IEEE PES General Meeting, Portland, OR, USA, August 2018

An Iterative Approach to Improve PV Hosting Capacity for a Remote Community

Kalpesh Joshi, Ramakrishna (Rama) Gokaraju
Department of Electrical and Computer Engineering
University of Saskatchewan
Saskatoon, Canada
kalpeshjoshi.in@ieee.org, rama.krishna@usask.ca

Abstract— **Remote communities are largely supplied by diesel generating plants. With weak grid and sparse communities over a large geographical area, photovoltaic distributed generation (PVDG) with battery energy storage systems (BESS) can be a viable alternative to grid upgrade while reducing dependence on fossil fuel based generation. This paper presents results of a research study for improving the hosting capacity of distribution systems in remote communities in the northwestern part of Canada. The proposed iterative approach seeks to exploit untapped potential of existing grid infrastructure along with the four-quadrant operation of BESS to maximize the feeder's hosting capacity. The proposed approach uses the headroom of overvoltage limit made available by several voltage regulators in the remote feeder to increase its hosting capacity by as much as 25%. Based on simulations with annual load profiles and site-specific PV generation profiles, it is shown that BESS can further improve the feeder hosting capacity by up to 60% with reactive power support. A comparison is also drawn between the options of grid-upgrade versus the use of BESS for improving hosting capacity. Three BESS technologies are compared with their cost metric for this application.**

Index Terms—**Battery energy storage system, hosting capacity analysis, photovoltaic distributed generation, step voltage regulators.**

I. INTRODUCTION

Improving Hosting Capacity (HC) for the feeders supplying electricity to sparse communities in rural areas is very important for utilities to incorporate more Renewable Energy Source (RES) based generation and also for the communities to gain reliance on local and sustainable energy systems. Remote communities are largely supported by local diesel generation plants to meet their electricity needs [1]. Utilities supplying Northwestern part of Canada face several challenges in meeting their ambitious targets of adding up to 50% of generation capacity based on RES by 2030 [2], especially with the long and weak interconnections to the main grid.

Feeder HC, as introduced in [3], is the amount of local generation which can be accommodated by the feeder without affecting availability of reliable power supply for other customers. Multiple ways of improving feeder HC such as optimal switching of shunt capacitors, adjusting voltage regulator taps, managing controllable branch switches, and controlling smart PV inverters, are discussed and incorporated in a generic algorithm [4]. Monte Carlo simulations are used for several utility feeders in [4] whereas stochastic mathematical model is developed in [5] to maximize the feeder hosting capacity. While several studies have proposed various ways to improve HC of feeders as a generic solution, effect of feeder specific factors is analyzed in [6] to support the argument of case-specificity and its importance is emphasized in [7] and [8].

The problem of voltage rise due to inclusion of local PV generation is the prime factor that caps the feeder hosting capacity. It has led to investigation of interaction between step voltage regulators (SVRs) and Photovoltaic Distributed Generators (PVDG) [9]-[10], use of voltage droop control strategies for active transformers [11] and balancing of loads and generations between the supply phases to mitigate the phase imbalances in low-voltage networks with residential PVDGs [12]. While the interaction of SVRs with PVDGs and adjustment of tap changers for improved voltage profiles have been researched in the literature for improving PV hosting capacity, the present case study attempts to exploit the headroom in overvoltage limit created by three SVRs located on a rural feeder. A simple iterative approach is developed to first find the available headroom in overvoltage limit on a remote feeder using the HC analysis. It then recursively determines and coordinates new settings for each SVR with increasing PV penetration. Lastly, improvement in HC is also extended by using battery energy storage system (BESS) along with its reactive power support to control the feeder voltage profile. An existing feeder is modeled to test this method using PSS/E and PSS SINCAL [13]-[14].

II. ITERATIVE APPROACH

In general, HC of a feeder is the function of following factors [3]: (a) squarely proportional to the voltage level, (b) directly proportional to the current carrying capacity of the conductors, (c) overvoltage limit margin available with SVRs and (d) inversely proportional to the distance of the DG from a transformer on the feeder. The proposed iterative approach utilizes the overvoltage limit margin and extends the same for upstream SVRs by appropriately modifying the voltage rise settings.

