A GA-based NZEB-cluster coordinated control towards power grid overvoltage optimization

Yelin Zhang, Haoshan Ren, Yongjun Sun*
Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong

Abstract
The increasing applications of net-zero energy buildings (NZEBs) will lead to more frequent and larger energy interactions with the connected power grid, thereby being able to result in severe grid overvoltage risks. Control optimization has been proven effective to reduce such risks. Existing controls have oversimplified the overvoltage quantification by simply using the aggregated power exchanges to represent the connected grid overvoltages. Ignoring the complex voltage influences among the grid nodes, such oversimplification can easily result in low-accuracy impact evaluations of the NZEB-grid energy interactions, thereby causing non-optimal/unsatisfying overvoltage mitigations. Therefore, this study proposes a novel coordinated control method in which a power-distribution-network model has been adopted for more accurate overvoltage quantification. Meanwhile, the battery operations of individual NZEBs are iteratively coordinated using a sequential optimization approach for achieving the global optimum with substantially reduced computation complexity. For verifications, the proposed coordinated control has been systematically compared with an uncoordinated control and a conventional coordinated control in grid overvoltage minimization. The study results show that the overvoltage improvements can reach 23.5% and 12.3% compared with the uncoordinated control and the conventional coordinated control in grid overvoltage minimization. The study results show that the overvoltage improvements can reach 23.5% and 12.3% compared with the uncoordinated control and the conventional coordinated control, respectively. The reasons behind the improvements have also been analyzed in detail. The proposed coordinated control can be used in practice to improve NZEB-clusters’ grid friendliness.

Highlights
• Frequent grid interactions of NZEB clusters can cause severe grid overvoltage risks.
• A novel coordinated control optimization is proposed to minimize such risks.
• It conquers the oversimplified grid-overvoltage-quantification in existing controls.
• It approaches the global optimum with reduced computation complexity.
• Systematic comparative studies show its superior performance in overvoltage reduction.

Introduction
By integrating renewable energy to satisfy energy requirements, net-zero energy building (NZEB) is considered as a promising solution to mitigating the growing energy consumption and global warming. On the other hand, the intermittent and unstable nature of renewable energy (e.g., solar energy) can cause severe problems in the power grid by introducing a mismatch between renewable generation and energy demand. One major problem is the grid overvoltage. For instance, during high renewable generation but low load periods, the surplus renewable energy exports of NZEBs will raise up the voltage at the load end exceeding the allowable limits, thereby causing the overvoltage problem. For the security of grid operation, as overvoltage occurs, the renewable energy is not allowed to be exported to the power grid, thereby causing wastes of renewable generation. In a demonstration study of residential photovoltaic (PV) systems in Japan, due to the concern of overvoltage risks, up to 46% of the daily renewable generation was found to be wasted at high PV penetrations (Ueda et al. 2008). To address the overvoltage problem, the grid side can curtail excessive renewable generation or install electronic equipment (e.g., voltage regulators or banks of capacitors) to regulate voltage (Tonkoski et al. 2011). On the other hand, through optimal NZEB system control, the building side can also contribute to the overvoltage risk reduction (Zhao et al. 2015; Harkouss et al. 2018). [6], which can help relieve the pressure and reduce the costs of the grid side in addressing overvoltage.

Existing studies have proposed control optimization methods to minimize the NZEB-grid energy interactions and thus reduce the overvoltage risk. For instance, Pinamonti et al. (2020) proposed a rule-based control strategy for increasing PV self-consumption of a high-insulated residential building in Italy. This strategy stored the solar energy surplus as thermal energy using water tanks and the activation of the building mass, without the need of electric storage. Results showed that the proposed control strategy can increase 22% of the PV self-consumption and cut down 17% of the amount of electricity purchased from the grid. Rule-based controls are effective in improving the grid interaction performance, but the control results may not be optimal, since the energy systems operate merely based on predefined rules. Many optimization algorithms have also been employed in building system control to optimize grid interactions including nonlinear programming (NLP) (Nasri et al. 2016), artificial neural network (ANN) (Palma-Behnke et al. 2011) and particle swarm optimization (PSO) (Faria et al. 2013). For instance, Zhao
et al. (2015) developed a model predictive control based optimal scheduling strategy, which used NLP algorithm to schedule the operation of electricity and cold generation/use and the cold storage 24 h ahead. It achieved effective reductions in CO2 emission, operation cost and total energy interactions with the grid. Compared with classic algorithm, intelligent algorithms (e.g., ANN and PSO) are more frequently utilized for control tasks with a large number of decision variables due to their powerful exploration and exploitation ability (Antonopoulos et al. 2020). Palma-Behnke et al. (2011) developed an ANN-based energy management strategy for a smart microgrid powered by PV, wind turbine (WT) and diesel generator. The strategy was able to minimize both the operation cost and the peak energy interactions with the external grid considering the forecast of renewable resources, load, and water consumptions.

