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IMPROVEMENT OF DISTRIBUTION LOAD AND GENERATION CAPACITY FOR EFFECTIVE OPERATION OF DISTRIBUTED STORAGE SYSTEM

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ABSTRACT:

This paper proposes Battery energy storage system (BESS) is increasingly becoming popular as a solution that facilitates seamless integration of DGs. Capacity support, congestion management, transmission and distribution loss reduction, voltage regulation, deferral of upgrade investments, reduction of peak demand charges, and improved power quality are some benefits of combining BESSs with high penetrations of PV. At present, cost of batteries is the main barrier preventing their adoption. optimization strategy that considers two primary factors: 1) distribution system cost; and 2) battery cycling cost. Quantitative analyses on the benefits and trade of BESS installations are carried out considering different service options. BESS is investigated for three main service options: 1) voltage regulation; 2) loss reduction; and 3) peak reduction. The approach is developed using MATLAB interior-point algorithm. Simulations are conducted for the medium voltage (MV) IEEE 33 bus system and a low voltage (LV) distribution network in Western Australia studied during the Perth Solar City Trial.

INTRODUCTION

Renewable generation affects power quality due to its nonlinearity, since so largene ration plants and wind power generators must be connected to the grid through high-power static PWM converters. The non uniform nature of power generation directly affects voltage regulation and creates voltage distortion in power systems. This new scenario in power distribution systems will require more sophisticated compensation techniques. In order to address these concerns, several policies and subsidies have been established globally to support the deployment of non hydro renewable distributed generation (DG), particularly wind and photovoltaic (PV). These measures along with the recent technology advancements have attracted investments in both private and government sectors to help with transforming the typically monopolistic market. The primary objective of papers are peak shaving. The rule-based or real-time strategies do not consider daily cycling of the battery. Therefore, the proposed strategies cannot optimize the battery techno-economic performance. In addition, do not discuss the problem of optimal placement and sizing. This is a crucial problem, as the benefits of BESS strictly depend on the location and sizing. BESS management strategy optimizes the day-ahead operation of the battery storage by controlling the battery external parameters including charge/discharge rates, depth of discharge (DOD), and daily cycling. Day-ahead scheduling determines the extent to which source (grid or BESS) operates at any given time interval, amount of power exchange, direction of power flow, and the mode of operation at the point of common coupling. Optimized battery operation patterns are then utilized to evaluate the

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optimal BESS capacity requirements. Optimal installation sites are chosen as the buses at which the cost function is at minimum. This paper also provides a review on usage of storage for the exclusive and simultaneous control of voltage regulation, peak demand, and loss reduction. This paper proposes a strategy for optimal integration of distribution network operator (DNO)-owned BESSs to improve the load and DG hosting ability of the grid. This paper addresses the issues of optimal management and sizing of a community scale BESS for distribution systems with high penetrations of DG. A quantitative analysis on the impact of installation site on the purpose of installation, dispatch management scheme, and size of BESS is also carried out. So far, implementations of predictive control in power converters have been used mainly in induction motor drives. In the case of motor drive applications, predictive control represents a very intuitive control scheme that handles multivariable characteristics, simplifies the treatment of dead-time compensations, and permits pulse-width modulator replacement. However, these kinds of applications present disadvantages related to oscillations and instability created from unknown load parameters.

A.BATTERY STORAGE SYSTEM

However, the cost of battery storage is steadily reducing with the recent advances in battery technologies and competitive manufacturing in the vehicle market. suggests that with current falling PV prices, “grid parity” against retail electricity prices could be achieved if battery storage prices drop to 20 cents per kWh.

Fig. 1(a) demonstrates the capacity and impedance as a function of cycling for a 12V A123 ALM 12V7 Lithium-ion (Li-ion) battery rated at 4.6 Ah/10 A. From Fig. 1(a), at the 1C/1C rate and 100% DOD, the battery delivers more than 7000 cycles with an excellent energy preservation capability.

