Chapter

Battery Energy Storage Systems and Rooftop Solar-Photovoltaics in Electric Power Distribution Networks

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Abstract

Energy storage technologies is transforming the way the world and utility companies utilize, control and dispatch electrical energy. In several countries, the consequential effect of meeting electrical demands continues to burden the electrical infrastructure leading to violation of statutory operating limits. Such violations constrain a power system's ability to supply suitable energy whilst meeting daily load and growth demands. While optimization techniques can be used to reduce violations, these are still limited do not provide effective short-term solutions when dealing with constrained networks in dense and radial distribution systems. Battery energy storage systems (BESS) and solar rooftop photovoltaics (RTPV) are a viable distributed energy resource to alleviate violations which are constraining medium voltage (MV) networks.

Keywords: battery energy storage systems (BESS), rooftop solar-photovoltaics (RTPV), power distribution, voltage limits, thermal limits, technical performance

1. Introduction

In designing and operating electric power networks or implementing major expansions to existing networks, a number of key issues regarding the technical performance of the network at both the transmission and distribution (T and D) levels must be ascertained. These include voltage regulation, voltage fluctuations, rapid voltage rise, electrical loses, distribution plant loading and utilization, fault level, generation stability, harmonics, phase balancing, system security, and supply availability [1]. The approach of Power Utilities to address any constraints or violations, experienced within medium voltage networks, would be based on extensive technical evaluation. While overvoltage is a concern if roof-top solar-photovoltaic (RTPV) penetration is not regulated [2], this study shows the benefit of RTPV and/or including battery energy storage systems (BESS), as this offers relief for constrained networks.

2. Network model selection and appraisal

Real-time power system analysis deals with two critical criteria, from the network appraisal, this being Voltage and Thermal constraints/violations. From the analysis, a network was identified which has both voltage and thermal violations. This study explores the technical influence that RTPV has on MV networks. From the appraisal analysis, a most fitting network type was identified which is found most common amongst the feeders that were analyzed. The predominate network classification is found to be a C2, TZ2 type network [3, 4]. In-line with the investigative violations (voltage and thermal) these networks have a tolerable minimum voltage of 95.5% during normal conditions, and 93.5% during abnormal conditions.

The thermal limit defined in **Table 1** indicates this to be alarming above 90% of its rated capacity.

The MV network selected for this study is Madadeni NB36. **Table 2** shows the appraisal results of Madadeni NB36; this network has been selected due to having both voltage and thermal violations. This study goes on to showcase how RTPV and/or BESS influences the violations identified on NB36.

As stated in **Table 2**, NB36 peaks during a winter's weekday at 18:30. Annual statistical metering data was analyzed and using statistical analysis methods, data has been fashioned into four, twenty-four hours, thirty-minute intervals; seasonal profiles, based on the four weather seasons. The load profile for a winter's weekday demonstrates the peak loading period and is used throughout this chapter to demonstrate the effective influence of RTPV and/or BESS.

Figure 1 shows a typically generated PV profile which have been defined to represent each season [7, 8]. The duration of sunlight hours differs between each season. To be consistent with the network analysis, the winter PV profile was selected to match the network breakers winters statistical load profile.

When considering RTPV, some configurations should be considered to decide on the most cost-effective or technically beneficial solution for both the Utility and Customer. This chapter considers the following configurations:

- BESS alone
- RTPV alone
- RTPV with BESS
- Varied levels of BESS

Power simulation has been conducted in Power Factory, the results have been extracted, analyzed and stated in the legends field within the applicable figures.

Network type	Feeder type	Network class	Network voltage (kV)	Conductor size/type	Maximum allowed MV across backbone	Maximum allowed MV line/cable loading
Urban	Cable	C1	11	185 mm^2	2%	50% of normal to allow for N-1
Urban	Cable	C1	22	95 mm^2	2%	50% of normal to allow for N-1
Rural	Overhead	C2	11	Hare	7.5%	90% of rate A[3]
Rural	Overhead	C2	22	Hare	7.5%	90% of rate A

Table 1.
Network characteristics for calculating customer number limits [5].

Parameter	Value	Units
Nominal Voltage	11	kV
Time of Feeder Peak	Winter-WD-18:30	Seasonal Time
Feeder Peak S	4.35	MVA
Feeder P at Peak S	4.23	MW
Feeder Q at Peak S	0.58	MVARs
Feeder PF at Peak S	0.97	pf
OC Setting	250	A
Load % of OC Setting	93	%
Feeder Minimum Voltage p.u.	92.7	%
Max Equipment Loading %	102	%
MV/LV (11-22 kV/400-230 V) Xfr Count	65	Count
Installed Capacity	5.29	MVA
Total Line Length	23.77	km
Backbone Length	13.79	km
Customer Base	3378	Count

Table 2.
Madadeni NB36 appraisal data [6].