Authors are grateful for the financial support provided by Shastri Indo-Canadian Institute for this research.

While maximum load on the feeder determines the minimum voltage along the feeder, minimum load profiles determine the maximum voltage due to SVR. Real power injection at different lengths on a feeder affects the overall daily load profiles of the feeders and changes its minima and maxima depending on the size of PVDG. Inclusion of BESS also helps in making the load profiles even with less difference between maximum and minimum demands. A small headroom created with overvoltage limit can enhance the feeder HC substantially. Figure 1 explains the creation of headroom by changing the SVR settings under minimum and maximum load scenarios. A small PV injection at far end of the feeder increases the voltage at far end as well as it reduces the voltage drop along the length of feeder. The reduced voltage drop creates a small room for SVR to reduce its voltage rise settings. It is shown as a headroom-1 (HR-1) in Figure 1. HR-1 is created at SVR-2 and can be used to reduce its settings for the new load profile with an inferior peak demand. HR-2 at SVR-1 can be created by both PVDG at far end of the feeder as well as one close to SVR-2. It means that more locations along the upstream section of this feeder can host PVDG. Improved HC upstream can be used for higher PVDG penetration resulting in a cumulative rise in feeder hosting capacity. Values in Figure 1 are descriptive and do not reflect actual voltage profile.

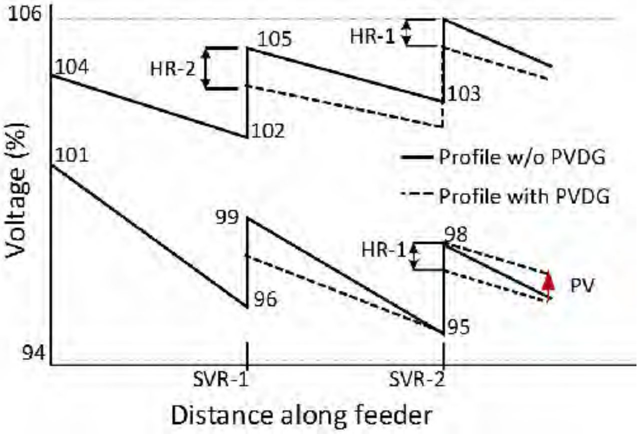


Figure 1. Voltage profile of a remote feeder with two SVRs

However, the cumulative rise in HC for PVDG is limited by the fact that: (a) effect of PV injection on load profile is limited during sun-shine hours only, (b) high PV penetration also creates new low load points for SVRs upstream resulting in reduced headroom, and (c) current carrying capacity of conductors impose limits on transfer of power. Use of BESS can help mitigate the effect of all these factors and thus help extend the HC of a feeder further. In order to calculate the available headroom based on the PVDG connected at far end of the feeder, basic SVR settings should be known. Calculation of projected maximum voltage can be done using (1), (2) and (3) based on the known SVR settings for two different SVRs on a same feeder, [3]:

$$v_{max-SVR1} = v_{max}^{db} - \kappa_v\left(v_{min}^{db} - v_{min}\right) + \Delta v_{rise} \quad (1)$$

$$v_{max-SVR2} = v_{max}^{db} - \kappa_v\left(v_{min}^{db} - v_{min}\right) + (2 - \kappa_v)\Delta v_{rise} \quad (2)$$

$$v_{max-end} = v_{max}^{db} - \kappa_v\left(v_{min}^{db} - v_{min}\right) + (2 - 2\kappa_v)\Delta v_{rise} \quad (3)$$

Where v_{min}^{db} and v_{max}^{db} refer to the minimum and maximum limits of dead-band (db) for SVR, v_{min} is minimum node voltage limit, Δv_{rise} is the voltage rise per stage and κ_v refers to the ratio of voltage drop at light loads to that at high load level. Calculation of κ_v is important as it is based on the voltage drop values under extreme load levels. With different real power injection from PVDG, the extreme load levels should be carefully obtained based on load profiles of at least one year and corresponding site-specific generation profile of a PVDG. The projected maximum voltage given by (1) and (2) can be used to obtain available headroom for overvoltage limit using (4) and (5). SVR settings can then be modified based on standard set of equations for line drop compensator, [15].

$$HR1 = \left|v_{max} - v_{max-SVR1}\right| \quad (4)$$

$$HR2 = \left|v_{max} - v_{max-SVR2}\right| \quad (5)$$

The steps required to check for available headroom of overvoltage margin are shown in Figure 2(b). The flowchart shown in Figure 2(a) summarizes the steps that were used for HC analysis.

