Coordinated Voltage Control in LV Distribution Systems using OLTC and BESS

Akansha Jain, Tanmay Tewari, Anubrata Das, Sandeep Anand and Abheejeet Mohapatra
Department of Electrical Engineering, Indian Institute of Technology Kanpur, India 208016
Email: akanshajain.0489@gmail.com; tantew@iitk.ac.in; anubrata@iitk.ac.in; asandeep@iitk.ac.in;
abheem@iitk.ac.in

Abstract—Voltage control is an important operational require- ment for efficient and reliable operation in distribution systems. The accelerated proliferation of Solar Photo-Voltaics (SPV) in distribution networks, has resulted in voltage fluctuations in the distribution system. This is due to the high R/X ratio in Low Voltage (LV) distribution network that leads to strong coupling between active power and voltage. This paper thus proposes coordinated control of voltage in LV distribution systems by On- Load Tap Changer (OLTC) and Battery Energy Storage Systems (BESS) so as to mitigate the issue of voltage rise/ drop. The objectives are to operate the slow-acting OLTC in the presence of fast-acting BESS and reduce the stress on battery charging/ discharging. This leads to increase in battery life and reduced operation of OLTC, which helps in utility asset optimization in terms of both the OLTC and BESS. In the proposed scheme, OLTC tap operation is based on the weighted average of the bus voltages. The feasibility of the proposed approach is demonstrated on a modified IEEE 13 node distribution system which is simulated in MATLAB/ Simulink. Simulation results verify the proposed coordination voltage control scheme.

Index Terms—Coordinated voltage control, Solar Photo- Voltaics, OLTC, battery energy storage system, load voltage regulation.

I. Introduction

SOLAR PhotoVoltaic (SPV) is one of the fastest growing renewable energy resources which is being integrated into distribution systems worldwide due to its easy installation and cost competitiveness [1]. However, this integration has detrimental impact on system operation [2]. Intermittency in SPV generation leads to deterioration of power quality and reliability of the grid. Among these, voltage fluctuation is one of the most severe problems. This problem emanates due to the high R/X ratio in LV distribution networks, that leads to strong coupling between active power and voltage. To compensate for the voltage variations, traditional distribution systems are usually equipped with On-Load Tap Changers (OLTCs), series voltage regulators and switched capacitor banks [3].

Fast voltage variations due to cloud movement in systems with SPV integration, cannot be effectively compensated by OLTC alone [4]. Various approaches are discussed in the literature to address the critical issue of voltage variation outside the statutory limits of distribution systems due to high SPV penetration. Reactive power control using inverters, although effective from transient response perspective, result in higher currents and losses and thus, necessitating increase in

inverter ratings in LV networks. This is due to the predominant resistive nature of LV distribution systems [5], [6]. Thus, Active Power Curtailment (APC) in LV distribution networks, is another favored approach to address the voltage fluctuation problem [7]. However, the active power output of SPV is curtailed in accordance with the terminal voltage, which restricts SPV from operating at maximum power. This hampers SPV output and therefore, unattractive from operational profits view point. Thus, use of Energy Storage System (ESS) in conjunction with SPV in distribution networks to mitigate the associated generation uncertainty is gaining popularity. It facilitates storage of energy during high SPV generation and light loads, and supplies energy during peak loads, thereby ensuring system voltages to be within limits. With the decreas- ing cost and increase in life-cycle of batteries, use of Battery ESS (BESS) is becoming a viable option. Application of ESS to mitigate voltage variations in LV distribution networks is discussed in [8]. In [9], a regulation strategy for PCC voltage is discussed which leverages operational characteristics of ESS and distributed generations along with OLTC. However, the use of OLTC in [9] is only for backup regulation when ESS is ineffective. In [10], a coordination strategy has been proposed to address voltage rise issue using distributed ESS and voltage regulators. These strategies have been realised in a decentral- ized structure. On the contrary, in [11], a centralized controller has been proposed for battery State Of Charge (SOC) signal coordination with OLTC and Step Voltage Regulators (SVR) to regulate voltage. However, a centralized controller requires fast and reliable communication. Also, it acts as a single point of failure, thus reducing reliability of the system. Thus far, the main challenge is to have a coordination control strategy that leverages the strength of traditional devices like OLTC with BESS, to regulate the PCC voltage of LV distribution system by considering actual SPV and load conditions and different SOC conditions of ESS. This shall increase the operational life of OLTC and relieving stress on battery.