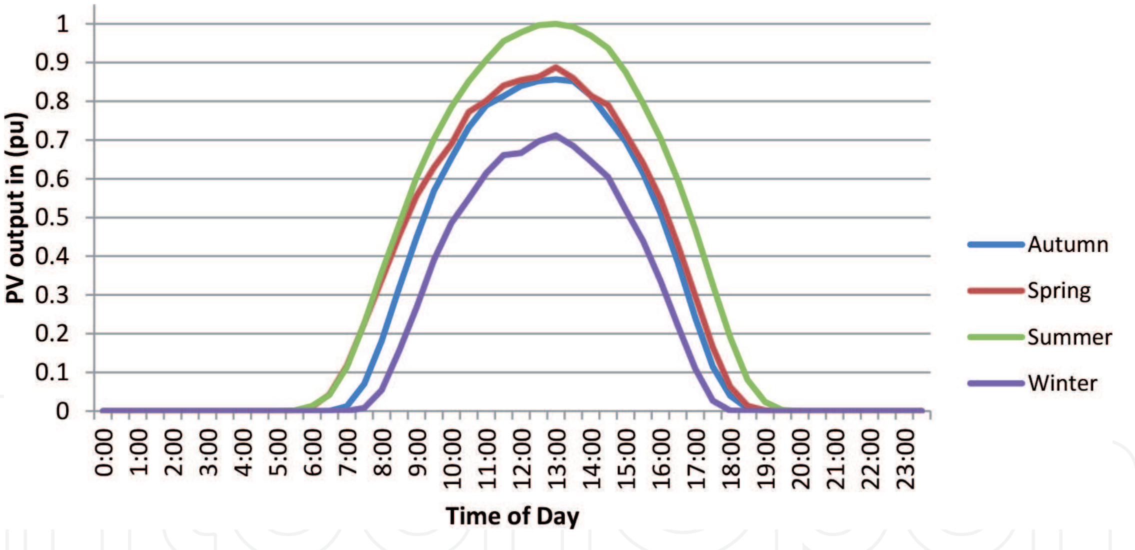

Figure 1.
Typical p.u. generated seasonal PV output profile.

3. Installed RTPV system

The scope of this study relates to RTPV installations connected to every customer connected to an MV network, this is defined as the high penetration of RTPV. The equipment type used in this study is found to be commonly available in South Africa.

While some studies consider large PV installation's sizes to show benefits to customers [9], this study utilizes an average solar panel output of a single 200 W panel installed at every connected customer [10], this is a very conservative approach taking into account that panel outputs degrade over time due to aging and associated output reduction [11], the build-up of dirt/residue and orientation.

Further to this the battery technology assumed in the assessments, also commonly available, are lead-acid type batteries. These batteries have a depth of discharge rate (DOD) and while it is common to find a DOD of 80%, for the purposes of this study it is assumed that a 100-ampere hour battery with a DOD or 50% is utilized offering 600 W of power. Inverter capabilities [12] have been assumed to operate at 7 amps due to low household breaker sizing and inverter costings. This simulation design, though very conservative, leads to defining the required design for households. The criteria of the PV, battery and inverter that have been utilized in this study are considered as a base design which can be improved upon implementation.

4. Battery energy storage system alone

Considering battery energy storage systems (BESS) without any external generating source would require that its charging is supported by the electrical grid. Analysis in [13] shows that there is not any reduction in the total daily energy supplied by the Utility, hence the only benefit that can be achieved would be for the Utilities' peak load shaving. This arrangement shows no customer benefit and does not result in any energy saving for the Power Utility either. For a consumer with a BESS installation only, a likely benefit is to run on charge cycles during periods of low load and inject at periods of high utility demand especially if tariffs are based on time of use.

5. Roof-top photovoltaic alone

Analysis has been considered for each residential customer having 200 W (watts) of installed roof-top photovoltaic (RTPV) capacity, an overview of this connection can be seen in **Figure 2**. It is assumed that if the power generated by the RTPV would exceed their instantaneous demand then the excess power would feed into the electrical grid.

