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Oktoviano Gandhi

# Reactive Power Support Using Photovoltaic Systems

## Techno-Economic Analysis and Implementation Algorithms

Doctoral Thesis accepted by
National University of Singapore, Singapore,
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# Supervisor's Foreword

Electricity generation using Solar Photovoltaic (PV) system is now one of the most promising sources of energy and is expected to become a major component in most, if not all, electricity networks across the world. Due to the rapidly falling cost of PV panels in recent years, solar energy is becoming an attractive source of renewable energy. However, due to this increasing penetration of solar PV systems in the utility grid, many utilities are experiencing technical challenges due to their intermittency and lack of system inertia. One of the potential enablers to solve some of these challenges and to help us transition towards smart grid is PV reactive power management. That is why this thesis, which gives insights into the cost-effectiveness and practical implementations of PV reactive power support, is very timely and relevant. Through this thesis, Okto has analysed the costs and benefits of reactive power support using PV, both to the PV owner and to the power system operator. Although many before him have investigated the use of PV reactive power, none has formulated and quantified the costs as extensively. The reactive power cost formulations developed in this thesis will allow system engineers to calculate the appropriate remunerations that should be given for reactive power support from PV, and to compare the performance of PV inverter as a reactive power compensator with other sources of reactive power currently in use.

The literature review provided in the thesis covers the full spectrum of advantages and technical aspects that act as building blocks in the development of models, as well as the essential background to help acquire a thorough understanding of the issues and challenges. The thesis makes extensive use of mathematical modelling techniques to formulate approximations of power lines, losses and impact of reactive power on inverters. The use of real weather, load and electricity market data makes this thesis relevant not only to academics but also to power system regulators, operators and PV owners. In addition to the theoretical contributions, this thesis also proposes practical methods and algorithms to optimise the reactive power dispatch from distributed PV systems.

This thesis will make an ideal reference for those working in the field of solar energy, and a valuable learning resource for advanced students undertaking courses and projects as part of a broader sustainable energy programme.

Singapore, Singapore
July 2020

Prof. Dipti Srinivasan

# Abstract

As photovoltaic (PV) systems are becoming more widespread as a supplement, or even replacement, to conventional generators, many researchers have begun utilising reactive power from PV inverters to provide benefits to the power system. However, the economic costs and benefits of the reactive power support, as well as its practical implementation, have not been analysed in detail. Nevertheless, it is of utmost importance to evaluate the impacts that PV reactive power support brings to the PV owners as well as to the power system, so as to prevent costly retrofitting in the future. Hence, this work aims to quantify the economic and technical impacts of reactive power provision using PV and to explore practical and effective ways to optimise the PV reactive power dispatch in the power system. Consequently, this thesis is divided into two main aspects: (1) the formulation of reactive power cost from PV and (2) the development of algorithms to optimise reactive power dispatch efficiently and effectively.

The cost of reactive power from PV has been divided into two components, the inverter loss and the inverter degradation costs. This work has formulated both components mathematically, as well as quantified and compared them to other sources of reactive power using numerous case studies. Through comprehensive analysis, the feasible range for monetary incentives for PV reactive power support has been identified. It was noted that although reactive power compensation using PV is not as economical as switched capacitors (SCs) yet, it will be increasingly so with higher PV penetration and inverter efficiency in the future. Nevertheless, it was found that combinations of PV and SC for reactive power provision can be more technically and economically beneficial than just PV or SC alone.

Two algorithms have also been developed in this thesis. The first one is an analytical approach to solving optimal reactive power dispatch. The proposed approach overcomes the weaknesses of mathematical and metaheuristic programming, as it is able to incorporate non-convex cost functions, and is up to a 100 times faster compared with metaheuristic approaches commonly used in the literature. The second one is a data-driven local optimisation of global objectives. The proposed method is able to control the reactive power dispatch from PV and other distributed energy resources and was shown to perform almost as well as centralised optimisation, without any communication and without any information regarding the grid topology.