This paper, thus proposes a coordinated control strategy of BESS with conventional OLTC to solve the voltage reg- ulation problem, caused by the high SPV penetration in LV distribution network. Contrary to the use of APC in LV distribution networks, this scheme is based on utilizing the full capacity of SPV by leveraging the characteristics of BESS. The objective of this coordination strategy is to maintain the load bus voltages within allowable voltage range, through complimentary usage of both OLTC and BESS. This relieves

stress on OLTC operation and also improves battery cycle life.

The rest of the paper is organized as follows. Issues relevant to voltage control and proposed voltage control scheme have been discussed in section II. Simulation results are given in section III. Finally, section IV concludes the paper.

II. Voltage Control by OLTC and BESS

Issues related to voltage variation in conventional distribution network are discussed first, followed by the conventional OLTC controller. The proposed coordinated voltage control scheme is then discussed next.

A. Voltage variation in distribution network with SPV

Vast majority of power distribution networks are radial systems. Feeders are connected in tree-like topology rooted at the secondary of the transformer, typically with an OLTC. This implies that power flows downstream from a single source (substation) to the loads. Integration of SPVs creates more sources on the feeder. The imbalance between SPV generation and load may cause power flow along the feeder. Depending on its direction and amount of power flow, voltages along the feeder rise/ drop. Especially, at the end of the feeder, voltage may exceed its limits during peak SPV generation or the peak load period as illustrated in fig. 1. The solid lines show the voltage along the feeder with SPV penetration with voltage at feeder end exceeding the allowable limit. With the integration of BESS, power imbalance between SPV and load can be reduced. The regulated voltages are shown by the dashed lines which are within the limits.
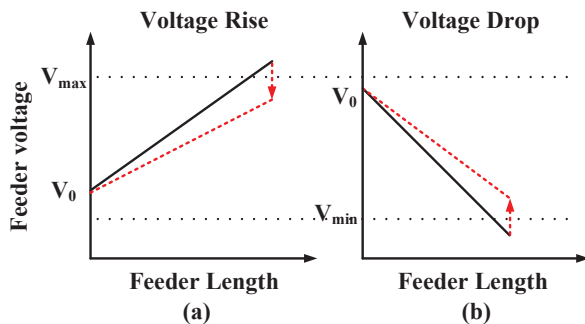

Fig. 1. Voltage profile along radial feeder (a) Peak SPV (b) Peak load

B. Traditional OLTC controller

In general, the voltage control in traditional distribution networks is achieved using OLTC taps, switched capacitors and SVR. The OLTC controls the low voltage secondary by changing its tap position [12]. Traditional line drop compensation [13] is the general control strategy for tap changer regulator. In this method, the secondary voltage signal is fed back to the OLTC along with the transformer secondary current and line impedance, to regulate the secondary voltage based on the voltage drop in the line. With the batteries installed along with PV, any deviation in voltage outside the statutory band, will be regulated by the associated battery. With traditional OLTC controller, the battery regulates the

bus voltage when the OLTC is still in its wait period. As a result, OLTC participates less in voltage regulation, whereas the battery regulates continuously.

C. Proposed Scheme

This section discusses the coordinated control of BESS with OLTC for the mitigation of voltage drop/ rise issue in LV distribution networks with high SPV penetration. The primary objective is to eliminate the redundancy associated with OLTC operation in the presence of fast acting BESS. The tap operation in the proposed scheme is based on the weighted average of the system bus voltages. The weights are computed such that buses with high voltage deviation and low SOC availability are given high priority.