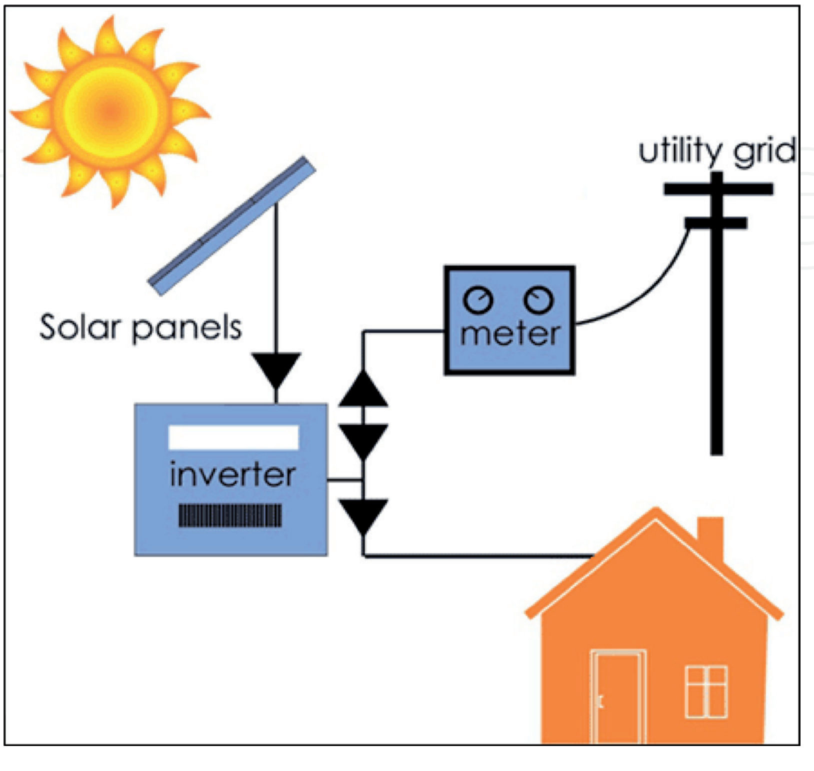

Figure 2.
Conventional RTPV installation [14].

Figure 3 shows the comparison of RTPV and the network normal power curves. The network normal (P) is the load profile for the study. It can be seen that during daylight hours RTPV dispatches power; hence the reduction of power can be seen when compared to the network normal curve.

From this analysis, it is seen that the Utility loses 5.76% in revenue resulting from an overall reduction in dispatched power. While the supplied power to the customer from the utility is reduced by 5.8%, referring to data in **Figure 4**. Hence the

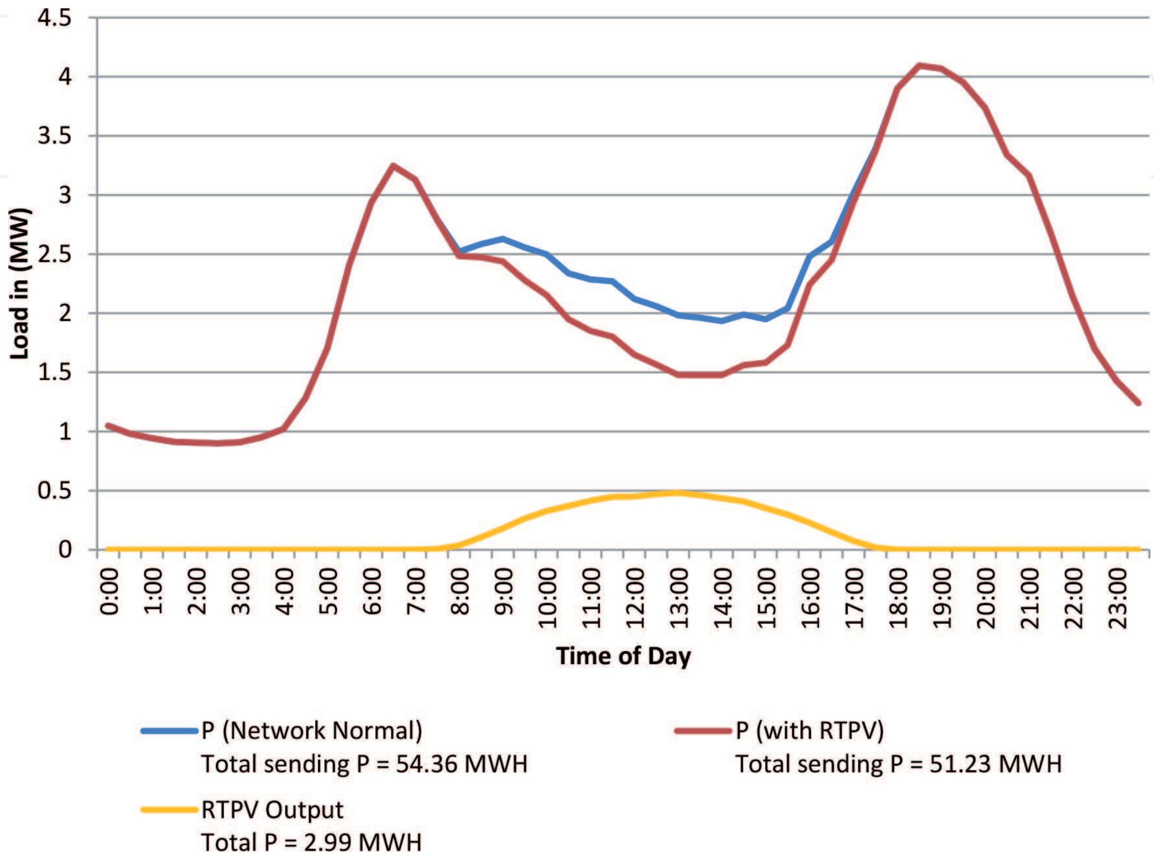

Figure 3.
Active power of NB36 with 200 W RTPV penetration, considered for a winter weekday.