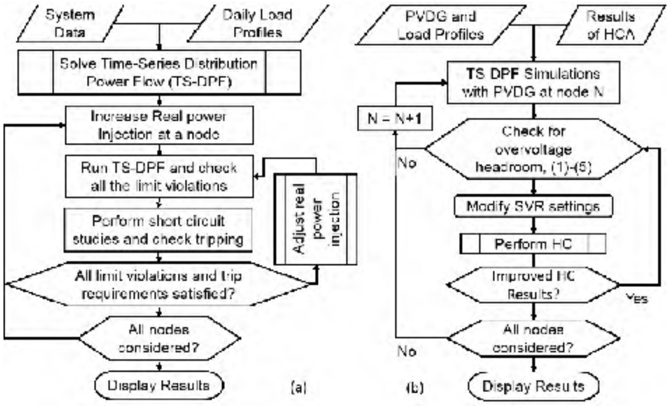


Figure 2. Flow chart for (a) HC analysis and (b) iterative approach to modify SVR settings and improve feeder hosting capacity

For assessing the capacity of a feeder to host PVDG, time-series distribution power flow (TS-DPF) and fault analysis is performed iteratively for incremental real power injection at each node sequentially as shown in Figure 2(a). Exhaustive data sets for three-phase unbalanced feeder are represented by the block named 'System Data'. Combination of industrial, commercial and residential load profiles are used to populate each node with realistic daily load profiles. The TS-DPF module simulates the unbalanced distribution power flow for every time interval specified. In this exercise, hourly time interval is used. Real power injection at each node is incremented in pre-defined steps at each node. The HC analysis module can also inject reactive power or combination of real and reactive power to assess the impact of VA injection. VA injection is used in simulations with BESS profiles including the reactive power dispatch. Fault analysis is performed by short-circuit module to check the performance of desired and undesired tripping in the presence of new local generation. If all the limits for node voltage, branch currents and equipment loading are satisfied, then real power injection is further incremented. The iterative HC module considers all probable nodes for PVDG and displays results in terms of MVAs that can be hosted at each node, along with the corresponding maximum node voltages, line sections and equipment utilization values.

Based on the HC analysis, recommended size of PVDG is connected to the specified nodes and headroom in overvoltage limit margin is obtained, as shown in Figure 2(b). HR-1 and HR-2 are obtained from annual TS-DPF simulations. SVR settings are then modified and HC analysis is performed to observe the limit violations. If the calculation shows further improvement of HC for PVDG at the same node, the procedure is repeated. All the nodes on the feeder with SVRs are considered in the second phase to maximize the HC. It should be noted that HC module can also help in determining size of BESS and its reactive power dispatch as well. All the steps shown in Figure 2 (a) and (b) are repeated with BESS as a source as well as load (discharging and recharging modes) to obtain improved HC with BESS. A customized small module is used to track the energy capacity of BESS and keep the charging-discharging limits within the BESS energy capacity once fixed by first phase of exercise (Figure 2(a)).

III. REMOTE FEEDER AND DATA SETS

A distribution feeder in Northwest Saskatchewan is used for testing the proposed method. The rural feeder supplies electricity to remote communities of Patuanak, Pinehouse and La Ronge. These remote communities are sparse and represent low load density; with population in the range of 1,500 to 3,000 inhabitants. Three SVRs are placed on a – more than 100 km long – section of the remote feeder to maintain healthy voltage. A model of Northwest Saskatchewan feeder is developed in PSS SINCAL for this implementation. Figure 3 shows the feeder topology and major components along with the proposed sites with improved HC for PVDGs. BESS is also shown at the most preferred location to further boost the HC.