1) OLTC Controller: The proposed scheme for coordinated voltage control using OLTC and BESS is shown in fig. 2. Various steps involved in this scheme are as follows.
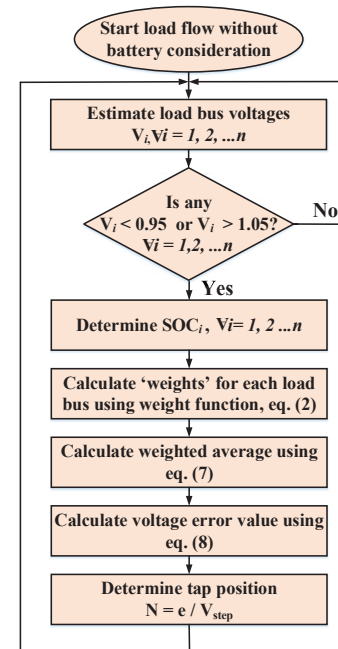

Fig. 2. Flowchart of the proposed scheme

1) Load bus voltages are estimated using Teng's distribution load flow [14]. The voltages obtained, $V_i, \forall i = 1, \ldots, n$ are the voltages of the n node system without considering the presence of BESS.
2) Using the voltages obtained in step 1, state (within or outside the allowable voltage limit) of the bus voltages are determined. According to IEEE Std $1547.2 - 2008$, maximum permissible deviation from nominal system voltage at PCC is 5%. Hence,

$$V_{lb} \le V_{pcc} \le V_{ub} \qquad (1)$$

where, $V_{lb} = 0.95pu$ and $V_{ub} = 1.05pu$.

3) If none of the estimated voltages are outside the threshold limits, then go to step 1 again, else collect SOC information from all the batteries connected at the buses.

4) Weight w_i is calculated using (2). Weight is assigned to each bus to indicate the priority of regulation associated with it. The higher is the voltage violation, and lesser is the available SOC capacity for regulating the bus voltage, the higher is the weight assigned.

$$w_i = (\Delta V_i)^2 + (\Delta SOC_i)^2 + k_1 \qquad (2)$$

where, $k_1 = 1$ for utility defined critical bus or $k_1 = 0$, otherwise. ΔV_i is the normalised pu i^{th} bus voltage deviation from the nominal/ reference voltage value, given as

$$\Delta V_i = \frac{V_{ref}(pu) - V_i(pu)}{V_{limit}} \qquad (3)$$

where, maximum allowable $V_{limit} = 0.05pu$ as per standard. ΔSOC_i is the normalised pu i^{th} node battery SOC deviation from the desired SOC value, given as

$$\Delta SOC_i = \left[\frac{1 + sgn(\Delta V_i)}{2}\right] \Delta SOC_{charge}$$
$$+ \left[\frac{1 - sgn(\Delta V_i)}{2}\right] \Delta SOC_{discharge} \qquad (4)$$

where, $sgn(\Delta V_i) = 1$ if $\Delta V_i < 0$. If $\Delta V_i = 0$, then $sgn(\Delta V_i) = 0$. If $\Delta V_i > 0$, then $sgn(\Delta V_i) = -1$. In order to extend the battery cycle life, battery's depth of discharge is limited to 30% in the proposed SOC control [15]. The operating range for battery is SOC_{min} to SOC_{max} and hence,

$$\Delta SOC_{charge} = SOC_{max}(pu) - SOC_{available}(pu) \qquad (5)$$

$$\Delta SOC_{discharge} = SOC_{available}(pu) - SOC_{min}(pu) \qquad (6)$$

5) The weights obtained from step 4 are used to calculate the weighted voltage average of the load buses as follows

$$V_{wt.avg}(pu) = \frac{\sum_{i=1}^{n} w_i V_i}{\sum_{i=1}^{n} w_i} \qquad (7)$$

where, w_i and V_i are the assigned weight and estimated voltage without battery at i^{th} bus, respectively.

6) The voltage error function is determined by calculating the deviation of weighted voltage average $V_{wt.avg}$ from the nominal PCC bus voltage $V_{pcc(nom)}$. The error function e is given as

$$e = V_{pcc(nom)}(pu) - V_{wt.avg}(pu) \qquad (8)$$

7) The voltage error function is used to calculate the desired tap position as

$$e = N * V_{step} \qquad (9)$$

where, N is the desired tap position and V_{step} is the voltage improvement in each tap step of OLTC.

