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Economic and technical analysis of reactive power provision from distributed energy resources in microgrids

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HIGHLIGHTS

- Reactive power costs for photovoltaic system and battery energy storage are proposed.
- Providing reactive power locally is not always economically or technically beneficial.
- Reactive power costs consideration is especially important in poorly distributed systems.
- DERs are found to be competitive with switched capacitors for reactive power provision.
- Inverter efficiency is the most crucial factor affecting DERs' reactive power provision.

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ABSTRACT

This work analyses the economic and technical impact of local reactive power provision in grid-connected microgrids with distributed energy resources. Costs of reactive power provision by photovoltaic systems and battery energy storage systems are explicitly formulated and an objective function incorporating the costs is proposed. The advantage of the proposed objective function is validated by comparing it with other objective functions frequently employed in the literature. From various case studies, the extent of economic and technical benefits of local reactive power provision for the microgrid is established. Subsequently, the technical and economic competitiveness of reactive power provision using inverter-based distributed energy resources are compared against those using switched capacitors. Extensive sensitivity analyses are performed to determine the scenarios in which one technology is more competitive than the other. Inverter efficiency has been identified as the most important parameter for reactive power provision from distributed energy resources while electricity price is the most crucial factor for switched capacitors' competitiveness in producing reactive power.

In this paper, all active, reactive and apparent power quantities have the units [kW], [kVA], and [kVAr] respectively.

1. Introduction

Reactive power dispatch (RPD) is an integral part of power systems operations, especially to manage voltage stability and line losses [1]. In distribution systems and microgrids, where the ratio of resistance to reactance is higher than in transmission systems, local reactive power compensation can significantly reduce the power losses, and thereby the operational costs [2,3]. To provide reactive power locally, many researchers have analyzed the optimal allocation and operation of reactive power compensation devices in distribution systems [4–7]. Recently, with the rise of inverter-based distributed energy resources (DERs) such as photovoltaic systems (PVs), many works have also proposed to use the inverters for local reactive power compensation [8–11], which have been shown to be capable in producing reactive power with little to even no additional costs [12,13]. Compared to traditional power factor correction devices that are used in distribution systems, i.e. capacitor banks, inverters have faster response time and therefore can regulate voltage more accurately, especially during transient disturbances [14]. Yet, despite the possibility to manage both active and reactive power of the DERs, most works have focused on one or the other.

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Nomenclature

Indices

- j,k distribution network node indices. Node j and k are adjacent, where current flows from j to k
- t index of time period ($1 \leqslant t \leqslant T$)
- x index of BESS, PV, and SC
- X indicators of BESS, PV, and/or SC quantities

Parameters

- $\eta^{\mathrm{CH}},\eta^{\mathrm{DCH}}$ charging and discharging efficiency of BESS
- η_{DOD} battery degradation constant related to depth-of-discharge (DOD) [SGD]
- η_P battery degradation constant related to charging and discharging power [SGD/kW^2]
- η_{SOC} battery degradation constant related to state-of-charge (SOC) [SGD]
- η_T power temperature coefficient of solar cells [°C^{-1}]
- c_R current-dependent loss coefficient of an inverter [kW^{-1}]
- c_{self} standby loss coefficient of an inverter [kW]
- c_V voltage-dependent loss coefficient of an inverter
- B,M number of BESS, and PV in the system
- E_x^{BESS} energy capacity of the xth BESS [kW h]
- H length of time period t [h]
- NOCT nominal operating temperature of solar cells [°C]
- $P_{\mathrm{rated}}^{\mathrm{PV}}$ rated power of the PV at standard test conditions
- $P_{\max}^{\mathrm{BESS}},P_{\min}^{\mathrm{BESS}}$ maximum charging and discharging power of BESS
- $P_{\max}^{\mathrm{X,invloss}}$ active power loss in BESS/PV inverter when $S_{\max}^{\mathrm{X}}$ flows through the inverter
- S_j^{bus} apparent power demand at node j. Available from the distribution system data
- $S_{\max}^{\mathrm{X}}$ BESS/PV inverter rating
- $\mathrm{SOC}_{\max}$ upper limit of the SOC of the BESS [%]
- $\mathrm{SOC}_{\min}$ lower limit of the SOC of the BESS [%]
- $\mathrm{SOC}_{\mathrm{ref}}$ reference SOC of the BESS for the degradation cost [%]