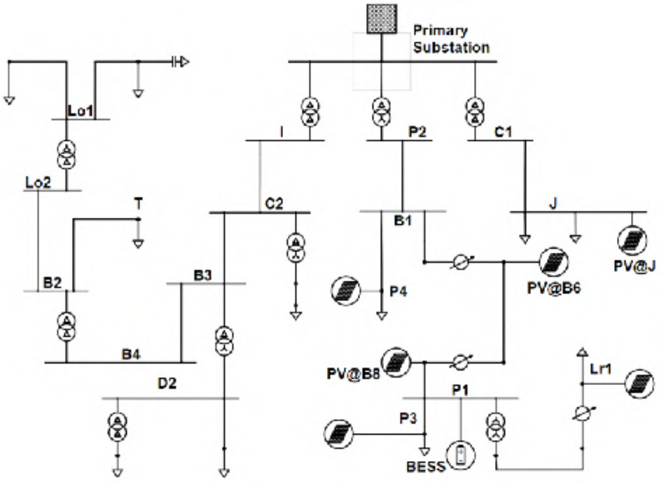


Figure 3. Schematic diagram of a remote feeder in Northwest Saskatchewan

TABLE I FEATURES OF THE REMOTE FEEDER

Type	**Sub-Transmission, Distribution**
Nodes	30
Lines	17
Source to load distance (maximum)	278 km (approx.)
Transformers	9
Voltage Regulators	3
Voltage Levels	Three - 72 kV, 25 kV, 14.4 kV

Figure 4 shows hourly load profiles for industrial, residential and commercial customers. Publically available datasets are used to populate the nodes with realistic load profiles and PVDG profiles. Site-specific solar radiation data for the year 2015 from [16] are used for PVDG profile whereas combination of load profiles from [17], [18] and [19] are used to populate nodes with annual load profiles. Annual PVDG production is estimated by using a PV model implemented in [6], which is based on [20].

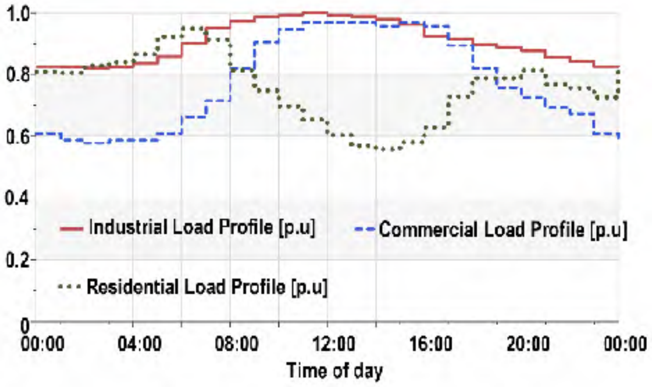


Figure 4. Daily load profiles for industrial, commercial and residential users

IV. SIMULATION RESULTS

Simulations for HC analysis are performed in three stages: (a) base case analysis to estimate HC of the feeder, (b) extend the HC analysis while modifying SVR settings to exploit the available overvoltage margin, and (c) further extend HC using BESS with real and reactive power dispatch. For the sake of brevity, results of improved HC are provided in Table II and Table III; whereas seasonal variations are shown by two representative days of each season of winter and summer.