The basic OLTC controller of the proposed scheme is shown in fig. 3. The OLTC tap operations lead to reduction in battery stress at certain buses depending power the weights obtained from the weight function. For buses unregulated by OLTC operation, the voltage regulation is addressed by BESS. The BESS controller is discussed next.
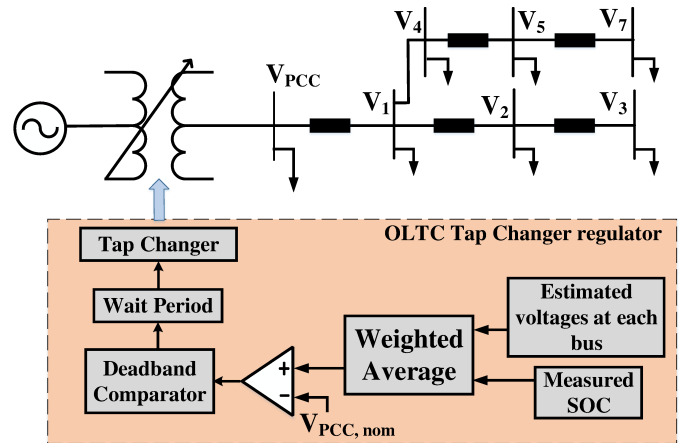

Fig. 3. Basic OLTC operation in proposed scheme

2) Battery Controller: Localized controllers control each of the BESSs. The controller limits the battery SOC between its operational range ($50\% - 80\%$ considered here) to maximize the battery life and cuts the battery off in the respective direction when it hits any of the SOC limits. Further, if the bus voltage is outside the regulation band, the battery charges or discharges to maintain the voltage within the regulation band. This indirect control strategy generally leads to the battery storing the excess energy when SPV output is more than load resulting in rise in bus voltage and vice versa when load is more than SPV output. The charging/ discharging power is limited by the battery and its converter's thermal limits. The control block diagram is shown in fig. 4. When voltage exceeds the limits, the bus reference voltage is selected just inside the respective limit through a reference selector. The bus voltage is then regulated by feeding/ drawing power through the battery at the bus, the value of which is determined by a proportional integral controller that takes the voltage error as input.
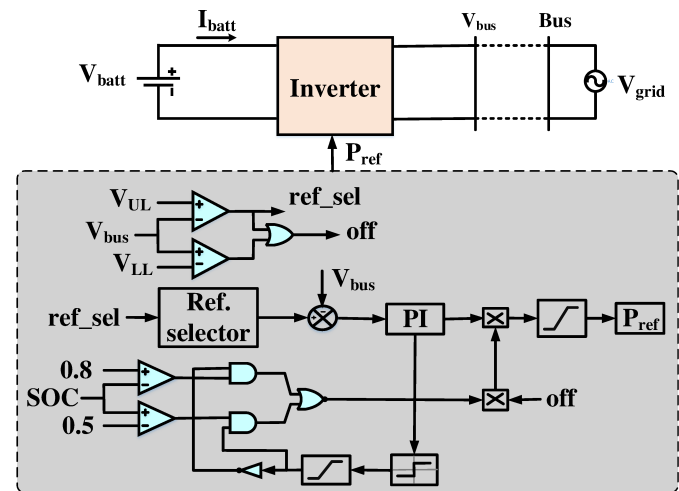

Fig. 4. Control logic for battery controller

III. SIMULATION RESULTS

A. Test System

The proposed scheme has been tested on the modified IEEE 13 node distribution system [16] as shown in fig. 5. The

model includes OLTC at the substation for voltage regulation. The traditional OLTC controller regulates the PCC voltage by comparing the nominal bus voltage with the average of the load end bus voltages. The distribution system model is simulated in MATLAB/ Simulink. OLTC parameters are given in table I. The spot load data is given in table II. The battery specifications are given in table III. The feeder end load buses have SPV and BESS connected to them with capacities relative to that of loads on the same bus. The feeder R/X ratio is 3.
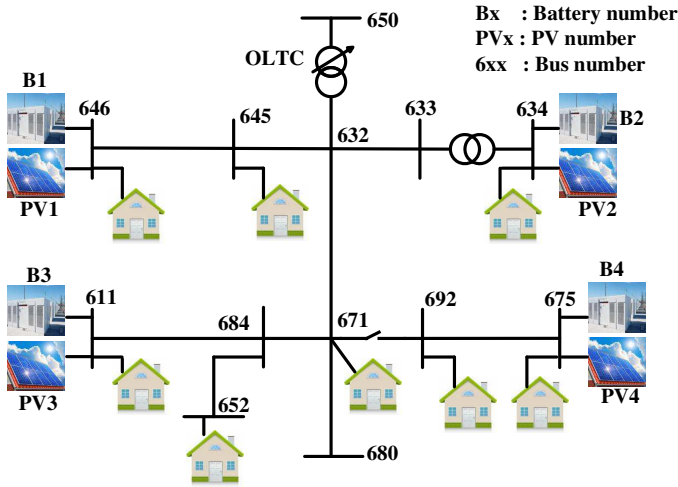