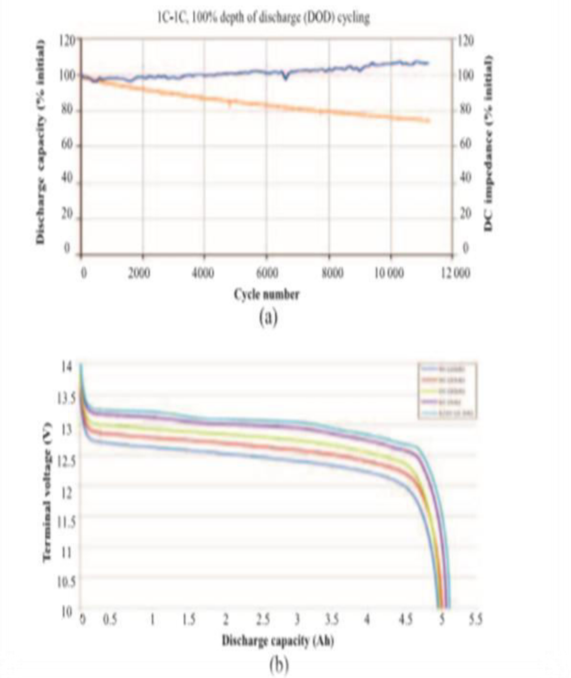

Fig. 1. (a) Capacity and impedance as a function of cycling at room temperature. (b) Terminal voltage against discharge capacity at various discharging rates and 40 ◦C

Fig. 1(a) demonstrates the capacity and impedance as a function of cycling for a 12V A123 ALM 12V7 Lithium-ion (Li-ion) battery rated at 4.6 Ah/10 A [22]. From Fig. 1(a), at the 1C/1C rate and 100% DOD, the battery delivers more than 7000 cycles with an excellent energy preservation capability. Fig. 1(a) shows that the internal cell impedance is a function of cycle life. The terminal voltage characteristics against the discharging capacity at various discharge rates are illustrated in Fig. 1(b). Battery voltage is almost flat in the region between 0% and 90% discharge capacity and rapidly drops over 90% discharge capacity. Thus, it is advisable to operate Li-ion batteries within this region. The EB−act (1)–(2) encompasses a linear and a nonlinear term. Linear component (EB) can be derived using the daily cyclic behavior. Nonlinear component reflects the effect of daily cycling and operating temperature on the battery internal parameters. Hence, typically the nonlinear component cannot be measured directly and may require mathematical estimation models like that derived in papers both linear and nonlinear elements strongly depend on the daily cycling. Thus, given that battery is operated within the nominal temperature range, the cycling primarily contributes to the capacity degradation. Therefore, with increased charge/discharge cycles, cycle age of the battery decreases. The proposed battery control strategy for feeder quality management effectively minimizes daily cycling through optimal charge/discharge and DOD management. Therefore, the life expectancy of BESS is extended by avoiding wear and tear due to unnecessary cycling. Extended cycle life translates to lower ownership costs improving the performance and value.

B. Modification of BESS

The BESS dispatch optimization problems rely on the repeated evaluation of a solution vector of battery power or energy. The length of the vector depends on the sampling interval. The solution could be a sequential list of the energy values (CiT) during the day .A vector of length (m) 24, could list the EB at 1-h, 30-min, or 15-min intervals. This vector should be subject to the following. 1) A daily energy balance constraint. This a voids over charging or discharging at the end of a cycle and correctly sets the battery for flexible operation on the following day. 2) Charging and discharging power constraints. Only limited differences can exist between any two adjacent charge states. 3) A solution vector presented as a list of power is resistant to efforts to compactly represent the solution. Power can be a discontinuous function and the daily charging power frequency spectrum has increased higher frequency components relative to the energy spectrum. Each constraint vector could be of the same dimension; thus, add extra burden on the optimization. Objective Function The cost function in is constructed to minimize distribution system costs (Csystem) in terms of costs incurred due to system losses (CLoss), peak demand (CP), and voltage regulation (CVR). Planning problem should contain the investment and operating costs of battery to optimize benefit tradeoffs. Hence, a cost factor that represents BESS capital and O&M expenditures (Cbattery) in a form of a daily cost is included in the objective function:

where $C_{\text{system}} = \gamma_2 C_{\text{Loss}} + \gamma_3 C_{\text{VR}} + \gamma_4 C_P$

$$C_{\text{Loss}} = \int_{t=1}^{T} \int_{k=1}^{n-1} |\{V_j^2(t) + V_i^2(t) - 2V_i(t)V_j(t) \times \cos(\delta_i(t) - \delta_j(t))\}|.G_{ij}.\Delta t.r_{\text{loss}}(t).dt$$

$$C_{\text{VR}} = \int_{t=1}^{T} \int_{i=1}^{n} |V_i(t)|^2 - V_{\text{ref}}^2|^{1/2}.\Delta t.r_{\text{VR}}(t)dt$$

$$C_P = P_{\max}.\Delta t.r_p$$

$$C_{\text{battery}} = \frac{\text{Cycles}}{\text{CycleLife}}.\text{BUC.BatterySize.}$$

$$\gamma_l = w_l / J_l.$$

4 l=1 wl =1, equally weighted), and Jl is the minimum of flow, respectively.