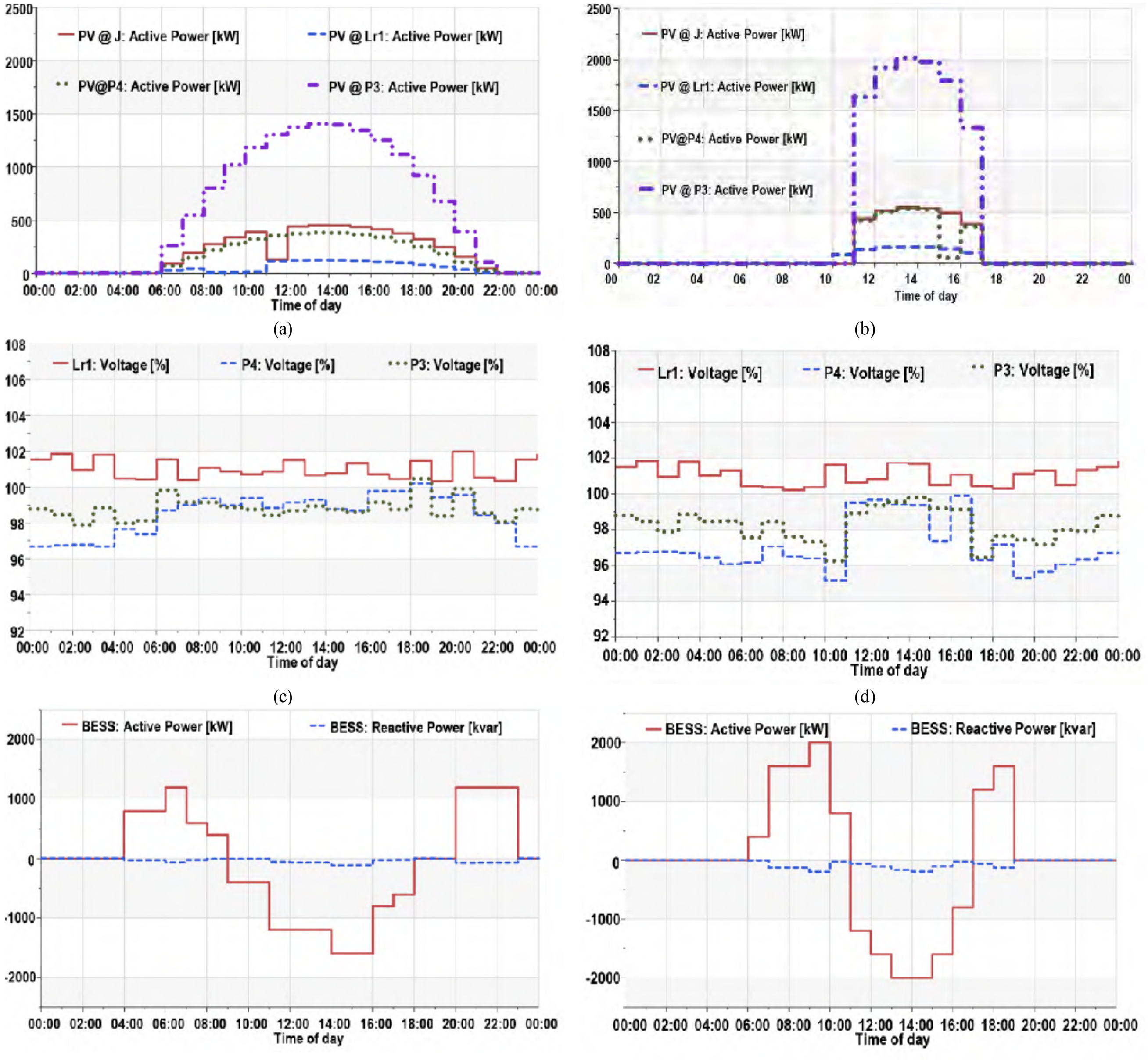
A. HC Improvement

Results of HC analysis for base case are listed in Table II. A section with three SVRs (Figure 3) has many nodes with high HC – B8, B6, P3 each can host 1.3 MW of PVDG, apart from the far end nodes P4 and Lr1.

TABLE II HC ANALYSIS RESULTS – BASE CASE

Node	S [MVA]	vmin [%]	vmax [%]	idh [%]
B8	1.299	95.649	105.270	45.536
B6	1.299	95.649	105.270	47.538
P3	1.299	95.649	105.270	45.536
J	0.675	95.837	105.270	48.260
P4	0.675	95.649	105.486	47.544
C3	0.675	95.649	105.880	48.253
C4	0.675	95.649	105.918	48.253
Lr1	0.207	95.649	105.479	45.536

Table II also shows the maximum and minimum feeder voltages – these voltages are within the limits of ±6% of nominal value, as per the limiting values specified by CSA, [21]. Note that the last column in Table II lists the equipment loading condition, including transformers, SVRs and line sections. Nodes B8, B6, P3, P4, and Lr1 are connected with the PVDG capacity listed in Table II for second phase of analysis to improve HC. Nodes C3 and C4 are excluded as these are far off to have any effect of change in SVR settings.