Fig. 5. Modified IEEE 13 node distribution system

TABLE I
OLTC PARAMETERS

Power rating	$5MVA$
Voltage rating	$115/4.16kV$
Number of Taps	16 (±8)
Deadband	1 ± 0.05
Step Voltage	1.5% of V_{rated}
Wait period	$1s$
Tap selection time	$8s$
Tap transition time	$60ms$

TABLE II
SPOT LOAD DATA FOR IEEE 13 NODE SYSTEM

Bus	Phase a		Phase b		Phase c	
	kW	$kVAr$	kW	$kVAr$	kW	$kVAr$
634	160	110	160	110	160	110
645	0	0	170	125	0	0
646	0	0	230	132	0	0
652	128	86	0	0	0	0
671	385	220	385	220	385	220
675	290	212	290	212	290	212
692	0	0	0	0	170	151
611	0	0	0	0	170	80

TABLE III
BATTERY SPECIFICATIONS

Bus No.	Energy Rating		Power Rating (kW)
	Actual (kAh)	Scaled (Ah)	
634	15.67	13.06	200
646	14.02	11.06	200
675	17.32	14.43	200
611	14.85	12.37	720

B. Baseline Scenario

Fig. 6 shows the load profiles [17] considered for all the load buses. Fig. 7 shows the SPV power profile for the considered 4 panels. Solar data is taken from Solar Energy Research Enclave at IIT Kanpur, India ($26°30'18.0547''N$, $80°13'30.7196''E$). For the sake of demonstration of the proposed scheme and simulation on MATLAB/ Simulink, actual 1 hour real time data has been scaled to $3s$ of simulation time and hence, timescale of fig. 6 and fig. 7 are $0-45s$. All the data including SPV power profile, load profile, battery response and OLTC operating times have been scaled down in accordance with the considered scale.
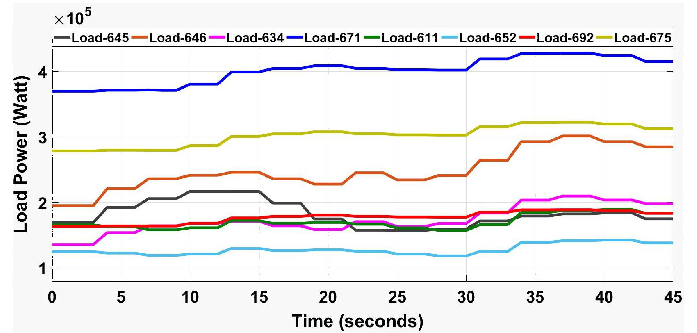

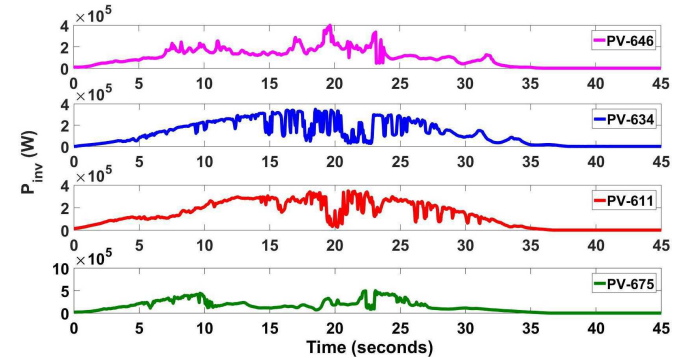Fig. 6. Actual load profile from 6 AM to 9 PM, scaled to (1hr = 3s) for simulation purpose.

Fig. 7. Actual SPV power profile from 6 AM to 9 PM, scaled to (1hr = 3s) for simulation purpose.