Therefore, the power system operator can analyse the benefits of PV reactive power, determine the appropriate remuneration for the reactive power support and choose from the two proposed algorithms to optimise the reactive power dispatch based on its situation. All in all, this research has for the first time comprehensively quantified and analysed the techno-economic cost and benefits of reactive power support using PV. Practical methods to implement reactive power dispatch in distribution systems have also been proposed. The findings and approaches in this work would then be able to help power system planners and operators in making sound regulations with regard to reactive power support from PV.

## Publications Related to This Thesis

### Journal Publications

[1] O. Gandhi, C. D. Rodríguez-Gallegos, W. Zhang, D. Srinivasan, and T. Reindl, "Economic and technical analysis of reactive power provision from distributed energy resources in microgrids," *Applied Energy*, vol. 210, pp. 827–841, 2018.

[2] O. Gandhi, W. Zhang, C. D. Rodríguez-Gallegos, D. Srinivasan, M. Bieri, and T. Reindl, "Analytical approach to optimal reactive power dispatch and energy arbitrage in distribution systems with DERs," *IEEE Transactions on Power Systems*, vol. 33, no.6, pp. 6522–6533, 2018.

[3] O. Gandhi, C. D. Rodríguez-Gallegos, N. B. Y. Gorla, M. Bieri, T. Reindl, and D. Srinivasan, "Reactive Power Cost from PV Inverters Considering Inverter Lifetime Assessment," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 2, pp. 738–747, 2019.

[4] O. Gandhi, C. D. Rodríguez-Gallegos, T. Reindl, and D. Srinivasan, "Competitiveness of PV Inverter as a Reactive Power Compensator considering Inverter Lifetime Reduction," *Energy Procedia*, vol. 150, pp. 74–82, 2018.

[5] O. Gandhi, W. Zhang, C. D. Rodríguez-Gallegos, H. Verbois, H. Sun, T. Reindl, and D. Srinivasan, "Local Reactive Power Dispatch Optimisation Minimizing Global Objectives," *Applied Energy*, vol. 262, 2020.

### Conference Publications

[1] O. Gandhi, W. Zhang, C. D. Rodríguez-Gallegos, D. Srinivasan, and T. Reindl, "Continuous optimisation of reactive power from PV and EV in distribution system," in *2016 IEEE Innovative Smart Grid Technologies—Asia (ISGT-Asia).* Melbourne: IEEE, nov 2016, pp. 281–287.

[2] O. Gandhi, C. D. Rodríguez-Gallegos, and D. Srinivasan, "Review of optimisation of power dispatch in renewable energy system," in *2016 IEEE Innovative Smart Grid Technologies—Asia (ISGT-Asia).* Melbourne: IEEE, nov 2016, pp. 250–257.

[3] O. Gandhi, D. Srinivasan, C. D. Rodríguez-Gallegos, and T. Reindl, "Competitiveness of Reactive Power Provision using PV Inverter in Distribution System," in *2017 IEEE Innovative Smart Grid Technologies—Europe (ISGT-Europe).* Torino: IEEE, sep 2017.

[4] O. Gandhi, C. D. Rodríguez-Gallegos, T. Reindl, and D. Srinivasan, "Locally-determined Voltage Droop Control for Distribution Systems," in *2018 IEEE Innovative Smart Grid Technologies—Asia (ISGT-Asia).* Singapore: IEEE, may 2018, pp. 425–429.

