Voltage regulation in LV distribution networks with PV generation and battery storage

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PAPERS

Voltage regulation in LV distribution networks with PV generation and battery storage

Jordan Radosavljević[1]

High penetration of photovoltaic (PV) generation in low voltage (LV) distribution networks can leads some power quality problems. One of the most important issues in this regard is the impermissible voltage deviation in periods with a large imbalance between PV generation and local load consumption. Accordingly, many authors deal with this issue. This work investigates voltage regulation for LV distribution networks equipped with the hybrid distribution transformer (HDT), and with high penetration of PV units. A two-stage algorithm for voltage regulation is proposed. In the first stage, a local (distributed) voltage control is performed by minimizing the injection power of the PV-battery storage system (BS)-local load entity at the common bus. In the second stage, optimal coordination is performed between the HDT and the local voltage control. In fact, the second stage is an optimal voltage regulation problem. The aim is to minimize the voltage deviations at load buses by optimal settings the voltage support of the HDT. A PSO algorithm is used to solve this optimization problem. the proposed approach is implemented in MATLAB software and evaluated on the IEEE european LV test feeder.

K e y w o r d s: battery storage, LV distribution network, PSO, PV generation, voltage regulation

1 Introduction

Modern distribution networks are evolving into smart grids that integrate distributed generation (DG), nonlinear loads, information and communication technologies, and power electronics technology. A large share of renewable energy based DG sources can cause deterioration of the power quality. Improvement of the power quality in various aspects becomes one of the most important tasks of electricity distribution companies to increase competitiveness in the liberalized electricity market.

The most important parameter of power quality is the voltage magnitude. The lower and upper voltage magnitude limits in distribution networks are defined by appropriate technical standards, such as the European voltage disturbances standard E 50160 [1]. Accordingly, the voltage limits for low voltage (LV) distribution networks in the EU is $400\,\mathrm{V} \pm 10\%$, whereas in the UK, the limits is $400\,\mathrm{V} + 10\%, -6\%$.

One of the key actions of a distribution system operator (DSO) is voltage regulation which consists of a set of control actions to ensure that the voltage magnitudes at all buses of the distribution network be within the permissible limits.

As well known, integration of DG units such as inverter based PV systems into the LV distribution networks changes the nature of these networks from passive (unidirectional power flow) to active distribution networks with bidirectional power flow. Depending on size and location of the PV units, they could positively impact the network and consumers, such as improving supply reliability, improving voltage profile, and minimizing power losses [2]. However, if PV generation significantly exceeds local load demand (for example during a few hours at midday) it can lead to unacceptable voltage rise at load busses. The stochastic nature of PV generation as well as load demand may cause significant voltage fluctuations during a day. In addition, voltage rise exceeding the G83/1 limits may cause unplanned switch-off the PV system from the network [3]. Therefore, the voltage regulation of LV distribution networks with integrated PV systems is very important issue that cannot be solved in a traditional way, *ie* using seasonal voltage control for passive distribution networks (using the MV/LV off-load tap-changing transformers and shunt capacitor banks) [4].

In recent years, the authors have proposed application of various equipment based on power electronic converters for voltage regulation in LV networks, as well as appropriate algorithms for their control and coordination. Four different solutions based on using power electronic converters for voltage regulation in LV networks are presented in [3]. The performances of these power electronic solutions, namely power electronic substation (PES), online tap changer (OLTC), active power filter (APF), and mid feeder compensator (MFC) were evaluated and compared on a representative LV test network. The authors in [5] proposed a compact power electronic converter that can compensate an under-voltage or over-voltage condition on an LV feeder. It is considered as a power electronic solution to the problem of mid feeder regulation in LV networks. Power electronic compensator (PEC) in

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output voltage control mode was considered in [6] for voltage regulation in LV networks with high penetration of PV generation and electric vehicle charging stations. The authors proposed placement of the PEC between the feeder and each customer (point-of-load compensation, PoLC), and compared this solution with the already proposed solution where the PEC is placed somewhere on the feeder (mid-feeder compensation, MFC).

Many authors in their research have focused on the development of efficient methods for optimal coordination of regulation resources in LV distribution networks. Some of these methods just aim to maintain the voltage within the permissible limits. Another group of approaches are methods for optimal volt/var regulation aiming to minimize voltage deviation and/or power loss in the networks. Different control schemes proposed for voltage regulation in distribution networks can be classified into four main groups: local control, centralized control, distributed control, and decentralized control. References [7–10] give a comprehensive overview of these approaches.

Conti *et al* [11] proposed a local control strategy based on PV generation curtailment to prevent overvoltage at the point of common coupling. The active power produced by the PV generators is adjusted according to the local bus voltage. In [12], a distributed control scheme was proposed to solve overvoltage problems in LV distribution networks due to high PV generation. The control scheme is based on adjusting the active and reactive power output of PV inverters to prioritise the use of reactive power and minimize the active power curtailment. Distributed energy storage systems (ESSs) have been proposed in [13, 14] to solve the voltage deviation problems in LV distribution networks with high penetration of rooftop PVs. The authors considered the distributed control based on a consensus algorithm for buses voltage regulation, whereas a local control scheme was employed to regulate the state of charge (SoC) of each ESS within desired SoC range. A similar approach was proposed in [15], where a coordinated control strategy is a combination of the local droop based control method and a distributed control scheme based on consensus algorithms each of which having specific objectives in regulating the charge/discharge of ESS and ensuring that bus voltages remain within specified limits. Also, a distributed control strategy based on two consensus algorithms is proposed in [16] to achieve cooperative control of plug-in electric vehicles (PEVs) and the active power curtailment of PV generators for voltage regulation in LV distribution networks.