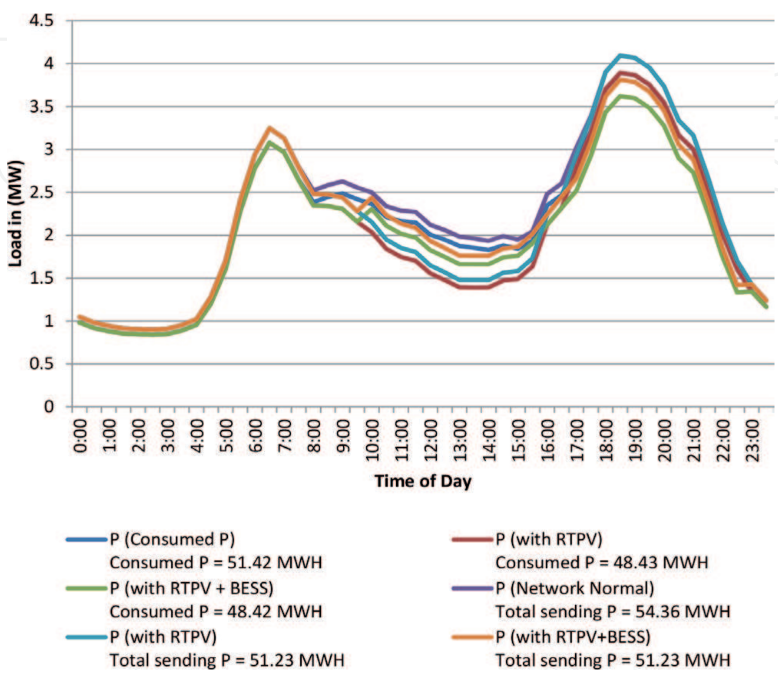

Figure 4.
Sending active power, power consumed by customers and P losses, considered for a winter weekday.

benefit to the customer is credited to the RTPV injection. The disadvantage when considering RTPV alone is that it feeds only during daylight hours, there is no effect to the network morning and evening peaks period; the peak violations mainly exist during the evening peak time. This leaves the question of what will be the influence of RTPV combined with BESS.

6. Roof-top solar photovoltaic with battery energy storage system

Considering the same RTPV installed capacity of 200 W per residential home. In addition to this, it is assumed that each home is equipped with a battery which has 600 W of dispatchable power; an overview of this connection is seen in **Figure 5**. This inclusion of BESS is limited only by its charge and discharge rate. Based on the available power generated by a 200 W RTPV source, it was then assumed that the battery would reasonably charge and discharge at less than 7 amps.

The network normal (P) is the load profile for the study. **Figure 6** shows the comparison of RTPV with and without BESS. During daylight hours 80 W of power is allowed to charge the battery while the remaining power supplies the customer or overflows onto the electrical grid. During the evening peak period, the same 80 W is dispatched from the stored energy over a period of 7.5 hours.

As demonstrated in **Figure 6**, RTPV including BESS can be seen to benefit both the Utility and Customer. The Utility benefits by the reduced voltage regulation and thermal violations which are experienced during the evening peak, and the