C. Results and Discussion

SPV sources are connected as shown in fig. 5. OLTC regulates the PCC voltage. Battery locally operates to regulate the respective load bus. Transients due to OLTC and battery operations are neglected. Voltage regulation by the traditional (UC: uncoordinated) method and proposed (C: coordinated) scheme are compared at different system loads and SPV penetrations. The maximum and minimum bus voltages reached during the day with the proposed and traditional schemes are given in table IV. It can be observed that with the proposed scheme, most of the bus voltages are within the specified band, except for bus 633, phase a voltage of bus 652 and phase c voltage of bus 675, which are just outside the permissible limit. On the contrary, with the traditional method, significant voltage violation is observed at most of the buses. This is primarily due to high SPV fluctuations and high R/X ratio of

TABLE IV
BUS VOLTAGES WITH AND WITHOUT PROPOSED SCHEME

Bus	C/UC	V_{amx}	V_{amn}	V_{bmx}	V_{bmn}	V_{cmx}	V_{cmn}
645	C	-	-	1.05	1.034	-	-
	UC	-	-	1.031	0.971	-	-
646	C	-	-	1.048	1.026	-	-
	UC	-	-	1.059	0.953	-	-
633	C	**1.069**	1.057	**1.069**	1.057	**1.069**	1.057
	UC	**1.2**	0.98	**1.3**	0.981	1.041	0.98
634	C	1.043	1.038	1.043	1.038	1.043	1.038
	UC	1.01	**0.906**	**1.165**	**0.907**	1.007	**0.906**
671	C	0.988	0.972	1.009	0.991	0.975	0.961
	UC	0.957	**0.902**	0.968	**0.926**	0.952	**0.87**
684	C	0.981	0.964	-	-	0.979	0.958
	UC	0.952	**0.9**	-	-	0.956	**0.86**
611	C	-	-	-	-	0.983	0.952
	UC	-	-	-	-	0.973	**0.86**
652	C	0.963	**0.948**	-	-	-	-
	UC	**0.94**	**0.9**	-	-	-	-
692	C	0.988	0.97	1.009	0.99	0.975	0.961
	UC	0.957	**0.902**	0.969	**0.926**	0.952	**0.871**
675	C	0.985	0.96	1.005	0.98	0.969	**0.949**
	UC	0.965	**0.885**	0.974	**0.91**	0.957	**0.854**
680	C	0.988	0.97	1.009	0.991	0.975	0.961
	UC	0.958	**0.902**	0.974	**0.927**	0.952	**0.872**

feeder lines which leads to significant voltage drops. Voltage profiles for two feeder end buses are shown in fig. 8 - fig. 11.

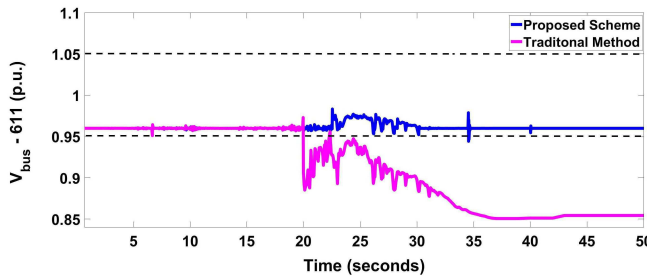It is to be noted that bus 611 has a SPV source and a BESS

Fig. 8. Bus 611 voltage profile from 6 AM to 9 PM, scaled to (1hr = 3s) for simulation purpose.
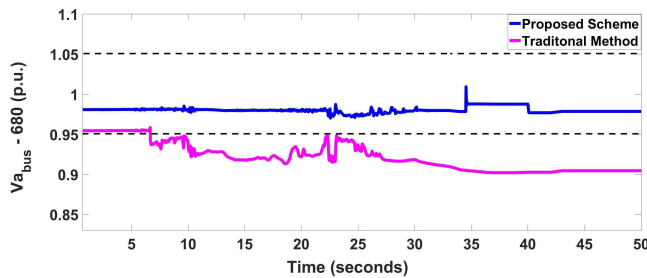

Fig. 9. Bus 680 phase a voltage profile from 6 AM to 9 PM, scaled to (1hr = 3s) for simulation purpose.

installed along with its load while bus 680 does not have SPV source or BESS. It can be seen from fig. 8 - fig. 11 that there is significant improvement in voltage profiles by the proposed scheme. This quantifies the voltage regulation efficiency of proposed scheme compared to traditional scheme.

