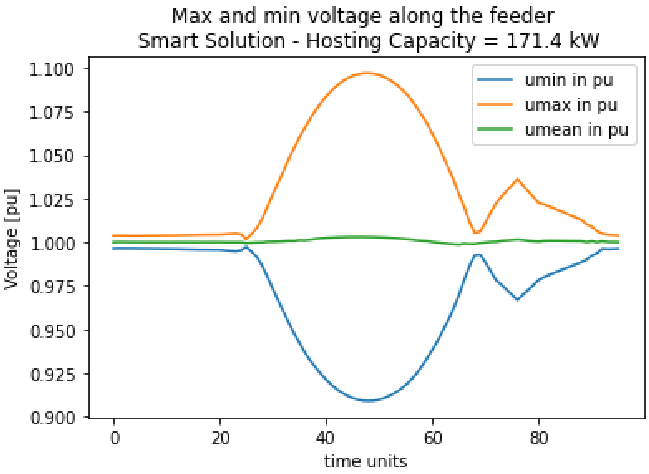

Figure 10: Maximum and minimum voltage at Village 2, Case d

The simulations have shown that the maximum hosting capacity of renewable energy resources with active voltage control at the LV terminals of the distribution transformers (smart transformers) is significantly greater than the cases without active voltage control (Off-Load-Tap-Changer traditional transformers).

The analysis also put in evidence that the voltage regulation provided by the smart transformers is more effective than the voltage regulation provided by the PVs. This can be inferred by the fact that the delta hosting capacity from Case a) and Case b) is smaller than the delta hosting capacity between Case a) and Case c) or Case b) and Case d). However, the combination of the two voltage controls (from smart transformers and PVs) provides the best results (Case d).

Figure 11 shows the summary of all the four simulated cases.

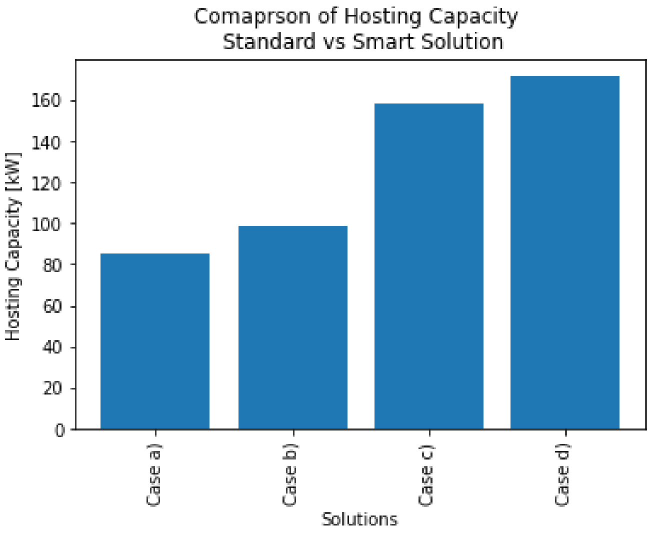

Figure 11: Summary of Hosting Capacity for the simulated cases

Table 3: Legend of figure 11

Case	Description
a	Base Case
b	Base Case with PV voltage control
c	Smart Transformer Case and constant Q PVs
d	Smart Transformer Case with PV voltage control

Conclusion

In this work the effect of rising electrification rate in LV networks in 2 villages in Uganda is studied and analyzed. Classical grid reinforcement measures are applied to cope with the rising load demand and increasing power losses as well as increasing voltage drop due to transmitting electricity from generation location to the end users. As a solution, distributed renewable energy resources (i.e. PV) are integrated in the villages where electricity is produced and consumed locally. As a result the power losses and voltage drop are reduced. New technologies such as smart transformers and PMUs are used to increase the renewable energy hosting capacity. Results shown that the hosting capacity can be doubled and the imported power from the grid can be kept at minimum.

Acknowledgements

This work was conducted within the project Smart Grid LAB Hessen financed by the ministry of economic affairs, energy, transport, and housing in the state of Hesse and the European regional development fund (ERDF).

References

[1] SAIC, “Smart Grid Around the World - Selected Country Overviews,” 2011.

[2] E. R. Authority, “era.go.ug,” 16 March 2022. [Online]. Available: https://www.era.go.ug/index.php/stats/transmission-stats/energy-purchases-sales-and-losses. [Accessed 2022 August 2022].

[3] T. W. Bank, “DataBank - World Developement Indicators,” The World Bank, 2020. [Online]. Available: https://databank.worldbank.org/reports.aspx?source=world-development-indicators. [Accessed 02 August 2022].

[4] K. Mokveld and S. v. Eije, “Final Report Uganda,”Ministry of Foreign Affairs, 2018.

[5] S. M. Elkhodary and A. Y. Abdelaziz, “Capacity Development of Rural Distribution Networks with Local Constructions in Developing Countries,” in *The 9th international middel-east power systems conference, MEPCON*, Shebin El-Kom, 2003.

[6] “Electricity (Primar Grid Code) Regulations,” 2003.

[7] G. Monfredini, M. Delfanti and M. Merlo, “Voltage Regulation Issues for Smart Grids,” in *CIGRE "Grid of the future", electricity markets and regulatory aspects - general issues: environement, standardization*, Bologna, 2011.

[8] J. Tlusty, “Management of the Voltage Quality in Distribution Network within Disperced Generation Sources,” in *18th international conference on electricity distribution CIRED*, Turin, 2005.