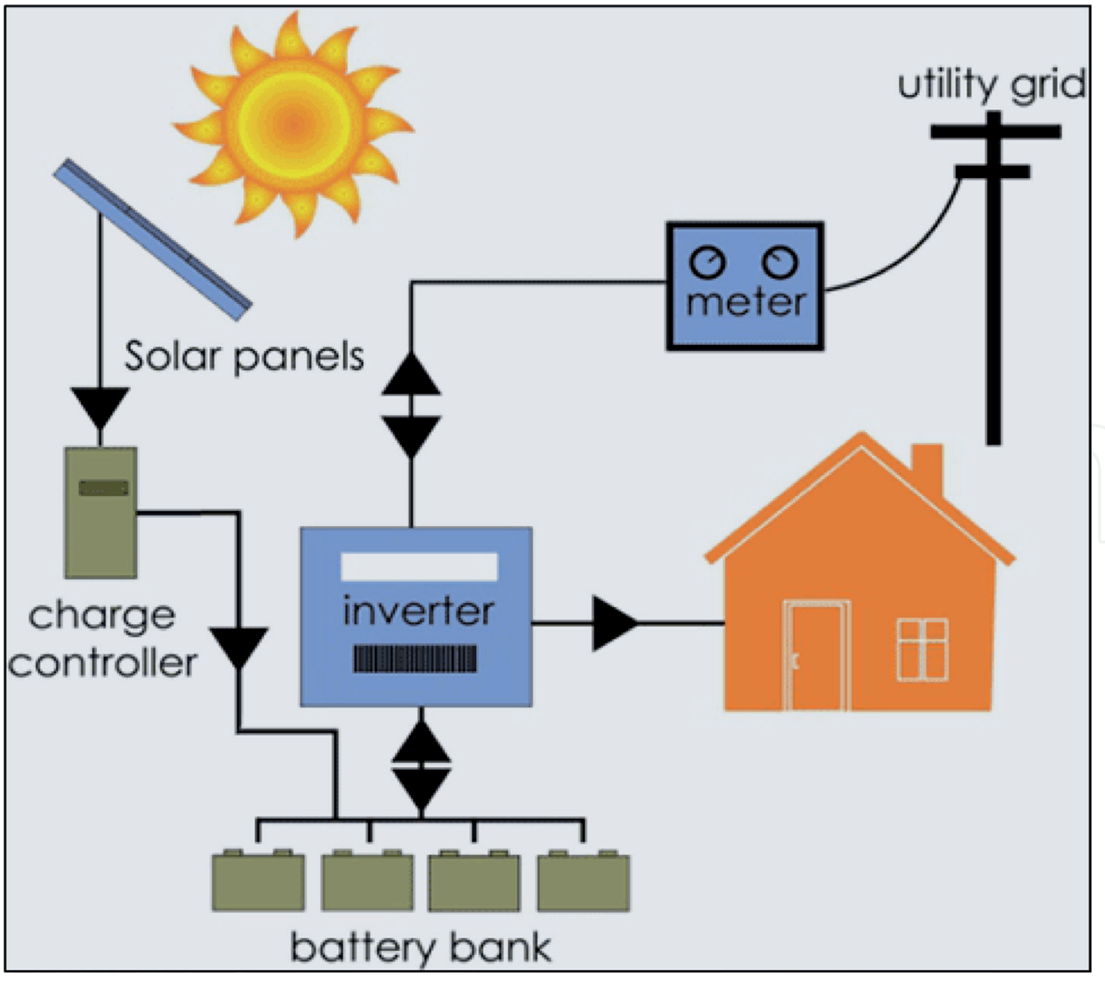

Figure 5.
RTPV with battery storage [15].

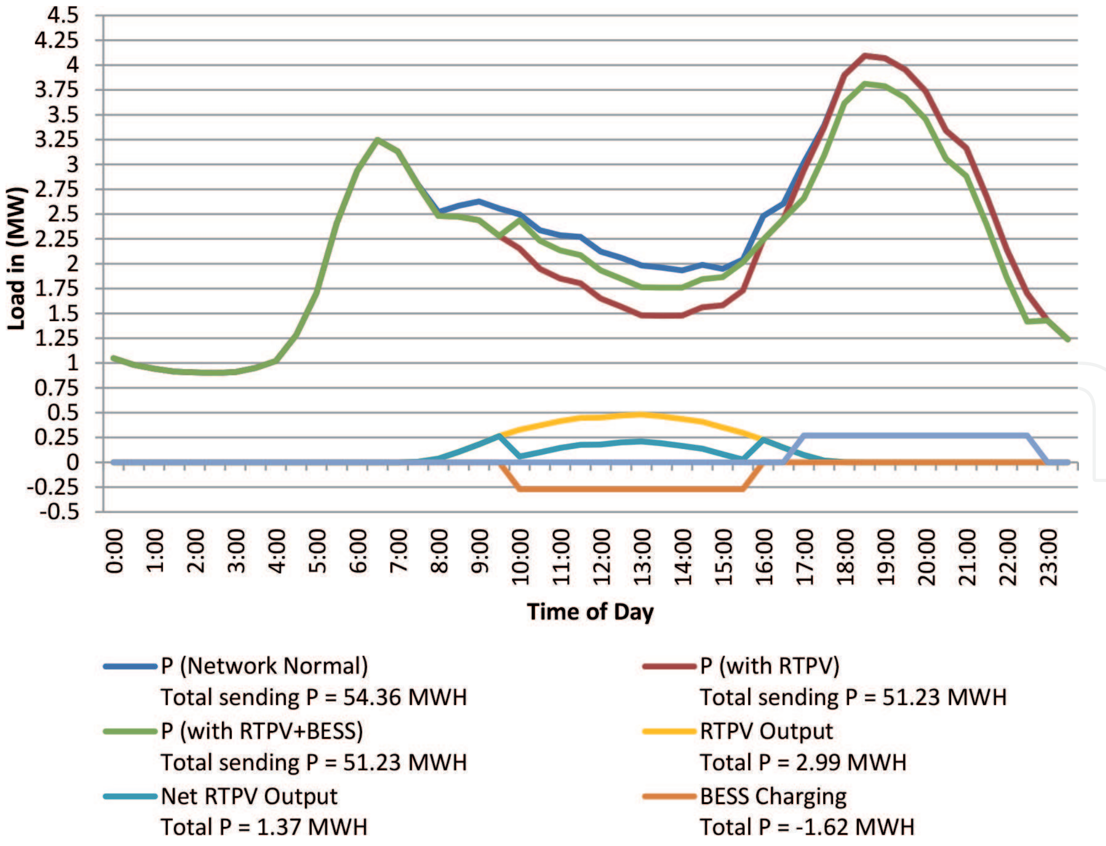

Figure 6.
Active power of NB36 with 200 W RTPV penetration and BESS, considered for a winter weekday.

Customer benefits by an overall reduction in power consumed. From this analysis, it is seen that the Utility loses 5.76% in revenue. While the customer's power consumption, referring to data in **Figure 4**, is reduced by 5.8%. Further investigation of **Figure 4** shows a negligible difference of power consumed if the customer has RTPV alone or including BESS.