The authors [17] consider voltage regulation in LV distribution networks with PV units using OLTC-fitted transformers. For this purpose, they propose a practical remote voltage estimation method for the end nodes of LV feeders without remote monitoring. Kostolas *et al* [18] proposed a control framework for optimal coordination of OLTC distribution transformers, battery energy storage systems, and distributed energy resources including rooftop PV installations to assure admissible voltage magnitudes in LV distribution networks. The methodology comes down to a multi-objective multi-period optimal power flow solved by the interior-point algorithm. A centralized approach for volt/var control in distribution network with PV generation is presented in [19]. This approach uses particle swarm optimization (PSO) for optimal coordination of step voltage regulators and distribution static synchronous compensator with objectives to minimize the active power loss while the voltages keep within the allowable limits. In [20], optimal reactive power management and active power curtailment of PV inverters have been defined as a multi-objective optimal power flow problem with objectives to simultaneously improve voltage magnitude and minimize power loss, and solved using PSO.

Garcia *et al* [21] analyzed a combined centralized/decentralized voltage regulation method consisting of coordination of control actions performed by the DSO with local control at the PV inverter level. Using this strategy the authors determines reactive power references for PV inverters integrated into an LV distribution network. To mitigate the voltage rise issues in LV networks with PV generation, the authors [22] proposed a coordinated volt/var control scheme between the LV distribution transformer and PV inverters to optimize the PV generation level, considering two standard concepts for reactive power control, $\cos\varphi(\mathrm{P})$ and Q(U). A multi-objective genetic algorithm solved this optimization problem. The problem of coordinating the operation of PV inverters, battery storage systems, and tap-changers has been considered in [23] as a multi-objective OPF problem. The optimization problem is then solved by applying the epsilon-constrained technique to simultaneously improve the voltage profile, minimize power loss, and reduce peak load power.

As noted above, the traditional voltage regulation in LV networks using off-load tap changing transformer is very limited. A potential solution for LV distribution networks is hybrid distribution transformer (HDT). This is a concept that represents a combination of a classic distribution transformer and a fractionally rated power electronic converter [24]. The HDT can provide additional control capabilities such as dynamic voltage regulation and reactive power compensation. Therefore, the HDT can be used to continually adjust the voltage magnitude on an LV feeder. On the other hand, it has been shown [13–16] that in LV networks with a large share of PV sources, the impermissible voltage deviation can be solved by using distributed ESS to balance power injection at the buses where PV sources connected. It seems that the combination of these two approaches can give the best results in voltage regulation of LV networks with a large share of PV generators.

This work discusses the voltage regulation problem in LV networks equipped with the HDT, and with high penetration of rooftop PV sources. A two-stage algorithm for voltage regulation is proposed. In the first stage, a local (distributed) voltage control is performed by minimizing the injection power of the PV-BS-Load system at their

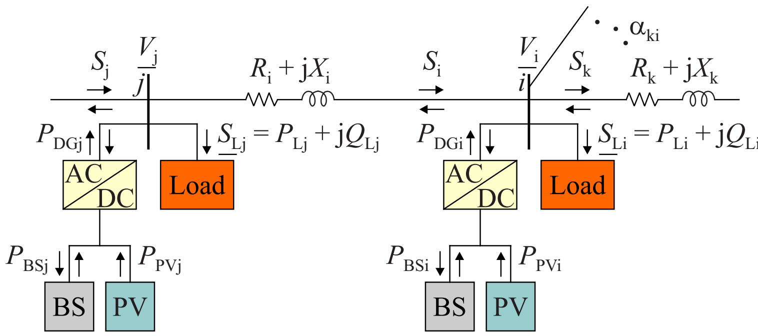

Fig. 1. A part of LV distribution network with PV and ESS

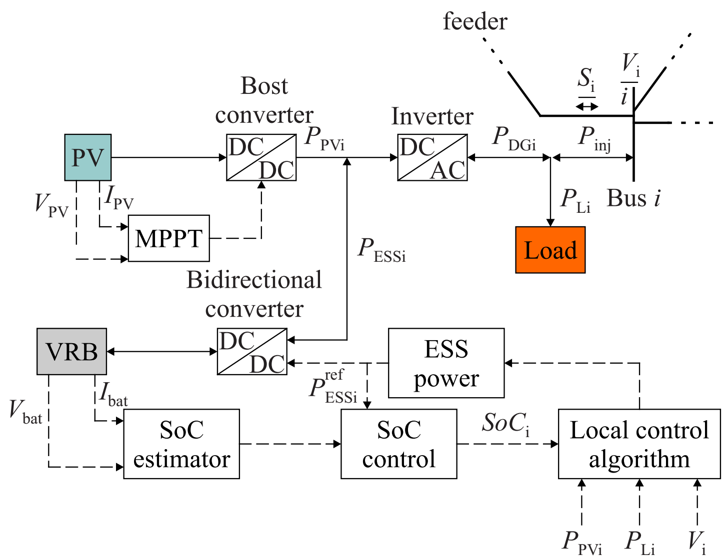

Fig. 2. Schematic diagram of the proposed strategy for local voltage control

common connection point. In this way, the power flow between the nodes of the distribution network is minimized, and thus the voltage drops are minimized, which implies less deviation of bus voltages from nominal values, i.e. tends to keep the bus voltages within permissible limits. In the second stage, which can be activated if the first stage fails to bring the voltages within permissible limits, optimal coordination is performed between the HDT and the local voltage control. In fact, the second stage is an optimal voltage regulation problem. The aim is to minimize the voltage deviations at load buses by optimal settings the voltage support of the HDT. To solve this optimization problem, a PSO algorithm has been proposed.

2 Local voltage control

Well-known characteristics of LV distribution networks are radial topology, high R/X ratio, and negligible shunt admittance. Accordingly, a part of LV distribution network can be presented as in Fig. 1. A PV source, a BS and a local AC load are connected at the bus i.