Most of these existing control methods focus on optimizing the NZEB performance at single-NZEB-level. The coordination among NZEBs was ignored and the total power exchange at NZEB-cluster-level was not optimized. As studied by Sun et al. (2018), coordinated control can effectively reduce the peak interaction by as much as 56%. A few latest studies have proposed coordinated control at NZEB-cluster-level to improve the grid interactions and thus the overvoltage performance. For instance, Gao et al. (2016) developed a GA (genetic algorithm)-based coordinated demand response control in which all batteries’ charging rates were optimized simultaneously to minimize the building-group-level peak demand. Similarly, Zhang et al. (2018) proposed a coordinated control in which a cluster-level controller was utilized to simultaneously manage local energy transactions among microgrids for minimizing the overall energy interactions with the grid.

Existing coordinated controls have achieved the reduction of grid power interactions at NZEB-cluster-level. However, they ignored the distribution network characteristics (e.g., feeder resistance and structure) and directly used the total grid power interaction to represent connected grid overvoltage. Such oversimplification can easily result in unsatisfactory/poor accuracy when evaluating the impacts of NZEB-grid power exchanges on the actual power grid, which eventually caused that existing studies cannot achieve grid overvoltage minimization. Therefore, this study proposes a novel NZEB-cluster coordinated control method in which a grid model has been adopted for accurate overvoltage quantification. Meanwhile, the battery operations of individual NZEBs are iteratively coordinated using a sequential optimization approach for achieving the global optimum. In the method, based on previously optimized NZEBs’ operation, the battery operations and associated power exchanges of individual NZEBs are optimized in series for grid overvoltage minimization. The research output has been published in Building Simulation (Zhang et al. 2022).

Methodology

Overview

Fig. 1 shows the basic idea of the proposed method which includes two parts. Part I is to conduct coordinated control optimization which coordinates individual NZEBs to achieve the minimization of the grid peak overvoltage. In this study, a typical grid model (i.e., IEEE Radial Distribution 33 Node Test Feeder) has been selected to represent the real power grid. Based on the power grid model, a global estimator is established for precise overvoltage quantification. In the proposed coordinated control method, the coordination is achieved by an iterative sequential optimization approach, which uses the updated optimal power exchanges of other NZEBs to optimize the power exchanges of individual NZEBs in series until the grid overvoltage converges.

Part II is to verify the optimal results with the following two steps implemented. Step II-1 firstly compares the overvoltage performance of the proposed coordinated control with an uncoordinated control. The uncoordinated control separately optimizes the battery operation of each NZEB for minimizing the individual peak power exchange. After performance comparison, the contribution effectiveness of power exchange reduction of both controls is evaluated to elaborate the reasons why the proposed coordinated control outperforms the uncoordinated one. In step II-2, the overvoltage performance of the proposed coordinated control is firstly compared with a conventional coordinated control. The conventional coordinated control oversimplifies the overvoltage quantification by using the total power exchange at NZEB-cluster-level to represent grid overvoltage. After performance comparison, the negative impacts of quantification oversimplification are evaluated to explain why the proposed control can achieve better performance.

The proposed coordinated control for minimizing grid peak overvoltage

To avoid the operation insecurity of electrical and electronic devices caused by the overvoltage problem, the voltage variation should be controlled at the prescribed limits, i.e., smaller than 6% of rated voltage in Hong Kong (Hong Kong Electric 2019). Following this control goal, a fitness function is expressed in Eq. (1), which aims to minimize the peak value of overvoltage (\(OV_{\text{peak}}\)) of the power grid (Zhang et al. 2020). Overvoltage of jth node in ith hour (\(OV_i^j\)) is defined as the ratio of its voltage variation to the voltage variation limits, as shown in Eq. (2).

\[
J = \min (OV_{\text{peak}}) = \min \left( \max \{OV_i^j\} \right) \quad \text{for } (i=1,2,\ldots,24; \ j=1,2,\ldots,n) \quad (1)
\]

\[
OV_i^j = \frac{\Delta V_i^j}{\Delta V_{\text{limit}}} \times 100\% \quad (2)
\]

Where, \(\Delta V_{\text{limit}}\) is the absolute value of the allowed voltage variation in Hong Kong; \(\Delta V_i^j\) is the voltage variation of...
Due to the low computation cost and easy convergence, an iterative sequential optimization approach is adopted to coordinate the battery operations of individual NZEBs in the cluster. In each iteration, the battery operations and power exchanges of individual NZEBs are sequentially optimized using GA (see Section 2.2.3). The optimized power exchanges of individual NZEBs are stored in the power exchange matrix in the global estimator and used for the power exchange optimization of the next NZEB.