(a) (b)

(c) (d)

(e) (f)

Figure 5. (a)-(c)-(e) Generation profile of PVDG, voltage profile for PVDG nodes and BESS dispatch profile for a summer day respectively; (b)-(d)-(f) are similar profiles in the same order for a winter day

TABLE III HC IMPROVEMENT

Node	HC – base case (MVA)	HC – Stage 2 (MVA)	HC – Stage 3 (MVA)
B8	1.299	1.625	2.3
B6	1.299	1.625	2.5
P3	1.299	2.025	2.5
J	0.675	0.675	0.675
P4	0.675	0.675	0.675
Lr1	0.207	0.207	0.207
Total	5.454	6.832	8.857

Table III shows stage wise improvement in HC for all the five nodes of interest. Nodes B8, B6, and P3 close to the SVRs have considerable improvement in HC at the end of Stage-2. Modifications in SVR settings affect these nodes most. Node Lr1 is also close to an SVR but the benefit of overvoltage margin is exploited at node P3. The total increase in HC at the end of stage 2 is 25% from 5.454 MW to 6.432 MW. Further gain in HC is achieved by using a 2 MW, 9 MWh BESS at node P3. After considering high PVDGs at the end of stage 2, annual simulations are performed to estimate the new headroom available to upstream SVRs. The modified SVR settings are used with BESS. Rise in HC at the end of stage 3 is close to 60% from 5.454 MW to 8.857 MW.

B. Results with seasonal variations

Profiles of PV generators, BESS dispatch of real and reactive power along with node voltage profiles for sample days of summer and winter are shown in Figure 5. Real power injection is high in winter, whereas generation peak is low in summer but PV generation is available over a longer time of day in summer. Seasonal variations play a major role in PVDG impact on network operations. Node voltage profiles are smoother in summer as compared to winter, which also implies less tap-changer activity in summer. However, the change in SVR settings have to be based on yearly analysis so that minimum and maximum node voltages remain within specified limits during seasonal variations in load and PV generation profiles. Note that the BESS dispatch of real and reactive power helps in maintaining voltage profile within limits while PV generation keeps varying. It is also a major reason for substantial rise in HC of the feeder with BESS. Results shown in Figure 5 are representative results only. The exercise of improving HC is based on yearly data sets for the year 2015.

C. Cost Metrics

Planning decisions have to be based on cost-benefit analysis for several years. However, as a pointer, a small exercise for comparison of involved costs in network upgrade and BESS deployments is presented here. To improve HC of the remote feeder, two sections of close to 180 km length need to be upgraded – one section with voltage level upgrade and the other section with higher capacity conductors. The gross costs involved in this upgrade is estimated based on [2]. Whereas, the cost metric for three BESS technologies – suitable for this application – are estimated based on [22] and [23]. Vanadium Redox Flow Battery (VRFB), Sodium Sulphur (NaS) battery and advanced Lead Acid battery are considered for cost comparison. As per the size, application and economics of scale [22], these three battery technologies are most suitable in the present study. Table IV shows all costs in CAN Dollars.

TABLE IV COST METRIC FOR BESS AND INFRASTRUCTURE UPGRADE

	VRFB	**NaS**	**Ad. Lead-Acid**
Specs: Power, Energy	2 MW, 5 Hrs	2 MW, 5.5 Hrs	2 MW, 10 Hrs
Depth of Discharge, η_{trip}	100%, 72%	80%, 75%	80%, 90%
Plant Life (Yrs)	15	15	15
Plant Cost	9,014,589	8,242,454	12,056,215
Fixed O & M (Annual)	17,956	25,190	24,024
Variable O & M (Annual)	4,276	3,110	1,944
100 km of upgrade to 25 kV line @ $ 70,000 /km			7,000,000
Capacity upgrade for 80 km @ $ 35,000 km			2,800,000
Transformers, Communications etc.			1,500,000
Total upgrade cost			11,300,000

V. CONCLUSION

The case study presented in this paper proposes a simple iterative approach to exploit the long and weak sections of a remote feeder for improving its PV hosting capacity. Availability of multiple voltage regulators on the long rural section feeding power to remote communities can be exploited for creating headroom in overvoltage limit margins to host more PVDG. Coordination of voltage regulator settings with four-quadrant operation of BESS can further improve HC from about 5.5 MW to up to 8.8 MW. A comparison of costs involved with the alternative of network upgrade shows that BESS deployment can be a cost-competitive option for extending PV hosting capacity of feeders with weak interconnection to main grid.