The voltage drop ΔV_i along the line between two adjusted buses (j and i) can be expressed as follows

$$\Delta \mathcal{V}_i = \frac{R_i P_i + X_i Q_i}{\mathcal{V}_i^*} + j\mathcal{V}_i \frac{X_i P_i - R_i Q_i}{\mathcal{V}_i^*}. \qquad (1)$$

As noted above, LV distribution networks have a high R/X ratio. In addition, the power factor in LV networks is high, typically 0.95, which means that active power flow (P_i) dominate over reactive power flow (Q_i). Accordingly, the imaginary part of (1) can be neglected. Assuming the DG inverter operates with unity power factor ($Q_{\mathrm{DG}} = 0$), the relative voltage drop for LV network can be expressed

$$\frac{\Delta V_i}{V_i} = R_i\Big(P_{\mathrm{L}i} - P_{\mathrm{DG}i} + \sum_{k\in\alpha_{ki}} P_k\Big) + X_i\Big(Q_{\mathrm{L}i} + \sum_{k\in\alpha_{ki}} Q_k\Big), \quad (2)$$

where $P_{\mathrm{L}i}$ and $Q_{\mathrm{L}i}$ are the active and reactive power of load at the i-th bus, $P_{\mathrm{DG}i}$ is the active power of DG consisting of PV and BS at the i-th bus; P_k and Q_k are the active and reactive power in branch k emanating from bus i.

According to (2), the voltage drop can be controlled by controlling injection/absorption of active power at the i-th bus

$$P_{\mathrm{inj/abs}} = P_{\mathrm{L}i} - P_{\mathrm{DG}i} = P_{\mathrm{L}i} - \big(P_{\mathrm{PV}i} \pm P_{\mathrm{BS}i}\big). \qquad (3)$$

The active power of DG, $P_{\mathrm{DG}i}$, depends on PV generation and control strategy of BS charging/discharging. It is clear that the appropriate control of the P_{BS} can enable minimization of active power injection at the ith bus, and consequently less voltage drop ΔV_i, which means less voltage deviation at the i-th bus in relation to the nominal value.

The aim of the local control strategy is to reduce the power imbalance between PV generation ($P_{\mathrm{PV}i}$) and load demand ($P_{\mathrm{L}i}$) to overcome the impermissible voltage deviation. Wheres the BSs function is to reduce the bus power injections during the high PV generation and reduce the power absorption from the network during the night [13]. Simply put, the goal is to the energy that is produced locally to be consumed locally, that is to minimizing energy exchange between the customer (an entity consisting of PV-BS and Load) and the distribution network.

The proposed strategy of local voltage regulation for the customer on the i-th bus is shown in the form of a functional scheme in Fig. 2. The solid lines show the power flow, whereas the dotted lines denote the communication among equipment. The PV panel is connected to the DC link through the boost converter controlled by the MPPT algorithm to achieve the maximize power generation under different condition of solar irradiance and ambient temperature. In this work, a residential Vanadium redox battery (VRB) model is adopted for energy storage purposes within the BS. The parameters for the VRB are shown in Tab. 1 [14]. The BS is connected to the DC link through the bidirectional converter to enable the charging/discharging process. The active power is transferred between the DC link and the AC load and the distribution network through the DC/AC inverter. The inverter can enable reverse process, *ie* transferring the active power from the distribution network to the BS.

High PV generation in periods with low load power can cause overvoltage at the i-th bus due to the high value of power injection (P_{inj}). Active power injection from PV can be limited by storing the extra power in the BS. On other hand, in periods with low (or zero) PV generation and high load, when the voltage at the i-th bus can drop below the lower limit, the stored energy in BS can be used for the local load and thus reduce the voltage drop in the network.

The aim of the local voltage regulation algorithm is to control the process of charging/discharging the BS under various operating conditions, such as the periods of peak PV generation coinciding with low load periods, and vice versa. This is a way to ensure that the power injection into the i-th bus is minimal, and thus the voltage deviation at the i-th bus is minimal.

As explained in [14], the SoC of the BS is

$$SoC(t) = SoC(t-\Delta t) + \Delta SoC\,, \qquad (4)$$

$$\Delta SoC = \frac{P_{\mathrm{BS}}\Delta t}{C_{\mathrm{B}}} = \frac{V_{\mathrm{bat}} I_{\mathrm{bat}} \Delta t}{C_{\mathrm{B}}}\,, \qquad (5)$$

where C_{B} is the total energy capacity of the VRB, Δt is the time interval, V_{bat} and I_{bat} are the output voltage and current of the VRB, respectively.

Unlike the distributed control based on consensus algorithm [13–16], there is no need for communication between neighbouring customers. Local voltage regulation is performed at each customer based on local information on the current power of the PV source, consumption, voltage and condition of the BS. The proposed local voltage regulation algorithm provides determination of the reference power of the BS ($P_{\mathrm{BS}}^{\mathrm{ref}}$) at the time t based on the estimated SoC of the BS, PV generation (P_{PV}), the power of load (P_{L}) and the voltage magnitude (V) at time ($t-\Delta t$), evaluated through a communication system. As noted above, Δt is the time interval adopted for the time-series power flow analysis (usually, $\Delta t = 1$ min, 5 min or 10 min).

The efficient operation of the BS means that its power and SoC are within defined limits

$$-P_{\mathrm{BS}}^{\mathrm{rated}} \le P_{\mathrm{BS}}(t) \le P_{\mathrm{BS}}^{\mathrm{rated}}, \qquad (6)$$

$$SoC^{\min} \le SoC(t) \le SoC^{\max}, \qquad (7)$$

To take into account the value of the voltage $V_i(t)$ in determining the $P_{\mathrm{BS}}^{\mathrm{ref}}(t)$, a control signal is introduced

$$e(t) = \begin{cases} 0 & \text{if } |1 - V_i(t)| < V_{\mathrm{th}}^{\min}, \\ 1 & \text{if } |1 - V_i(t)| > V_{\mathrm{th}}^{\max}, \\ 1 - k_v\big(V_{\mathrm{th}}^{max} - |1 - V_i(t)|\big) & \\ \quad \text{if } V_{\mathrm{th}}^{\min} \le |1 - V_i(t)| \le V_{\mathrm{th}}^{\max}, & \end{cases} \qquad (8)$$

where $V_{\mathrm{th}}^{\min}$ and $V_{\mathrm{th}}^{\max}$ are the minimum and maximum thresholds. In this work $V_{\mathrm{th}}^{\min}$ was adopted as 0.01 pu, whereas $V_{\mathrm{th}}^{\max}$ could be considered as maximal permissible voltage drop (we adopted $V_{\mathrm{th}}^{\max} = 0.05$ pu).