**Figure 1:** The overall framework of this study.
After the power exchanges of all NZEBs are optimized, the whole power exchange matrix in the global estimator is correspondingly updated and used as the initial value of the next iteration. The iteration continues either until the number of iterations reaches a pre-defined value, or until the solutions are converged, as expressed in Eq. (3). Where \( \varepsilon \) is a user-defined threshold value; \( k \) is the number of iterations.

\[
\frac{|OV_{peak}^{k} - OV_{peak}^{k-1}|}{OV_{peak}^{k}} < \varepsilon
\]  

(3)

The output of the iterative sequential optimization is the optimized power exchange matrix of the NZEB cluster in the future 24 h \( [P_{j=1,n, opt}^{ex, 1}, p_{j=1,n, opt}^{ex, 2}, \ldots, p_{j=1,n, opt}^{ex, 24}] \).

In the optimization of individual NZEBs, GA is adopted due to its powerful searching capability. In the search rounds of \( j \)th GA optimizer (\( j=1,2,\ldots,n \)), where \( n \) is the number of NZEBs inside cluster), trial values of battery charging rates \( [P_{ch,1}, P_{ch,2}, \ldots, P_{ch,24}] \) are firstly generated. Based on trials of battery charging rates and the power generation and consumption in future 24 h, the power exchanges \( [P_{ex, 1}^j, P_{ex, 2}^j, \ldots, P_{ex, 24}^j] \) are obtained according to Eq. (4) and sent to the global estimator. In the global estimator, the \( j \)th row of power exchange matrix is consequently updated. Then the matrix is input to the distribution network model as presented in Section 3.1, in which the overvoltage profile is precisely predicted. Based on the overvoltage profile, the fitness function (i.e., peak overvoltage \( OV_{peak} \)) can be calculated.

\[
P_{ex,i}^j = P_{RES,i}^j - P_{con,i}^j - P_{ch,i}^j
\]  

(4)

The GA simulation repeats either until the number of generations reaches a pre-defined value or until the optimal solution reaches the termination tolerances. The outputs from \( j \)th GA optimizer are the optimized power exchanges \( [P_{ex, 1}^j, P_{ex, 2}^j, \ldots, P_{ex, 24}^j] \) of NZEB \( j \).

It should be noted that the operation of batteries should meet the following two constraints: (1) The battery charging amount could not exceed the remaining battery capacity. (2) The battery discharging amount could not exceed the stored electricity in the battery. These two constraints are expressed by Eq. (5) (Huang et al. 2018; Huang et al. 2020),

\[
CAP^j \times SOC_{min} \leq \Phi_d^j + (P_{ch,1}^j + P_{ch,2}^j + \ldots + P_{ch,n}^j) \times \Delta t \leq CAP^j \times SOC_{max}
\]  

(5)

**Verification of the optimal results**

Uncoordinated control is widely used in previous studies due to its simple structure and easy application. The battery charging rate of each NZEB is optimized separately using GA without considering the and coordination among NZEBs. The aim of the uncoordinated control is to minimize the peak power exchange of individual NZEBs. Thus, a fitness function is established for each GA optimizer, as expressed in Eq. (6).

\[
j_{GA,j} = \min(P_{ex,peak}^j) = \min \left( \max \left( \left[ P_{ex,1}^j, P_{ex,2}^j, \ldots, P_{ex,24}^j \right] \right) \right) (i=1,2,\ldots,n)
\]  

(6)

Similar to the GA optimization in the proposed control (see Section 2.2.3), trial values of battery charging rates \( [P_{ch,1}, P_{ch,2}, \ldots, P_{ch,24}] \) are firstly generated by the GA optimizer. According to the trial values of battery charging rate and the power generation and consumption of each NZEB, the local estimator estimates the fitness function of the individual peak power exchange. It should be noted that the practical constraints mentioned above also apply in the uncoordinated control (see Eq. (5)). The outputs of \( j \)th GA optimizer are the optimized power exchanges of NZEB \( j \) in the future 24 h \( [P_{ex, 1}^{opt}, P_{ex, 2}^{opt}, \ldots, P_{ex, 24}^{opt}] \).