REFERENCES

[1] M. Kohler and Beans Robert, "Alaska Village Electric Cooperative Annual Report," Anchorage, 2017.

[2] SaskPower, "Connection Availability - T & D System," Saskatoon, 2016.

[3] M. H. J. Bollen and F. Hassan, *Integration of distributed generation in the power system*. Wiley, 2011.

[4] F. Ding and B. Mather, "On Distributed PV Hosting Capacity Estimation, Sensitivity Study, and Improvement," *IEEE Trans. Sustain. Energy*, vol. 8, no. 3, pp. 1010–1020, Jul. 2017.

[5] S. F. Santos, D. Z. Fitiwi, M. Shafie-Khah, A. W. Bizuayehu, C. M. P. Cabrita, and J. P. S. Catalao, "New Multistage and Stochastic Mathematical Model for Maximizing RES Hosting Capacity—Part I: Problem Formulation," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 304–319, Jan. 2017.

[6] K. A. Joshi and N. M. Pindoriya, "Case-Specificity and its implications in Distribution Networks with High Penetration of Photovoltaic Generation," *CSEE J. Power Energy Syst.*, vol. 3, no. 1, pp. 101–113, 2017.

[7] J. Smith, M. Rylander, L. Rogers, and R. Dugan, "It's All in the Plans: Maximizing the Benefits and Minimizing the Impacts of DERs in an Integrated Grid," *IEEE Power Energy Mag.*, vol. 13, no. 2, pp. 20–29, Mar. 2015.

[8] Electric Power Research Institute, "Alternatives to the 15% Rule - Final Project Summary," no. 3002006594, 2015.

[9] T. K. Saha, M. I. Hossain, and R. Yan, "Investigation of the interaction between step voltage regulators and large-scale photovoltaic systems regarding voltage regulation and unbalance," *IET Renew. Power Gener.*, vol. 10, no. 3, pp. 299–309, Mar. 2016.

[10] Y. P. Agalgaonkar, B. C. Pal, and R. A. Jabr, "Distribution Voltage Control Considering the Impact of PV Generation on Tap Changers and Autonomous Regulators," *Power Systems, IEEE Transactions on*, vol. 29, no. 1. pp. 182–192, 2014.

[11] S. Hashemi, J. Ostergaard, T. Degner, R. Brandl, and W. Heckmann, "Efficient Control of Active Transformers for Increasing the PV Hosting Capacity of LV Grids," *IEEE Trans. Ind. Informatics*, vol. 13, no. 1, pp. 270–277, Feb. 2017.

[12] P. K. C. Wong, A. Kalam, and R. Barr, "Modelling and analysis of practical options to improve the hosting capacity of low voltage networks for embedded photo-voltaic generation," *IET Renew. Power Gener.*, vol. 11, no. 5, pp. 625–632, Apr. 2017.

[13] E. M. Stewart, S. Kiliccote, and C. McParland, "Software-Based Challenges of Developing the Future Distribution Grid," *Lawrence Berkeley National Laboratories*, 2014.

[14] "PSS®SINCAL - Integrated Power System Engineering Software - Digital Grid - Siemens."

[15] W. H. Kersting, "The modeling and application of step voltage regulators," in *2009 IEEE/PES Power Systems Conference and Exposition*, 2009, pp. 1–8.

[16] National Renewable Energy laboratory, "National Solar Radiation Data Base," 2017.

[17] Market Surveillance Administrator, "Residential Load Profiles 28," 2004.

[18] A. Martinez *et al.*, "Integrated Canada-U . S . Power Sector Modeling with the Regional Energy Deployment System (ReEDS)," Golden, CO, USA, 2013.

[19] "Electric Reliability Council of Texas, Inc. – Annual Load Profiles," *ERCOT*, 2014.

[20] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, May 2009.

[21] Canada Standards Association, "Preferred Voltage Levels for AC Systems, 0 to 50 000 V - CAN3-C235-83 (R2015)." p. 11, 2015.

[22] A. A. Akhil *et al.*, *Electricity Storage Handbook*, no. February. Livermore California: DOE/EPRI, 2015.

[23] C. Bowman, E. Isaacs, and A. Poole, *Electricity: Interconnecting Canada A Strategic Advantage*. Ottawa: Canadian Academy of Engineering, 2009.