The current state of the i-th customer ($P_{\mathrm{PV}i}$, $P_{\mathrm{L}i}$, SoC_i, and V_i) is evaluated by a local communication system. Considering the current state and the defined power limits and SoC limits, the required output power of the BS is determined by a control algorithm which can be explained by the flow chart in Fig. 3.

3 Optimal voltage regulation

3.1 Hybrid distribution transformer

The development of power electronics has enabled the development of various solutions to mitigate voltage problems in LV distribution networks with high penetration of stochastically DG such as rooftop PV systems. One

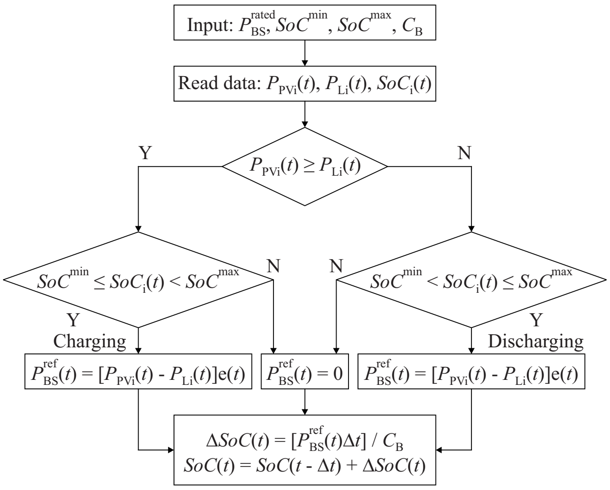

Fig. 3. Flow chart of the local voltage control

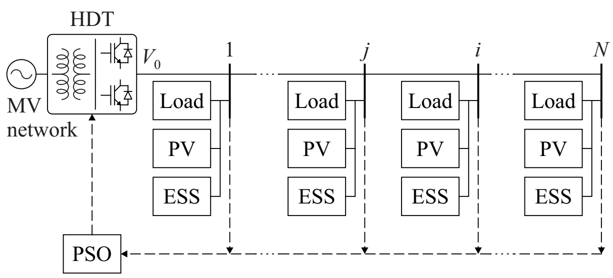

Fig. 4. Optimal voltage regulation in LV network

Table 1. Parameters of VRB

Configuration	38 series cell stack
Rated power, Prated	5 kW
Rated capacity, CB	20 kWh
Operation voltage	42-57 V
Region $\left(SoC^{\min}, SoC^{\max}\right)$	15 %, 85 %

optimal settings of the control variable - voltage support of the HDT, under various technical constraints. Generally, the optimal voltage regulation problem can be expressed by the following equations

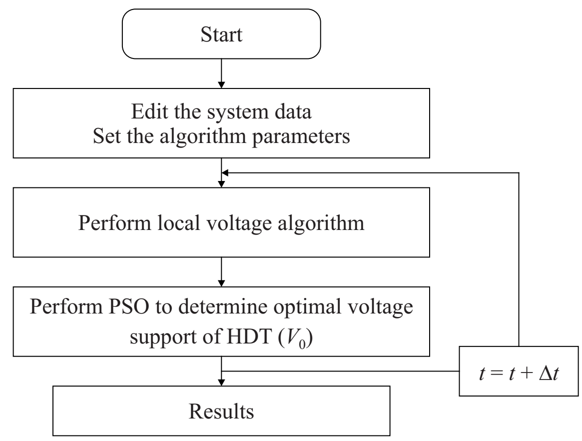

Fig. 5. Flow chart of the proposed algorithm

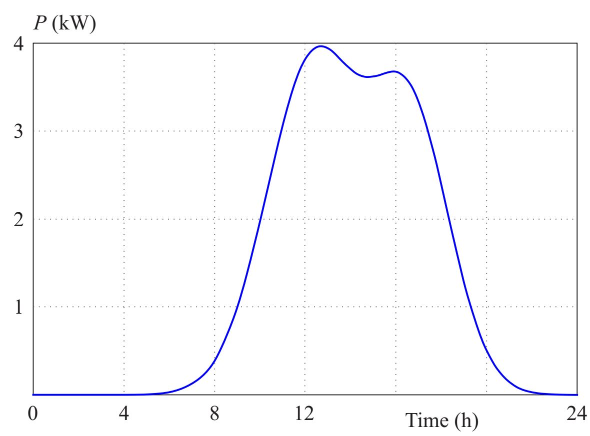

Fig. 6. PV generation profile

such solution is the application of the concept of hybrid distribution transformer (HDT), proposed in [24].

An HDT, as its name suggests, consists of a classic distribution transformer with built-in partial voltage electronic converter in the secondary side, as illustrated in Fig. 4. The partial voltage electronic converter allows the HDT to have continuous voltage regulation in a defined range.

High efficiency at lower cost and complexity are the main advantages of the proposed HDT concept compared to power electronic transformers [3, 24].

3.2 Problem formulation

In this work, optimal voltage regulation implies optimal coordination between the HDT and the local voltage control using PSO, as illustrated in Fig. 4.

The objective function of optimal voltage regulation is the minimization of voltage deviations at load buses, via

$$\min\{F(\mathbf{x},\boldsymbol{y})\} \text{ subject to: } \begin{cases} g(\mathbf{x},\boldsymbol{y}) = 0\,, \\ h(\mathbf{x},\boldsymbol{y}) = 0\,, \\ \mathbf{x} \in X\,. \end{cases} \tag{9}$$

where F is objective function to be minimized, $\mathbf{x}$ and $\boldsymbol{y}$ are vectors of control and dependent variables, respectively.