The following points are highlighted on the proposed BESS management strategy. 1) The primary inputs to the optimization problem are network characteristics, time-variant load and generation forecasts at 15-min interval, and an initial vector of the control variable, Fourier coefficient vector (CiF). The secondary inputs include battery and network constraints and the cost coefficients (rloss, rVR, rp, and BUC).

2) The direct output is the optimized Fourier coefficient vector, while BESS charge/discharge schedule, BESS energy profile, power flow coordination, and optimal BESS size can be derived using the optimized CiF. The optimization problem is a nonlinear constrained problem that is solved using MATLAB interior-point algorithm.

3) The rloss is the electricity price taken for Western Australia. This cost comprises four main components: 1) retail; 2) wholesale energy; 3) transmission; and 4) distribution costs. Out of this, wholesale energy and distribution costs are the major drivers representing more than 70% of the aggregated electricity price. The electricity price also reflects the costs of upgrades, O&M, and reinforcements driven by voltage and thermal limit violations as well as recovery costs of incentive schemes and carbon costs .

4) The factor rp is the peak demand charge assumed at $200/kWh/year. This is typically made up of peak support, demand supply capital, maintenance, and infrastructure development costs [29]. 5) Rate of voltage violations due to peak generation and load is represented by rVR =14.2c/kWh. This rate reflects the network charges and is about 50% of the end user electricity.The CVR encourages voltages to the nominal Vref. Most utility providers prefer near unity voltage

6) Cost function will not consider the transmission costs for two main reasons:

1) the transmission cost component is generally a small fraction of the aggregated electricity price seen by consumers; and

2) existing transmission lines have been developed with the aim of transporting electricity produced by centralized large scale generators. Improving the DG hosting ability of the low voltage (LV) grid through optimal integration of BESS reduces the power that needs to come from centralized sources. Hence, minimization of LV distribution cost will coincidentally reduce transmission and carbon emission costs.

C. Providing the Jacobian of Cost Function and Constraints

The nonlinear optimization problem is solved using the interior point (IP) method. The standard IP method is computationally very expensive and the computational burden increases with the size of the problem and network topology.

This is because it uses finite-difference method to determine the gradients of the cost function and constraints to evaluate Lagrangian and first-order optimality equations. Instead, in this paper, analytical gradient (Jacobian) of the cost function and constraints are provided to improve the optimization efficiency. Jacobians are found with respect to Fourier co efficients as shown in; dVi dPi is found from the inverse power flow Jacobian.

Analytical gradient also improves the numerical conditioning of the iterative process.