After the proposed coordinated control is compared with an uncoordinated control for verification, it is further compared with a conventional coordinated control. Similar to the proposed coordinated control, an iterative sequential optimization approach is adopted to coordinate the battery operation of individual NZEBs. The major difference between these two controls is that the conventional coordinated control aims to minimize the total power exchange instead of the grid overvoltage due to the grid overvoltage quantification oversimplification. The fitness function of the conventional coordinated control is expressed in Eq. (7).

\[
J = \min(P_{extot,peak}^j) = \min(\max(\sum_{i=1}^{n} P_{ex,i}^j))
\]  

(7)

**Case studies and results analysis**

This section presents the case studies and associated results analysis. In the case studies, the renewable generations and energy demands of the 32 NZEBs were calculated using TRNSYS and the weather data of Hong Kong (https://energyplus.net/weather). The simulation period was 1 year; the prediction horizon was 24 hours; the control step was 1 hour. In the iterative sequential optimization approach, the maximum iteration number was set as 100 and the termination tolerance \( \varepsilon \) was set as 0.1\%, assuming that 0.1\% deviation has negligible impacts on building and grid performance. In the GA simulation, the population size was set as 200; the termination tolerance was set as 1e-8, and the maximum number of generations was set as 1000. These GA parameters have been tuned using the trial-and-error method to ensure that the GA simulation terminates by reaching the fitness limit.

In the following parts, the proposed coordinated control was firstly compared with the uncoordinated control and then compared with the conventional coordinated control in terms of peak overvoltage reduction. Among the three controls, the uncoordinated control optimized the battery operation of each NZEB separately for minimizing the individual power exchange; the conventional coordinated control coordinated individual NZEBs for minimizing the total power exchange; the proposed coordinated control...
coordinated individual NZEBs aiming at minimizing the grid overvoltage. Detailed analysis was also provided to elaborate the reasons why the proposed control outperformed these existing controls. Finally, the overvoltage performances of the three controls with the increase of battery capacity were compared.

**Overvoltage performance comparison with the uncoordinated control**

Fig. 2 compares the node overvoltage after applying the proposed coordinated control and the uncoordinated control. Compared with the baseline case (i.e., overvoltage without control), the proposed control can effectively reduce the peak overvoltage from 232.0% to 96.8%. In this way, overvoltage can be successfully controlled within the safe range of smaller than 100%. On contrast, the reduction of peak overvoltage of the uncoordinated control was less effective (from 232.0% to 126.6%). Compared with the uncoordinated control, the proposed control can achieve a relative improvement of 23.5%.

![Flowchart of the conventional coordinated control](image)

**Fig. 2. Flowchart of the conventional coordinated control.**

![Battery SOC and power exchange reduction](image)

**Fig. 3. Battery SOC and power exchange reduction of (a) NZEB 21; (b) NZEB 4; and (c) NZEB 6 after applying the uncoordinated control.**
Fig. 3 and 4 are used to explain why the proposed coordinated control outperformed the uncoordinated control in reducing the peak overvoltage. Fig. 3 presents the battery SOC and the associated power exchange reduction of three typical NZEBs (i.e., NZEB 21, 4 and 6) under the uncoordinated control. Aiming at minimizing individual-NZEB-level peak power exchange, the uncoordinated control did not consider the peak overvoltage mitigation. When the peak power exchange period was inconsistent with the peak overvoltage period (see NZEB 21 in Fig. 3(a)), the battery was charged to reduce the power exchange during the peak power exchange period instead of during the peak overvoltage period. Such power exchange reduction contribution was completely ineffective in the peak overvoltage mitigation. When the peak power exchange period was consistent with the peak overvoltage period (see NZEB 4 in Fig. 3(b)), the power exchange reduction contribution was fully effective in the peak overvoltage mitigation. When there existed two peak power exchange periods and one of them was consistent with the peak overvoltage period (see NZEB 6 in Fig. 3(c)), only a part of power exchange reduction contribution was effective in the peak overvoltage reduction, indicating a partially effective contribution. It can be summarized from Fig. 3 that a large amount of power exchange reductions of individual NZEBs cannot effectively contribute to the peak overvoltage mitigation under the uncoordinated control.