For the distribution network under study, the vector of control variables $(\mathbf{x})$ consisting of root bus voltage V_0, that is voltage support of the HTD. Therefore, the vector of control variables can be expressed as

$$\mathbf{x} = [V_0]\,, \tag{10}$$

$$\boldsymbol{y} = \big[P_{\text{gr}}, V_1, \dots V_N, P_{\text{ESS}1}, \dots, P_{\text{ESS}N}, \\ SoC_1, \dots, SoC_N, S_{\text{l}1}, S_{\text{l}N}\big]. \tag{11}$$

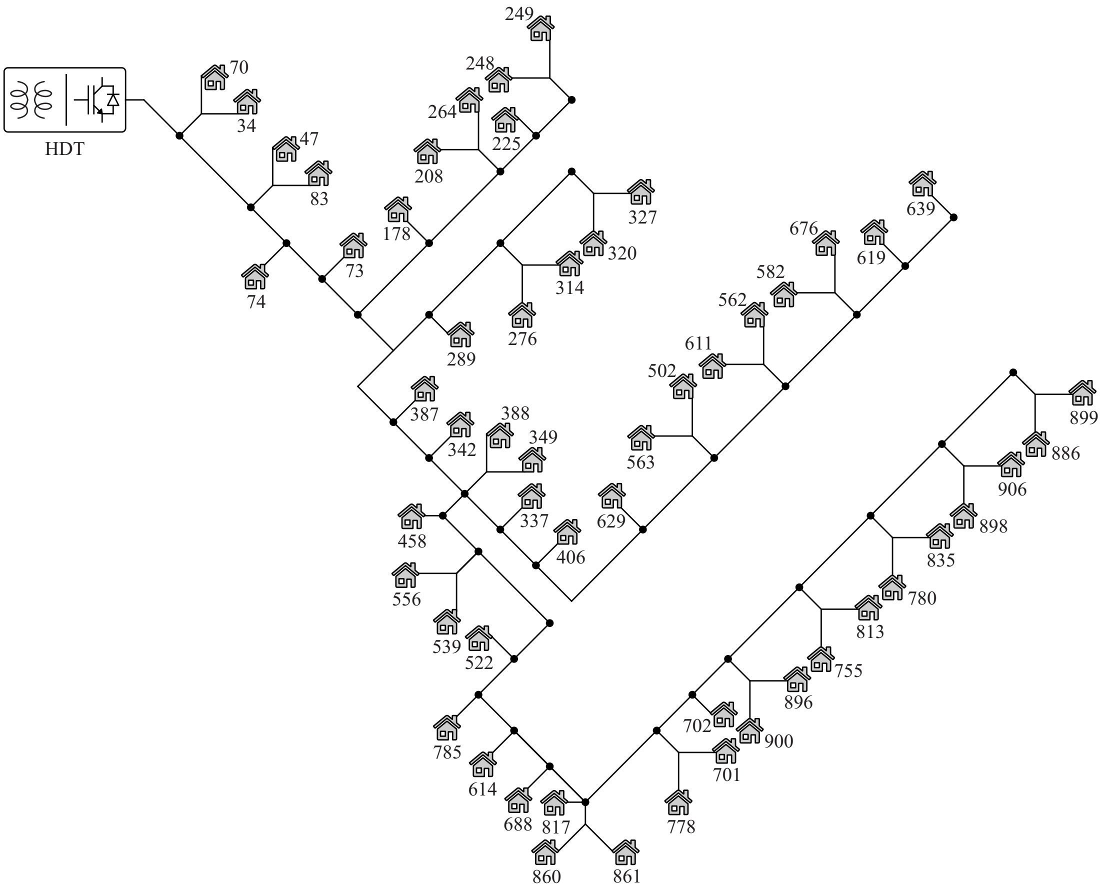

Fig. 7. Single-line diagram of the IEEE European LV test feeder [16]

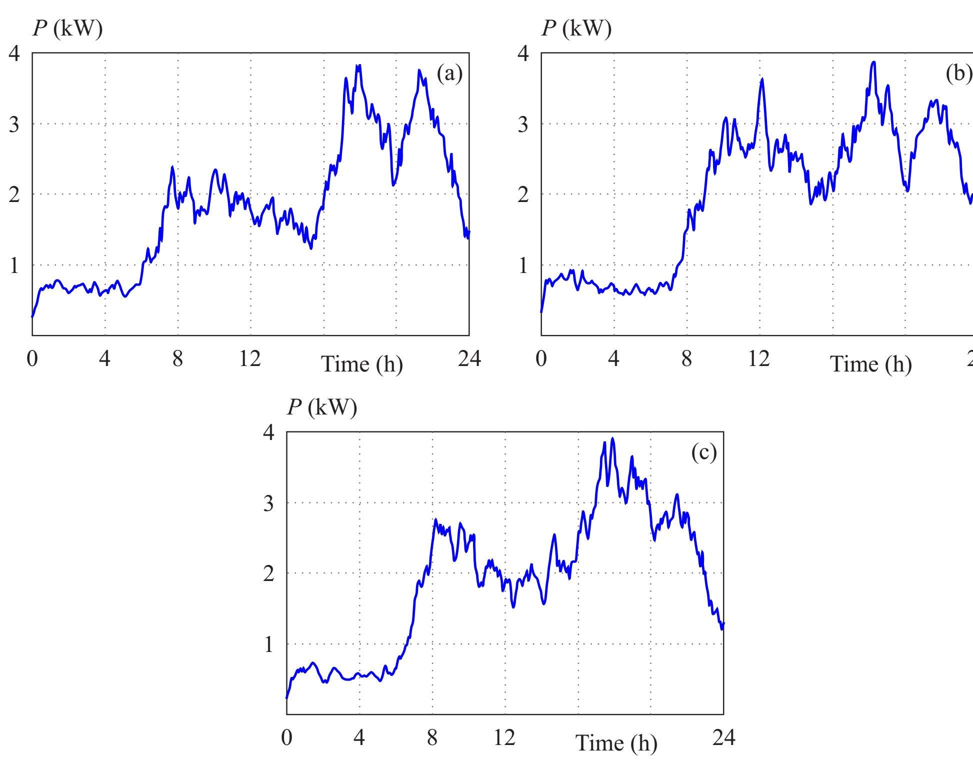

Fig. 8. Single-line diagram of the IEEE European LV test feeder [16]