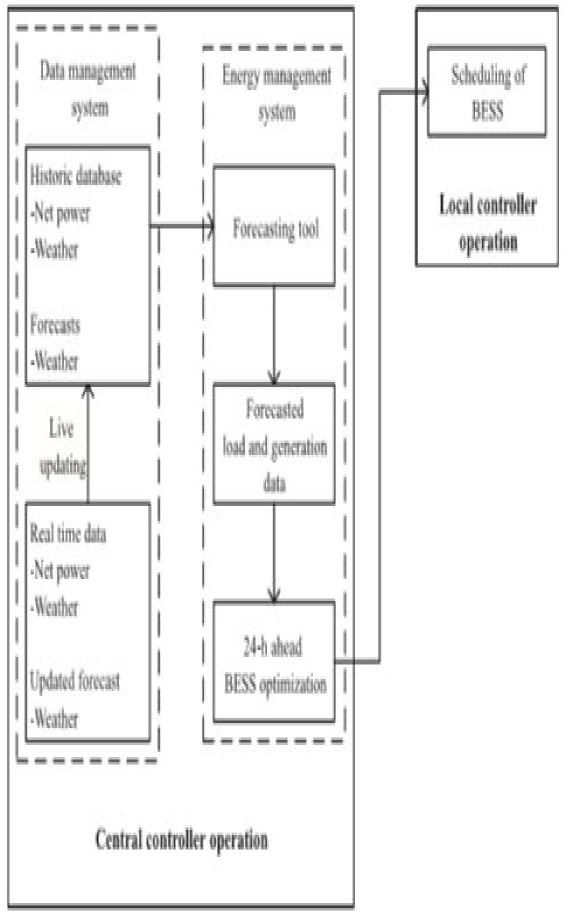

Fig. 2. Proposed system architecture

This paper proposes a receding horizon hierarchical control approach for BESS

management. The structure of the system is presented in Fig. 2. Central controller performs the proposed predictive optimization to identify the optimal parameters of BESS. It is composed of two systems: 1) data management system (DMS); and 2) an energy management system (EMS). DMS establishes a bidirectional communication link with the network for online data acquisition. By centralizing the information and controls, the DMS is able to consistently monitor the performance and provide safety oversights. Collected data are then fed to EMS. The EMS first carries out the forecasting of the load and generation data 24 h into the future. The BESS management system (BMS) uses the forecasted load data to solve the optimal power flow management problem. BMS returns the optimized CiF. Optimal Fourier coefficient vector determine the dispatch schedule of the BESS in terms of charging/discharging response and energy. The EMS then sends the optimized battery set-points for day-ahead scheduling of the BESS to the local controller in the power electronic interface. The control algorithm can be reapplied several times each day to allow the battery energy profile to be progressively updated, as new information and trends emerge in the operating distribution network. The new predicted battery charge profile EB−new (φ) is then used to update the previously optimized energy profile EB−old (φ) for the current updating times tep(φ). Updating could be performed using an exponential smoothing technique:

D.Test systems

The proposed approach is tested on a medium voltage (MV) and an LV distribution system. The voltage dependency of the loads is modeled using polynomial equations:

$$P_{L-i} = P_{0i}\left(a_p + b_p\,|V_i| + c_p|V_i|^2\right) \qquad (26)$$

$$Q_{L-i} = Q_{0i}\left(a_q + b_q\,|V_i| + c_q|V_i|^2\right) \qquad (27)$$

where Q_{L-i} is the reactive power load, $a_p + b_p + c_p = 1$, and $a_q + b_q + c_q = 1$.

In this paper, load flow calculations are performed using the total current injection method (TCIM) in [31] and [32] and bus 1 is considered as the slack bus with a voltage of 1 p.u.

A. MV Test System—Case 1

In Case 1, the proposed approach is tested on the hypothetical IEEE 33-bus distribution system of Fig. 3. Complete system data can be found in [33]. The substation voltage of the test system is 12.66 kV and the base is chosen as 10 MVA.

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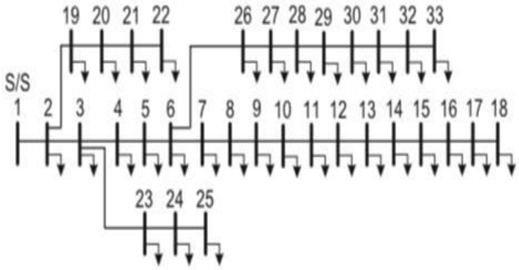

Fig. 3. Single-line diagram of IEEE 33 bus distribution system.

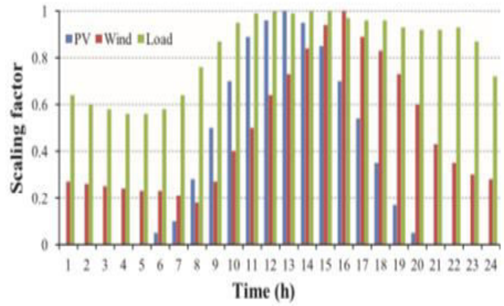

Fig. 4. Scaling factors of time-variant load and generation.

Two wind-based DGs and seven PV DGs were allocated to simulate a high DG penetration scenario. PV DGs could represent aggregated generation seen at the installed bus. Two wind DGs of 1 MW are sited at buses 18 and 24. Three 400-kVA PV DGs are installed at buses 5, 21, and 31 and four 500-kVA PV DGs are installed at buses 8, 12, 28, and 33. It was assumed that the loads follow the IEEE-RTS model as illustrated in Fig. and the load composition was set to ap = aq =0 .4, bp = bq =0 .3, and cp = cq =0 .3. Peak active and reactive load power of the system with the above load composition are 3.556 MW and 2.191 MVar, respectively. The output generation from wind and PV DGs are expected to follow the curves in Fig.