Also, with the traditional method, OLTC operates only once during the period of study, thus indicating that majority of voltage regulation is done by BESS which may be uneconomical. With the proposed scheme, the number of OLTC
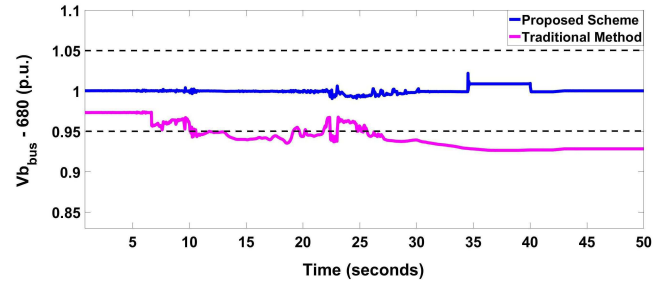

Fig. 10. Bus 680 phase b voltage profile from 6 AM to 9 PM, scaled to (1hr = 3s) for simulation purpose.
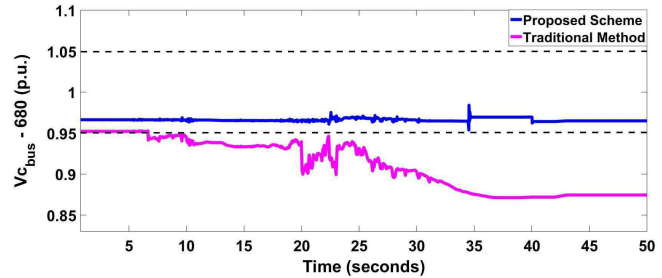

Fig. 11. Bus 680 phase c voltage profile from 6 AM to 9 PM, scaled to (1hr = 3s) for simulation purpose.

tap operations has increased (5 instead of 1), thus leading to better coordinated voltage regulation. Also, the number of tap operations with the proposed scheme is within the maximum allowable tap operations (typically $6 - 7$) [18].

To quantify and compare the BESS utilization in each of the methods, time integral of absolute value of battery current is chosen as the performance metric. This choice is justified since battery utilization, and conversely its degradation is due to the chemical reactions in the battery which is proportional to the battery charge/ discharge current. Results in fig. 12 show that Ah (scaled) of the batteries on buses 646 and 611 has reduced using the proposed method. On the other hand, bus 675 shows an appreciable rise in battery utilization. In the uncoordinated case, the batteries deplete early in the day. This observation is explained from the fact that, in the proposed method, since the OLTC tap change brings the voltages close to the regulation band, the batteries operate at lower power levels to further regulate the bus. In fig. 9, it is observed that there is a sudden fall in the bus voltage at about 20s. It is because the battery hits its lower SOC limit and is thus, cut off by the controller. On the other hand, using the proposed scheme, the battery operates through most of period of study to keep the voltage within band.

IV. CONCLUSION

In this paper, a new coordinated voltage control scheme in LV distribution network with high SPV penetration by OLTC and BESS, is proposed. The simulation results verify the advantages of the proposed scheme which are as follows:

1) It ensures voltage regulation at most of the remote end buses. Thus, feeder voltage diversity which is a major issue in LV distribution systems, is addressed in this methodology.
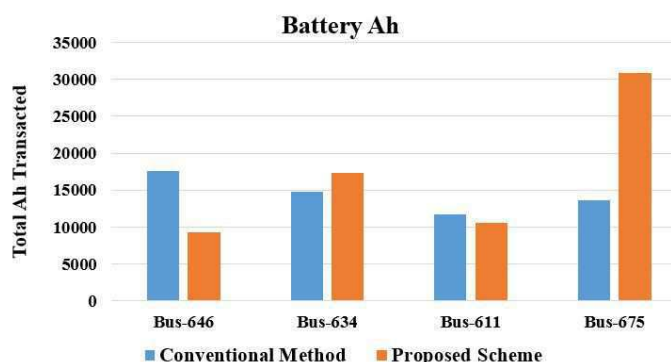
Fig. 12. Battery SOC

2) With coordinated control between OLTC and BESS, stress on the battery charging/ discharging is minimized.

3) Unlike in traditional BESS based voltage control method where the presence of OLTC is redundant, in the proposed scheme, the BESS and OLTC operate complimentarily to regulate the bus voltages.