The objective function can take different forms. However, in this study, minimization of voltage deviation at load buses is considered as the objective function

$$F = \sum_{i=1}^{N} |1 - V_i| \,, \tag{12}$$

Table 2. Parameters of local voltage control

$SoC^{\min}$	20%
$SoC^{\max}$	80%
$V_{\text{ths}}^{\min}$	0.01
$V_{\text{ths}}^{\max}$	0.05
k_{v}	10

Table 3. Parameters of PS

C_1	2
C_2	2
$w_{\min}$	0.4
$w_{\max}$	0.9
N	10
$t_{\max}$	20

where V_i is the voltage magnitude at load bus i, N is the total number of buses in the distribution network.

The equality constraints in (9) represent power flow equations. The inequality constraints are the functional operating constraints

$$V_i^{\min} \leq V_i \leq V_i^{\max},$$
$$-P_{\text{ESS}i}^{\text{rated}} \leq P_{\text{ESS}i} \leq P_{\text{ESS}i}^{\text{rated}},$$
$$SoC_i^{\min} \leq SoC_i \leq SoC_i^{\max},$$
$$S_i \leq S_i^{\max},$$
$$\text{for } i = 1, \ldots, N\,.$$

Constraint $\mathbf{x} \in X$ defines the feasibility region of the problem control variable, that is root bus voltage limits

$$V_0^{\min} \leq V_0 \leq V_0^{\max}.$$

3.3 Solution method

In this paper, a well-known metaheuristic optimization method – particle swarm optimization (PSO) is proposed to solve the problem of optimal voltage regulation. A detailed description of basic PSO algorithm and its improved, adaptive and hybrid versions can be found in [2]. Figure 5 shows a flow chart of the proposed algorithm for optimal voltage regulation using PSO.

4 Simulation results

The proposed two-stage algorithm for voltage regulation in LV distribution networks is coded in MATLAB software and implemented on the IEEE European LV test feeder. Two test cases have been considered to evaluate the proposed voltage regulation approach. These test cases are as follows:

Test case A: Local voltage control only;

Test case B: Optimal voltage regulation (coordination of HDT and local voltage control).

The parameters of the local voltage control algorithm and parameters of PSO used for optimal voltage regulation are given in Tabs 2 and 3, respectively.

To assess the effectiveness of the proposed approach for voltage regulation in large-scale realistic distribution networks, the IEEE European LV test feeder is considered which is a typical topology for European distribution networks. It is a radial LV distribution network at the voltage level of 416 (phase-to-phase) connected to the MV network through a transformer MV/LV (11/0.4 kV) at the substation. The test feeder has 906 buses. In 55 lateral buses are connected customers. Complete data on the IEEE European LV test feeder are given in [25]. In addition to network parameters, load profiles with a one-minute time resolution over 24 h are provided for each of the 55 loads. That is for time-series simulation.

In this work, the original IEEE European LV test feeder is modified as follows:

1) The test feeder is considered as symmetrical/balanced.
2) All loads are changed from single-phase to three-phase with a power factor of 0.95.
3) Load shapes are transformed from one-minute time resolution to five-minute time resolution (using 5-min mean values) giving 288 load data points for 24 hours.
4) The rooftop PV system with the capacity of 4 kWp and the BS based on VRB with data are given in Tab. 1, are integrated with each of 55 customers.
5) The output power profile shown in Fig. 6 is considered identical for all PV systems.
6) The MV/LV transformer at substation is considered as the HDT.
7) The maximum voltage deviation in the distribution network is considered as ±5%.

The single-line diagram of the modified IEEE European LV test feeder is shown in Fig. 7. The three typical load profiles shown in Fig. 8 were distributed to the customers at random.

4.1. Test case A: local voltage control

The proposed local voltage control algorithm is tested for an initial SoC value of 50 % for each BS, and a constant voltage magnitude at the HDT of 1 pu Figures 9–11 show the voltage profiles at buses 562, 906 and 249 which belong to different laterals of the LV network. The voltages at buses 562 and 906 exceed the upper limit of 1.05 pu in the period with high PV generation (from 12 h to 16 h). During the increased load in the morning and especially in the evening (from 6 pm to midnight) the voltage values at the considered buses are below the lower limit value of 0.95 pu. By applying the proposed algorithm for local voltage control, these voltages are improved during the entire period of 24 hours. However, during the peak load period, these voltages are still less than the allowable value of 0.95 pu. In the period with high solar irradiation, the PV generator supplies local load, and the excess power is used to charge the BS. Then, during