E. RESULTS AND DISCUSSION

The optimization determines the battery optimal charge/discharge strategy and the size which in turn coordinates the power flows at the interconnection point. Simulations were conducted for the optimization of 1) voltage regulation [fVR defined in (23)]; 2) loss reduction [floss defined in (24)]; 3) peak reduction [fp defined in (25)]; and 4) multiple services

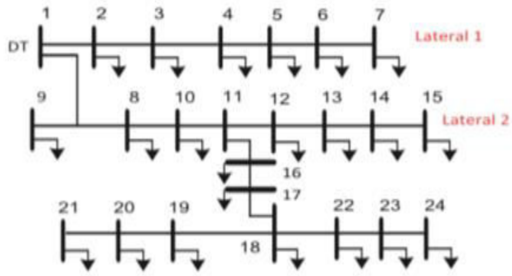

Fig. 5. LV test model.

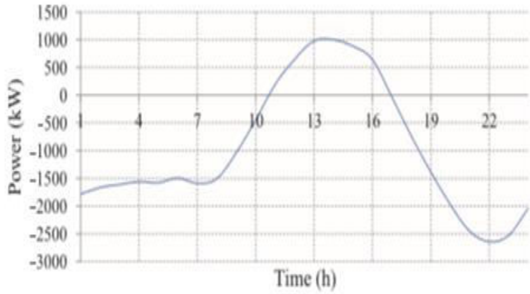

Fig. 6. Distribution transformer loading with no BESS.

simultaneously. The installation site is determined as the bus at which the cost function is minimal. A quantitative analysis on the effect of installation site on the optimal battery parameters and grid services to be provided is carried out in this section.

A. Test Case 1—MV Distribution System

1) Base Operation With No BESS: graphically illustrate the net distribution transformer load (without losses) and the voltage profile, respectively, without BESS. The system clearly experiences reverse power flow and overvoltage issues that are recognized as the major limiting factors for the widespread uptake of renewable DG. The peak export power is 1.002 MW and the

maximum voltage is 1.028 p.u. at bus 18. The total load energy demand is 71.2005 MWh

TABLE I
SUMMARY OF RESULTS FOR TEST CASE 1

Cost func.	Site (bus no.)	Voltage (p.u.) Min (bus#)	Voltage (p.u.) Max (bus#)	E_{loss} MWh	P_{max} MW	Battery Size (MWh)	Battery Life (years)
Base		0.934 (33)	1.028 (18)	1.79	2.642		
f_{VR}	26	0.960 (30,32, 33)	1.006 (18)	1.57	1.323	14.42	10.52
f_P	24	0.940 (33)	1.023 (18)	1.94	1.068	14.88	10.53
f_{loss}	12	0.943 (33)	1.000 (1)	1.49	1.997	7.27	10.53
f in (14)	27	0.956 (33)	1.007 (18)	1.57	1.091	14.75	10.52

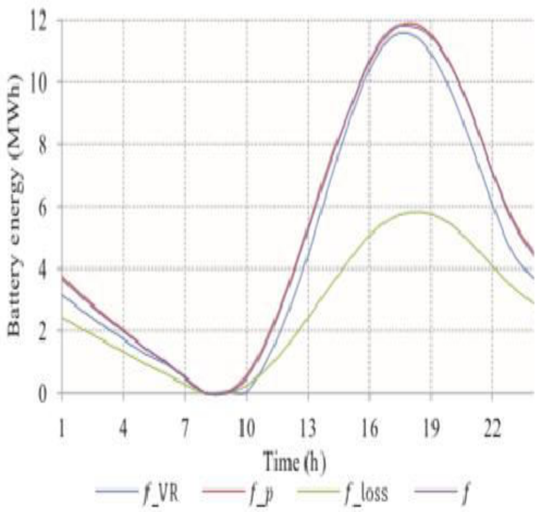

Fig. 8. Battery energy profiles for the various service options.

From Table I, bus 26 is the optimal BESS site for maximum voltage regulation. As shown in Fig. 8, battery discharges from 1:00 A.M. to 8:00A.M. and then operates at a very slow rate until 10:00 A.M. This improves the morning voltage profile. During peak generation, the BESS drops the voltage at bus 26 to allow reverse power flow to the BESS. Thus, BESS captures peak DG production effectively and delivers it during peak demand to enhance the voltages. The maximum and minimum voltages from fVR optimization are 0.960 and 1.006 p.u., respectively. The peak is reduced to 1.323

MW and energy losses are reduced by 12.22%.