7. Varied levels of BESS

While the results from the above analysis speak of how the Utility and Customers are affected, there still raises the fundamental concern related to the constraints experienced on NB36. At normal, when the load is peaking, it's found that the minimum Voltage is 92.7% and the network is thermally loaded to 102%. The analysis shows that if customers provide back-feeding, from their stored energy, during peak times, it will reduce the constraints on the network. Analysis has considered the back-feeding of 80 W, following the discussion above, and 250 W for each residential customer.

Figure 7 reflects the effect of the voltage along the backbone of NB36, also showing the ability of BESS to dispatch power at 80 W and 250 W. It can be seen that with an increasing ability of the BESS to dispatch power, it alleviates the voltage constraint by <1% at 80 W, and 2.1% at 250 W.

Figure 8 shows that the normal network condition exceeds the rating of the conductor at peak loading.

With BESS dispatching power we see that the thermal constraint is reduced from 102–94% when 80 W of power is dispatched, and improved further when 250 W is dispatched to 79.8%.

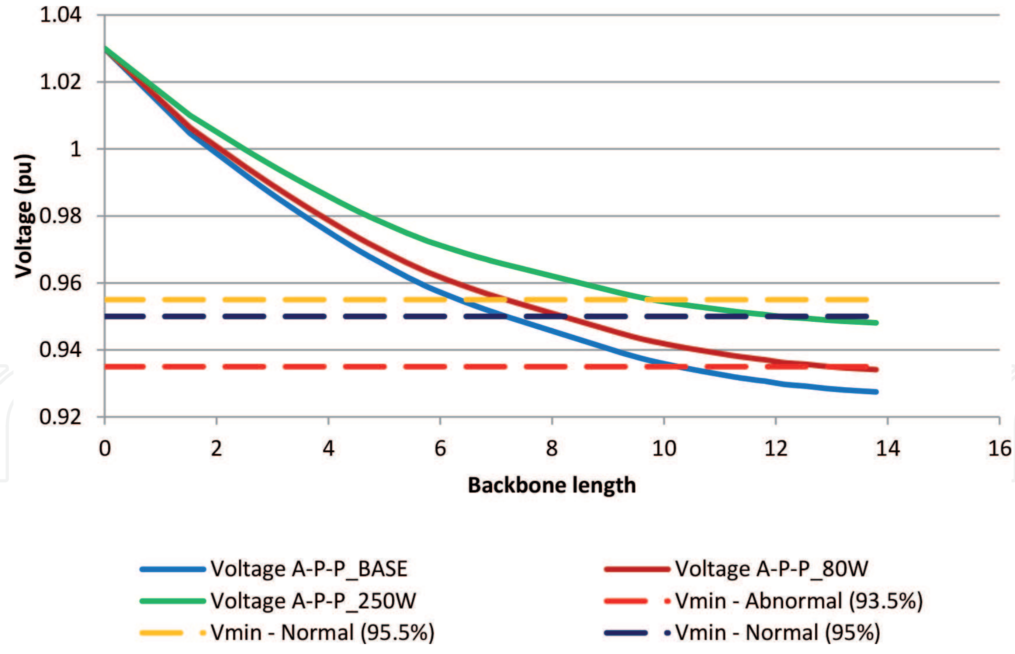

Figure 7.
NB36 minimum voltage at peak (winter weekday – 18:30).

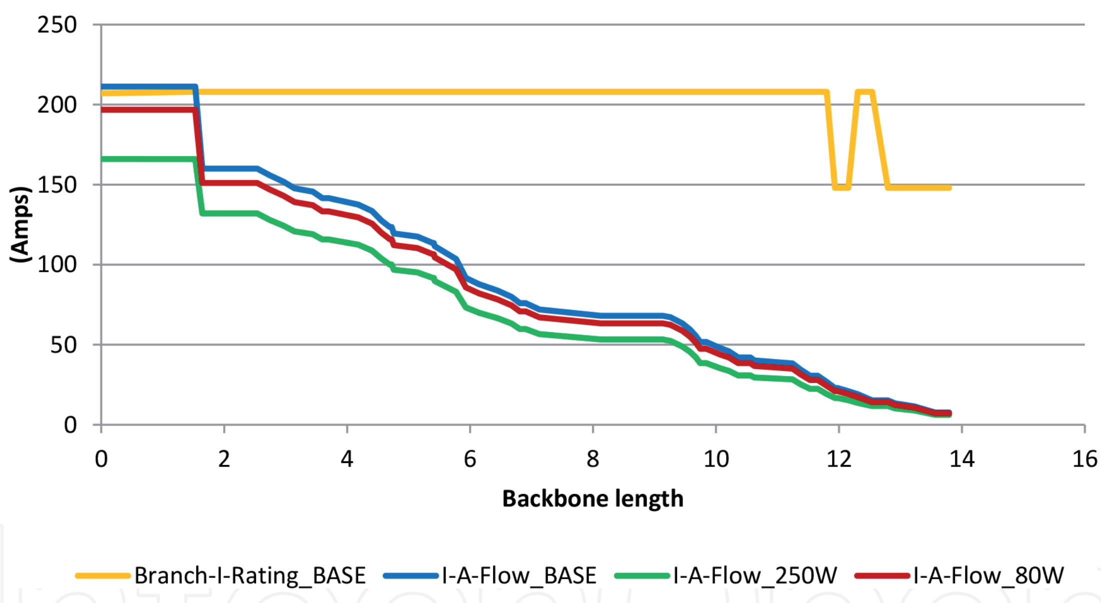

Figure 8.
NB36 thermal rating vs. load current.