Fig. 4 presents the battery SOC and the associated power exchange reductions of the three NZEBs under the proposed coordinated control. It can be observed that in all NZEBs, the batteries were charged to reduce the power exchanges during the peak overvoltage period. Such power exchange reduction contributions of individual NZEBs were fully effective in the peak overvoltage mitigation. For instance, the batteries of both NZEB 4 and 6 were all used and fully charged (i.e., SOC increased from 0.3 to 1) to reduce the energy export during the peak overvoltage period, as shown in Fig. 4(b) and (c). Since the surplus renewable generation of NZEB 21 was small during the peak overvoltage period, partially charging/using the battery (i.e., SOC increased from 0.54 to 0.95) can effectively reduce the power export to 0, as shown in Fig. 4(a). Through such coordinated control, the large energy export during peak overvoltage period can be avoided, thereby effectively reducing the overvoltage risk.

Overvoltage performance comparison with conventional coordinated control

Fig. 5 compares the node overvoltage after applying the proposed coordinated control and the conventional coordinated control. The proposed control can achieve a lower peak overvoltage (i.e., 96.8%) and a more stable overvoltage shape compared with the conventional control (i.e., 110.4%). The relative improvement achieved 12.3%.

Fig. 6 is used to explain why the proposed coordinated control outperformed the conventional coordinated control in peak overvoltage minimization. Compared with the proposed control, the conventional control oversimplified the overvoltage quantification by using the total power exchange of NZEB-cluster to represent the grid overvoltage. To investigate the negative impacts of quantification oversimplification, three scenarios with the same total power exchange but different power exchange
distributions were established. Meanwhile, the main feeder with Node 1 to Node 18 was extracted from the IEEE 33 node test system as the distribution network since a simplified network can more easily identify the key reasons.

Due to the different power exchange distributions, the three scenarios showed large differences in the overvoltage performance, as presented in Fig. 6. For instance, linear increase scenario had the highest peak overvoltage of 175.1% while the peak overvoltage of linear decrease scenario (i.e., 89.7%) was the lowest, although they had the same total power exchange. Such a high overvoltage difference was mainly because the power exchanges distributed to the downstream nodes (Nodes 14 to 18) were different among three scenarios. Node voltage is determined by feeder resistances and associated power exchanges. Extremely high overvoltage will occur if large power exchanges are distributed at nodes with large resistances. For instance, linear increase scenario distributed the extremely large power exchanges at the downstream nodes with the largest resistances, thereby causing the highest overvoltage. In comparison, linear decrease scenario distributed small power exchanges at these nodes, which resulted in a much lower overvoltage. The large overvoltage difference among three scenarios verified that simply using the total power exchange to represent overvoltage can cause severe inaccuracies in overvoltage quantification, which may eventually lead to undesirable high overvoltage.

**Conclusion**

In this study, a GA-based NZEB-cluster coordinated control method has been proposed towards the power grid overvoltage optimization. In the proposed control, a distribution network model with accurate consideration of the complex voltage influences among grid nodes has been adopted to quantify associated grid overvoltage. Meanwhile, the battery operations of individual NZEBs have been coordinated using an iterative sequential optimization approach for minimizing the peak overvoltage with reduced computational complexity. The performance of the proposed coordinated control has been verified by comparing with an uncoordinated control and a conventional coordinated control. Results showed that compared with the uncoordinated control, the proposed coordinated control can achieve 23.5% of improvements in terms of peak overvoltage reduction. This was mainly because the proposed coordinated control can coordinate individual NZEBs more effectively for reducing the energy exports in the peak overvoltage period, thereby avoiding the completely ineffective or partially effective reductions existed in the uncoordinated control. Compared with the conventional coordinated control, the proposed coordinated control can still achieve 12.3% improvements in the peak overvoltage reduction. This was mainly because the proposed coordinated control can precisely quantify the grid overvoltage, and thus overcome the oversimplified overvoltage quantification and associated negative impacts in the conventional coordinated method. With the proven effectiveness in reducing the grid peak overvoltage, the proposed coordinated control can be used in practice to improve NZEB-clusters’ grid friendliness, especially as more NZEBs will be constructed in future.

Fig. 5. Node overvoltage after applying (a) proposed coordinated control and (b) conventional coordinated control.

Fig. 6. Comparison of overvoltages and power exchanges of different scenarios.
Acknowledgement

The research work presented in this paper is supported by the Public Policy Research (PPR) Funding Scheme (Project No. 2020.A1.097.20A).

References