The maximum peak reduction is achieved at bus 24 when controlling peak exclusively (fP). From Fig. 9, both peak import and export powers are reduced considerably. The peak is reduced by 59.60% compared to the base case. At bus 24, the charge/discharge of the battery not only achieve peak shaving but also assist load leveling as depicted in Fig. During peak PV generation, the battery starts charging and reduces the voltage at bus 24 to allow reverse power flow . During peak demand, the discharge of battery raises the voltage at bus from 6:00 P.M. until midnight while supporting the load.

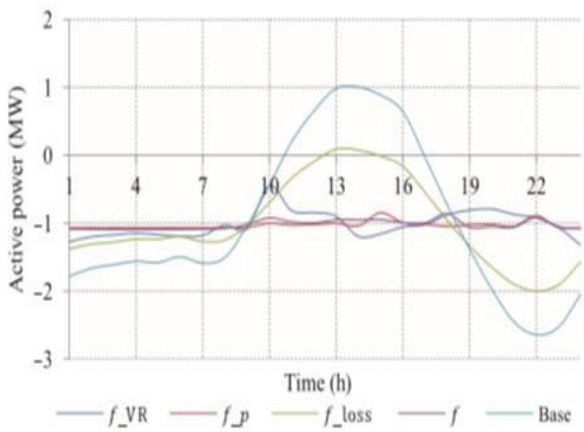

Fig. 9. Distribution transformer loading for various service options.

The maximum peak reduction is achieved at bus 24 when controlling peak exclusively (fP). From Fig. 9, both peak import and export powers are reduced considerably. The peak is reduced by 59.60% compared to the base case. At bus 24, the charge/discharge of the battery not only achieve peak shaving but also assist load leveling as depicted in Fig. 9. During peak PV generation, the battery starts

charging and reduces the voltage at bus 24 to allow reverse power flow. During peak demand, the discharge of battery raises the voltage at bus from 6:00 P.M. until midnight while supporting the load. However, no significant improvement in the overall voltage profile is evident and the exclusive peak management has increased the system losses by 8.06%. From Table I, the optimal size of BESS required to support peak exclusively is greater than for other services.Bus 12 is the optimal site that achieves most loss reductions when controlling the losses exclusively (floss). From Table I, the BESS capacity required for the pure control of loss is the lowest. System losses are reduced by 16.92%. However, as illustrated in Figs. 10(c) and 9, the improvement in the lowest voltage and the peak reduction is not as significant. The voltage profiles in Fig. 10 illustrate the improvements in the voltages with various controls. From Fig. 10(c), the optimization for exclusive control of system losses does not improve the minimum voltage. However, BESS management for loss control has effectively mitigated the effects of reverse power flow. Furthermore, it is evident from Fig. 10(b) that the BESS installation for exclusive management of peak shows no significant improvement in the lower or upper limit of the voltage profile. Thus, BESS for peak management only does not provide maximum benefits to the grid. Conversely, BESS management for voltage regulation in Fig.shows significant improvement in both minimum and maximum voltages. Similar enhanced voltage profile is obtained with the simultaneous control of (14) as shownin Fig. This is primarily at tributable to the voltage regulation factor in (14)

CONCLUSION

This paper proposes a tool that effectively deals with the problem of optimal sizing and dispatch management of BESSs considering various service options. Detailed simulation results show the potential of community-level BESS, controlled by DNO, in addressing distribution system overarching concerns including peak shaving, voltage regulation, and loss reduction for improving system efficiency. Simulations were carried out for an MV and an LV distribution test system. Based on the quantitative analysis, the main conclusions are as follows.

1) The proposed method is able to take the battery daily cycling into consideration, thus optimizes the BESS performance by effectively controlling the cyclic ageing.

2) In most literature, battery systems are installed for peak shaving only. However, based on results in Tables I and II, installation for peak support does not reconcile overvoltage (the primary DG limiting factor) or LV issues. Moreover, it increases system losses considerably.

3) Therefore, the problem needs to be addressed with the aim of improving system voltages to enhance the DG absorption. Maximum tradeoffs are achieved when installing battery considering its ability to simultaneously provide multiple services (Tables I and II).

4) Amount of tradeoffs in terms of voltage regulation, peak shaving, loss reduction, and battery parameters highly depend on the installation site.

5) Base on the results, the benefits and battery parameters are primarily characterized by the

system topology as well as the distribution of loads and generation.

6) A tanystage, the proposed BESS approach did not violate the capacity limit of distribution system, as the transformer loading is effectively minimized. Therefore, no upgrades will be required for peak support.

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