Variables

- $\delta_{x,t}^{\mathrm{CH}}$ charging variable that takes the value of 1 when $P_{x,t}^{\mathrm{BESS}} > 0$ and 0 otherwise
- $\delta_{x,t}^{\mathrm{DCH}}$ discharging variable that takes the value of 1 when $P_{x,t}^{\mathrm{BESS}} < 0$ and 0 otherwise
- $c_{x,t}^{\mathrm{BESS,deg}}$ cost of battery degradation from xth BESS [SGD]
- c_t^{Pgrid} price of active power from the grid (electricity price) at period t [SGD/kW h]
- c^{PPV} payment for active power generated by PV [SGD/kW h]
- c^{Qgrid} reactive power charge from the grid [SGD/kVArh]
- $c_{x,t}^{\mathrm{QX}}$ cost of producing reactive power using xth BESS/PV/SC at period t [SGD/kVArh]
- G_t solar irradiance at period t [W/m^2]
- $I_{jk,t}$ current flowing from node i to j at period t [p.u.]
- $I_{\max}$ upper limit of current flowing across the distribution lines [p.u.]
- P^{ave} average net load in the time periods considered
- $P_{x,t}^{\mathrm{BESS}}$ charging or discharging power of xth BESS at period t
- P_t^{grid} active power taken from the grid at period t
- $P_{j,t}^{\mathrm{load}}$ active power demand at node j at period t
- $P_{jk,t}^{\mathrm{loss}}$ active power losses on the line connecting node j and k at period t
- $P_{x,t}^{\mathrm{PV}}$ active power injected to the grid by xth PV at period t
- $P_{x,t}^{\mathrm{X,invloss}}$ active power loss in xth BESS/PV inverter at period t
- Q_t^{grid} reactive power taken from the grid at period t
- $Q_{j,t}^{\mathrm{load}}$ reactive power demand at node j at period t
- $Q_{jk,t}^{\mathrm{loss}}$ reactive power losses on the line connecting node j and k at period t
- $Q_{\mathrm{lim},t}^{\mathrm{X}}$ limit of reactive power generated by BESS/PV without reducing the BESS/PV active power output
- $Q_{x,t}^{\mathrm{X}}$ reactive power generated by xth BESS/PV/SC at period t
- $V_{j,t}$ voltage at node j at period t [p.u.]
- $S_{j,t}^{\mathrm{load}}$ apparent power demand at node j at period t
- $S_{jk,t}^{\mathrm{loss}}$ apparent power losses on the line connecting node j and k
- $S_{x,t}^{\mathrm{X}}$ apparent power flowing through xth BESS/PV inverter at period t
- $\mathrm{SOC}_{x,t}$ SOC of the xth BESS at period t [%]
- T_t^a,T_t^{PV} ambient and solar cells' temperature at period t [°C]

On the one hand, researchers have refined many optimization techniques to harness the potential of distributed active power generation, either to minimize power taken from the grid [15,16] or to minimize total costs of running a microgrid [17–21]. Nevertheless, many of them did not consider the test systems where the DERs are being implemented. Important indicators such as line losses and voltage variability were often ignored.

On the other hand, many works have also explored the optimization of reactive power provision by the DERs to provide ancillary services such as voltage support [22–24] as well as to reduce the transmission losses [9,24,25]. However, most of them took the active power component of the DERs as constant and did not take the system's economics or the reactive power costs into account.

Reactive power payment functions have been formulated for conventional generators [26,27] and reactive power devices [28]. The reactive power payment includes the availability payment, operation payment, and lost of opportunity payment. Using the payment functions, the reactive power dispatch optimization has been explored using market-based approaches, with objective functions ranging from minimization of expected payment function [26,27,29], societal advantage function [30], as well as other objectives including maximizing voltage stability and minimizing transmission losses [31]. However, the market-based approaches are mainly explored in transmission systems with limited number of DERs. In addition, the coefficients in the payment functions are generated randomly and therefore it is not clear how economical it is to produce the reactive power. Furthermore, the optimization generally occurs for only one time step, which is not suitable for time-dependent DERs such as PV.

Recently, there is more research considering the integrated optimization of active and reactive power. At the transmission level, [32] proposed the clearing of coupled of active and reactive power market, minimizing active and reactive power payment to the generators. Subsequently, [33] proposed multiobjective clearing of the coupled market.

Meanwhile, at the distribution level, [11] controlled the active and reactive power schedule of the BESS, together with the curtailment of wind power, to minimize the losses and wind curtailment. The scheduling of PV, BESS, transformers' settings, and controllable loads are optimized in [34] to minimize losses in distribution system. Liang et al. [6] proposed an enhanced firefly algorithm to solve multi-objective optimal active and reactive power dispatch, minimizing fuel costs, transmission losses, and voltage deviation. Sousa et al. [35] also minimized active power generation and voltage deviation, while considering various DERs, such as PV, wind, EV and biomass, in distribution system.

Both [10,36] solved the optimization of active and reactive power