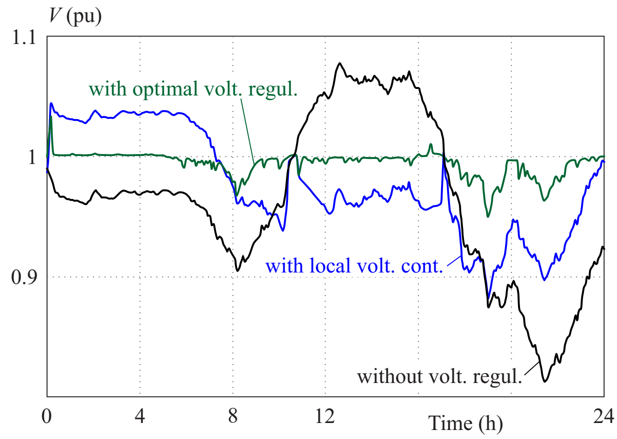

Fig. 9. Voltage profiles at bus 562

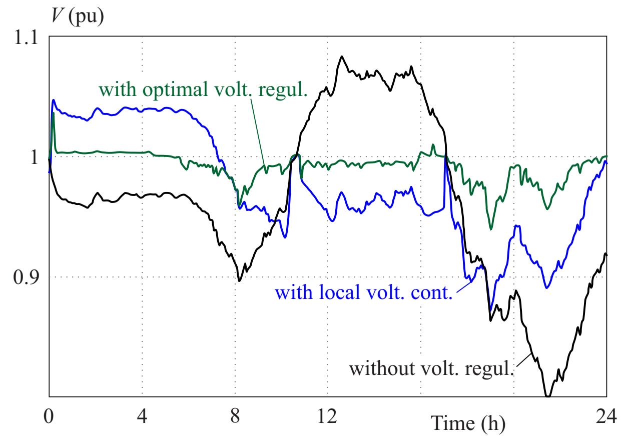

Fig. 10. Voltage profiles at bus 906

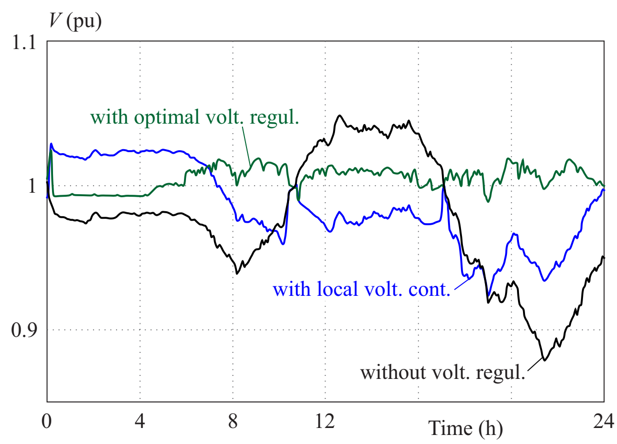

Fig. 11. Voltage profiles at bus 249

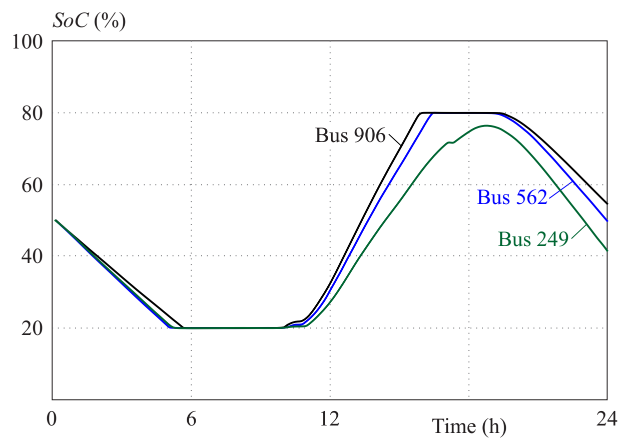

Fig. 12. SoC of BS at different buses

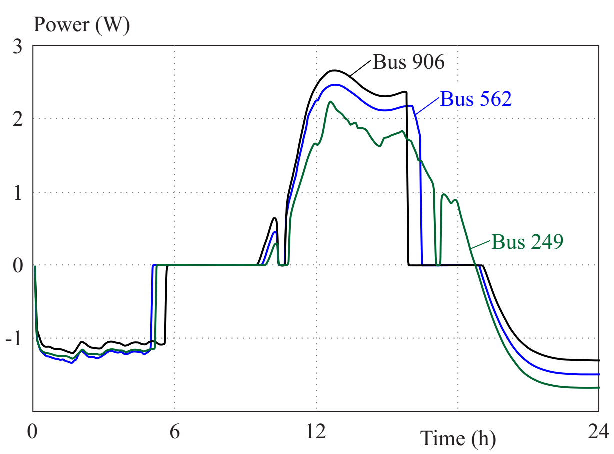

Fig. 13. Power output of BS at different buses

the peak load period in the evening the accumulated energy of the BS is used for supply of the local load enabling some improvement of the voltage, but the available battery power is insufficient to cover the entire local load and provide complete voltage recovery.

Figures 12 and 13 show the corresponding SoC profiles and the power outputs of the BSs at buses 562, 906 and 249 resulting from the local voltage control. These figures clearly show that the battery charging and discharging modes, as well as their power outputs are determined by the ratio of local loads and PV generation, in accordance with the proposed local voltage control algorithm in Fig. 3.

4.2. Test case B: optimal voltage regulation

It is supposed that the HDT may continuously control terminal voltage (V_0) in the range of 0.95 pu to 1.05 pu. Figure 14 presents the optimal voltage support of the HDT for the IEEE European test feeder obtained by the proposed optimal voltage regulation algorithm.

Figures 9–11 compare the voltages at bus 562, 906 and 249 for the basic case-without regulation, Case A – local voltage control and Case B – optimal voltage regulation. As can be seen, optimal voltage regulation keeps the voltage magnitude very close to the nominal value (1 pu). A very clear effect of optimal voltage regulation (Case B) on voltages in the whole distribution network can be seen in Figs. 15 and 16 presenting the total voltage deviation at load buses and the statistical indicators of load bus voltages during the day, respectively. The box plots shown in Fig. 16 cover all the load bus voltages over the day giving a notion about statistical indicators. The tops and bottoms of each "box" are the 25th and 75th percentiles