8. Power dispatched, consumed and its effect on technical losses

Figure 9 shows the network sending power, consumed power (including with RTPV, and RTPV+BESS). The difference between the sending power and consumed power is attributed to the technical losses resulting from transmitting power down the network.

Technical losses are calculated as a percentage of the total load of the feeder including both no-load and load losses. The results from the analysis help to obtain a view of the network losses; this can be used as a basis for historic trending and benchmarking and can be used as one of the triggers for network strengthening. Therefore, this statistic also aids the conditioning of the priority ranking criteria. DER's may have a significant effect on network losses.

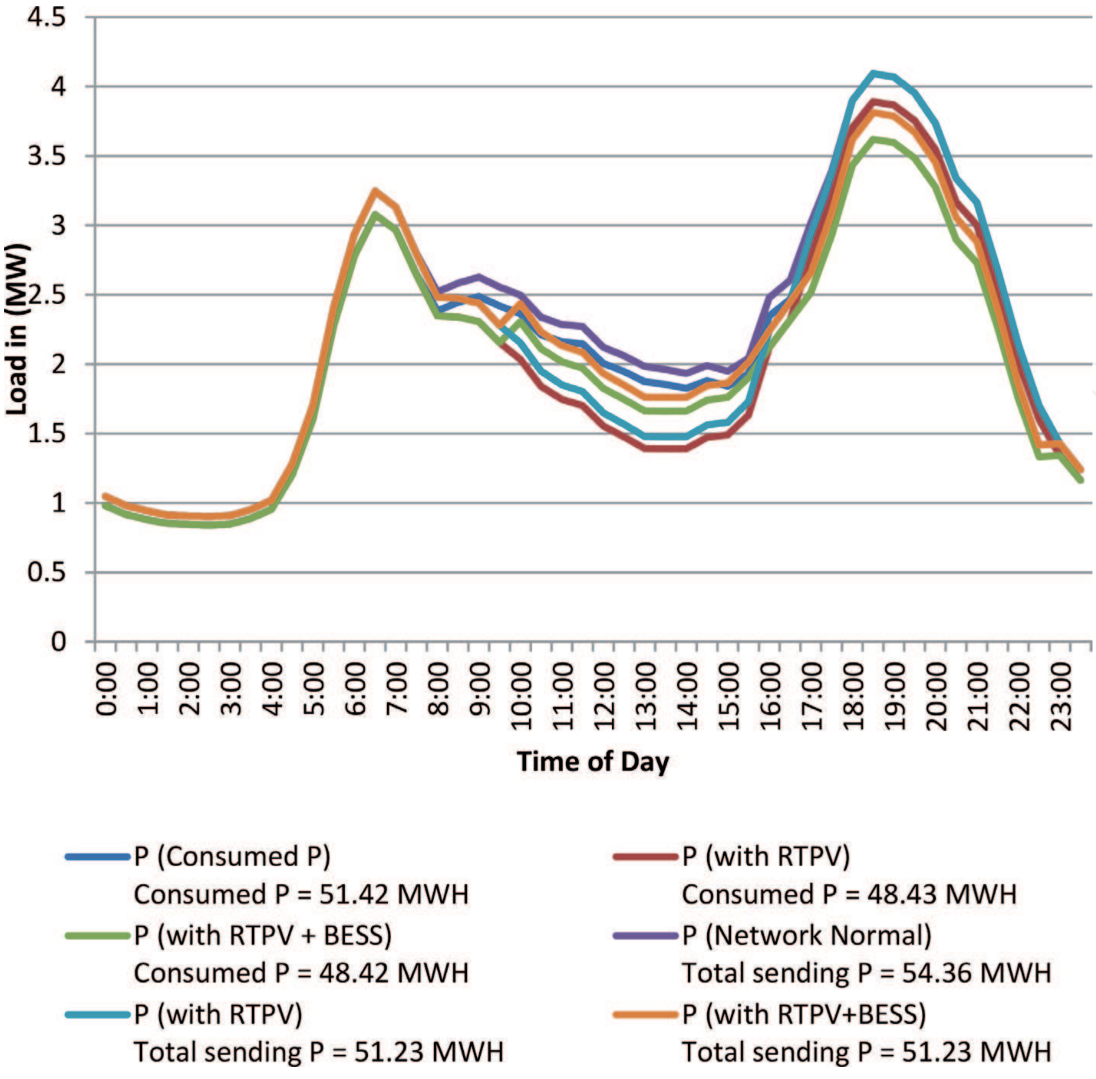

Figure 9.
Sending active power, power consumed by customers and P losses, considered for a winter weekday.