The use of estimated bus voltages and battery SOC to calculate weights ensure OLTC contribution in voltage regulation process. This leads to utility asset optimization in terms of both OLTC and battery. Rigorous optimization for the determination of weight function, explicit imposition of maximum allowable switching operations of OLTC and extending the proposed coordination scheme to include operation of switchable capacitors, SVR, etc. shall be the scope of future work.

REFERENCES

[1] F. Katiraei and J. R. Aguero, "Solar pv integration challenges," *IEEE Power Energy Mag.*, vol. 9, no. 3, pp. 62–71, May 2011.

[2] C. L. Maters, "Voltage rise: the big issue when connecting embedded generation to long $11kv$ overhead lines," *Power Eng.*, vol. 16, no. 1, pp. 5–12, Feb. 2002.

[3] A. Das, A. Gupta, S. R. Choudhury, and S. Anand, "Adaptive reactive power injection by solar pv inverter to minimize tap changes and line losses," in *National Power Systems Conference (NPSC), Bhubaneswar*, 2016, pp. 1–6.

[4] C. Dai and Y. Baghzouz, "Impact of distributed generation on voltage regulation by ltc transformer," in $11th$ *International Conference on Harmonics and Quality of Power, Lake Placid, NY, USA*, 2004, pp. 770–773.

[5] X. Su, M. A. S. Masoum, and P. Wolfs, "Comprehensive optimal photovoltaic inverter control strategy in unbalanced three-phase four-wire low voltage distribution networks," *IET Gener. Transm. Distrib.*, vol. 8, no. 11, pp. 1848–1859, 2014.

[6] J. M. Guerrero, J. Matas, L. Garcia de Vicuna, M. Castilla, and J. Miret, "Decentralized control for parallel operation of distributed generation inverters using resistive output impedance," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 994–1004, Apr. 2007.

[7] S. Ghosh, S. Rahman, and M. Pipattanasomporn, "Distribution voltage regulation through active power curtailment with pv inverters and solar generation forecasts," *IEEE Trans. Sustain. Energy*, vol. 8, no. 1, pp. 13–22, Jan. 2017.

[8] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "Mitigation of rooftop solar pv impacts and evening peak support by managing available capacity of distributed energy storage systems," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 3874–3884, Nov. 2013.

[9] C. Zhang and X. Chu, "Voltage regulation strategy for active distribution network coordinating dgs, ess units and oltc," in *IEEE Power and Energy Society General Meeting, Chicago, IL, USA*, 2017, pp. 1–5.

[10] M. N. Kabir, Y. Mishra, G. Ledwich, Z. Y. Dong, and K. P. Wong, "Coordinated control of grid-connected photovoltaic reactive power and battery energy storage systems to improve the voltage profile of a residential distribution feeder," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 967–977, May 2014.

[11] X. Liu, A. Aichhorn, L. Liu, and H. Li, "Coordinated control of distributed energy storage system with tap changer transformers for voltage rise mitigation under high photovoltaic penetration," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 897–906, Jun. 2012.

[12] Y. Liu, J. Bebic, B. Kroposki, J. de Bedout, and W. Ren, "Distribution system voltage performance analysis for high-penetration pv," in *IEEE Energy 2030 Conference, Atlanta, GA, USA*, 2008, pp. 1–8.

[13] C. Gao and M. A. Redfern, "A review of voltage control techniques of networks with distributed generations using on-load tap changer transformers," in $45th$ *International Universities Power Engineering Conference, Cardiff, Wales*, 2010, pp. 1–6.

[14] J.-H. Teng, "A direct approach for distribution system load flow solutions," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 882–887, Jul. 2003.

[15] [Online]. Available: http://www.sce.com/AboutSCE/Regulatory/load-profiles/loadprofiles.htm

[16] IEEE Resources - PES test feeders. [Online]. Available: http://sites.ieee.org/pes-testfeeders/resources/

[17] [Online]. Available: https://www.nationalgridus.com/Upstate-NY-Business/Supply-Costs/Load-Profiles

[18] A. Mohapatra, P. R. Bijwe, and B. K. Panigrahi, "An efficient hybrid approach for volt/var control in distribution systems," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1780–1788, Aug. 2014.