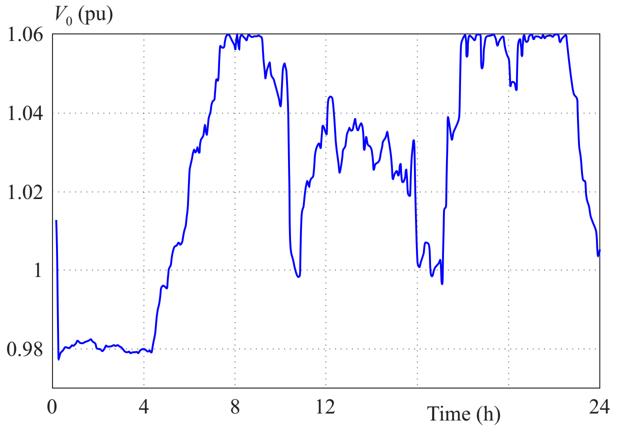

Fig. 14. Optimal values of the control variable (V0)

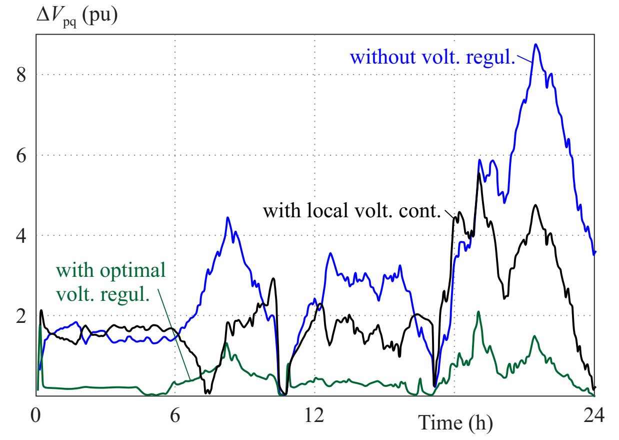

Fig. 15. Total voltage deviation in the distribution network

of the samples, respectively. The line in the middle of each box is the sample median of all load bus voltages at time t. It is clear that the optimal coordination of the HDT and local voltage control enables minimum voltage deviation at load buses.

5 Conclusion

In this paper, a two-stage voltage regulation approach for LV distribution networks with rooftop PV generation and BS has been considered. The proposed algorithms have been tested on the IEEE European LV test feeder. The simulation results lead to conclusions that can be summarized as follows:

- Local voltage control reduces the power imbalance between PV generation and load demand by managing the output power of the BS. In this way, the energy exchange between the customer and the distribution network is minimized enabling improving the voltage profile of the network.
- Unlike the distributed control based on a consensus algorithm, the proposed local voltage control does

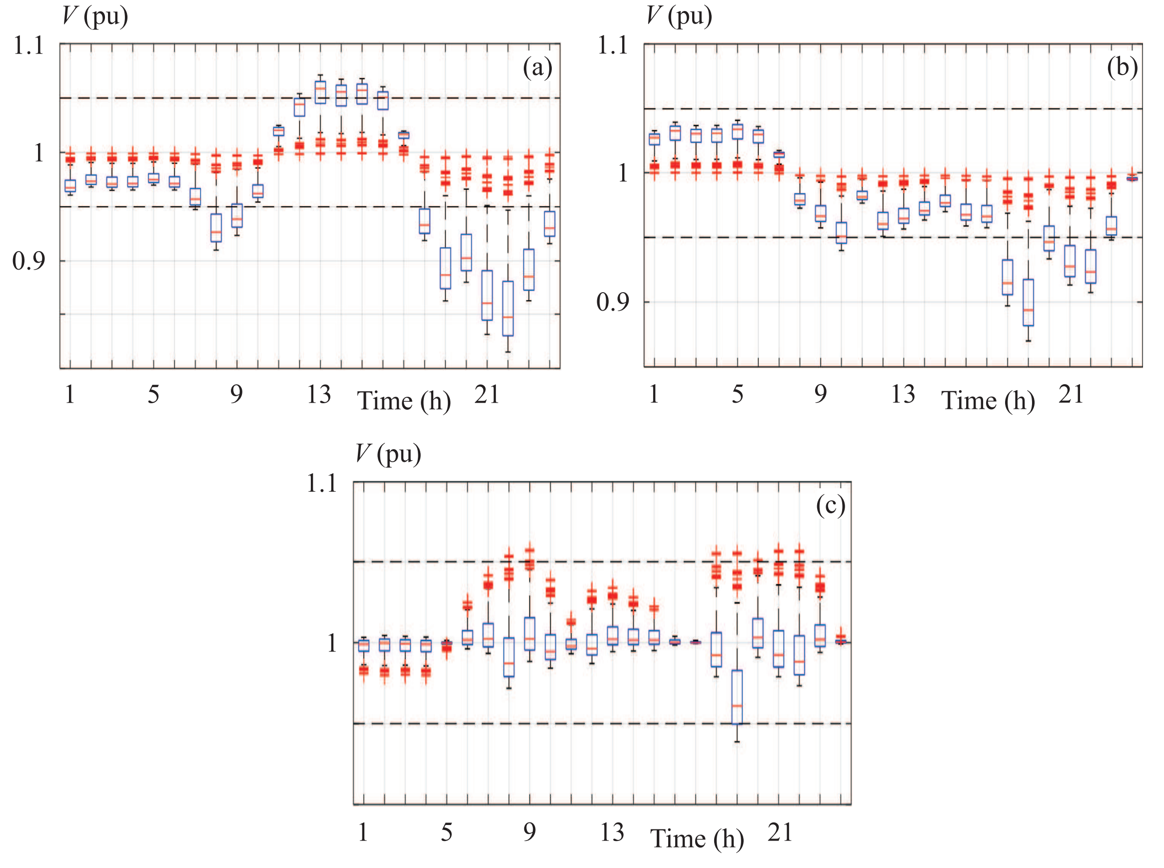

Fig. 16. Statistical indicators for load bus voltages

not require communication between neighbouring customers.

- Optimal voltage regulation based on optimal coordination of the HDT voltage support and local voltage control using PSO provides minimum voltage deviation at all load buses in the whole daytime.
- The proposed approach can be easily implemented for any practical LV distribution network with PV sources.

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