A generator can lower or increase losses, depending on its location and the network configuration [16].

The technical losses vary slightly between the different options analyzed:

- Network sending power vs. Consumed power (Network normal) = 5.41%
- Network sending power vs. Consumed power (with RTPV) = 5.47%
- Network sending power vs. Consumed power (With RTPV+BESS) = 5.49%

9. Conclusion

This chapter has demonstrated the benefit of roof-top solar photovoltaic and/or including battery energy storage systems. It offers relief for constrained networks in dense and radial distribution systems. While optimization techniques can be used to reduce violations, these are still limited do not provide effective short-term solutions when dealing with constrained networks in dense and radial distribution systems. Battery energy storage systems (BESS) and solar rooftop photovoltaics (RTPV) are a viable distributed energy resource to alleviate violations which are constraining medium voltage (MV) networks. The results show the following:

9.1 BESS only

This option does not benefit the customer, as the batteries require grid connection to charge and discharge, not to mention efficiency losses. If discharging the stored energy occurs during peak periods, this can benefit the utility by reducing the peak violations. Therefore, it is recommended that a tariff/time-of-use incentive is introduced to motivate customers for BESS only installations.

9.2 RTPV only

This is an excellent way for a customer to reduce his overall electrical utility bill. Unfortunately, the utility is negatively affected by the reduced sale of electricity.

9.3 RTPV+BESS

The results show that with the addition of RTPV including BESS the utility still loses revenue. However, with the addition of BESS, Utilities have the ability to reduce technical violations during peak periods. Installing BESS, in this manner, shows no benefit to the customer. Therefore, it is recommended that a tariff/time-of-use incentive is introduced to motivate customers for RTPV+BESS installations.

9.4 Varied levels of BESS

Though RTPV inclusive of BESS reduces the violations on the network; it can be seen from **Figures 7** and **8** that voltage and thermal violations persist for this specific network. Therefore, it is necessary to consider an increased installation of BESS. 250 W of dispatchable power offered the most appropriate quantity of power to alleviate the violations. The effect on technical power losses: seen in **Figure 9**, shows a constant 5.41%–5.49% of technical power losses for each of the above considerations. This demonstrates that technical losses are similarly proportioned to its source sending power when conducting analysis on the various installation types relating to RTPV/BESS. While these amounts are typical and expected for a reticulation network – losses will defer due to topology, loading and design of networks.

For Utilities and Municipalities, the extent of challenges encountered when considering large scale installations of RTPV would be related to availability and visibility of data for adequate analysis. Current standards do not address the practical design solutions needed for all variations within customer installations and expectancy from RTPV. This can result in non-standard customer installations which will lead to undesirable impacts on the source and shared utility power systems.

Visibility and compliance of electricity supply regulations are required at the point of supply which is conditioned to be met at the point of supply and not the point of generator connection which is embedded in the customer's installation. Therefore, smart metering systems with predefined charge and discharge times/durations need to accompany RTPV installations. This requires an evaluation of currently employed metering technology, to ensure they accommodate these operational scenarios.

The cost for an electrical system, in which a customer is partially or completely off-grid, will still be attributed to the Utility to ensure the security of supply. Hence Utilities should take the lead in this segment of small-scale embedded generation to remain viable and relevant. Utilities may consider engaging suppliers to carry out maintenance and/or repairs during initial warranty periods.

Data visibility, both topological and metered data, is crucial for power system analysis, and need to be available and validated from time to time to cater for load growth. Utilities must ensure competent staffing for data acquisition and analysis.

There may be a lack of data validity for non-telemetered devices, such as unknown tap positioning of reticulation transformers, conductors or cables which has been replaced with different ratings and types. This can be challenging when configuring simulation models.

For this study analysis was given to the network classification that was predominately found with residential type loads, which has been identified as C2 TZ2 type. This study, therefore, adopted a common sending voltage regulation set point of 1.03pu applied at reticulation busses. The voltage limit allowable for a normal condition is 95.5% and for abnormal conditions are 93.5. From an operations view, the abnormal limit is the benchmark to be adhered to, while network planners work with the normal limit of 95.5%.

Continuous network changes due to rising electrification and illegal connections discredits network analysis and requires more frequent update of simulation models. Pre-existing RTPV installations may pose a problem if they do not meet compliance requirements. Utilities need to conduct surveys of pre-existing RTPV installations and update its electrical connection to the power grid.

It is recommended that during site visits, meter re-programming including 'time-of-use' tariffs and amendments to supply agreements, can be implemented. Presently, there is no information on households which has become "self-suppliers" due to lack of a registry for small-scale embedded PV plants. This will assist in ensuring that customer contributions to unbalance be limited to 1% voltage unbalance at the point-of-common coupling.

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