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# Contents

# Symbols

| | |
|---|---|
| $\alpha$ | temperature coefficient of $I_t^{\mathrm{PV,SC}}$ |
| $\beta$ | temperature coefficient of $V_t^{\mathrm{PV,OC}}$ |
| $\Delta P_{\mathrm{nadir}}^{\mathrm{loss}}$ | difference in active power loss in a system because of the charging of BESS/EV at price nadir |
| $\Delta P_{\mathrm{peak}}^{\mathrm{loss}}$ | difference in active power loss in a system because of the discharging of BESS/EV at price peak |
| $\Delta P_{x,t}^{\mathrm{X,oppcost}}$ | active power of the *x*th DER that has to be curtailed to generate reactive power more than $Q_{x,t,lim}^{X}$ |
| $\Delta P_{x,t}^{\mathrm{BESS,invloss}}$ | additional power loss in the inverter of the *x*th BESS due to its reactive power injection/absorption |
| $\Delta P_{x,t}^{\mathrm{EV,invloss}}$ | total additional power loss in the inverters of the *x*th EV parking lot due to its reactive power injection/absorption |
| $\Delta P_{x,t}^{\mathrm{PV,invloss}}$ | additional power loss in the inverter of the *x*th PV system due to its reactive power injection/absorption |
| $\Delta P_{x,t}^{\mathrm{PV}}$ | maximum error prediction for $P_{x,t}^{PV}$ |
| $\Delta Q_{\mathrm{nadir}}^{\mathrm{loss}}$ | difference in reactive power loss in a system because of the charging of BESS/EV at price nadir |
| $\Delta Q_{\mathrm{peak}}^{\mathrm{loss}}$ | difference in reactive power loss in a system because of the discharging of BESS/EV at price peak |
| $\delta_{x,t}^{\mathrm{CH}}$ | binary variable that takes the value of 1 when $P_{x,t}^{\mathrm{BESS}} > 0$, and 0 otherwise |
| $\delta_{x,t}^{\mathrm{DCH}}$ | binary variable that takes the value of 1 when $P_{x,t}^{\mathrm{BESS}} < 0$, and 0 otherwise |
| $\eta^{\mathrm{LI,A0}}$ | numerator coefficient of the zeroth-order LR from fitting the values of LI to those of LR |
| $\eta^{\mathrm{LI,A1}}$ | numerator coefficient of the first-order LR from fitting the values of LI to those of LR |
| $\eta^{\mathrm{LI,B0}}$ | denominator coefficient of the zeroth-order LR from fitting the values of LI to those of LR |

| | |
|---|---|
| $\eta^{\mathrm{LI,B1}}$ | denominator coefficient of the first-order LR from fitting the values of LI to those of LR |
| $\eta^{\mathrm{LR,0}}$ | coefficient of the zeroth-order $Q_t^{\mathrm{PV}}$ from fitting the values of ILR cost per hour with $Q_t^{\mathrm{PV}}$ |
| $\eta^{\mathrm{LR,1}}$ | coefficient of the first-order $Q_t^{PV}$ from fitting the values of ILR cost per hour with $Q_t^{\mathrm{PV}}$ |
| $\eta^{\mathrm{LR,2}}$ | coefficient of the second-order $Q_t^{\mathrm{PV}}$ from fitting the values of ILR cost per hour with $Q_t^{\mathrm{PV}}$ |
| $\eta^{\mathrm{LR,3}}$ | coefficient of the third-order $Q_t^{\mathrm{PV}}$ from fitting the values of ILR cost per hour with $Q_t^{\mathrm{PV}}$ |
| $\eta^{\mathrm{P,0}}$ | coefficient of the zeroth-order $\tilde{P}^{\mathrm{loss}}$ from fitting the values of $\tilde{P}^{\mathrm{loss}}$ to those of $P^{\mathrm{loss}}$ |
| $\eta^{\mathrm{P,1}}$ | coefficient of the first-order $\tilde{P}^{\mathrm{loss}}$ from fitting the values of $\tilde{P}^{\mathrm{loss}}$ to those of $P^{\mathrm{loss}}$ |
| $\eta^{\mathrm{Q,0}}$ | coefficient of the zeroth-order $\tilde{Q}^{\mathrm{loss}}$ from fitting the values of $\tilde{Q}^{\mathrm{loss}}$ to those of $Q^{\mathrm{loss}}$ |
| $\eta^{\mathrm{Q,1}}$ | coefficient of the first-order $\tilde{Q}^{\mathrm{loss}}$ from fitting the values of $\tilde{Q}^{loss}$ to those of $Q^{\mathrm{loss}}$ |
| $\eta^{\mathrm{QLim}}$ | constant limiting the change in $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta^{\mathrm{T}}$ | power temperature coefficient of solar cells |
| $\eta_x^{\mathrm{BESS,DOD}}$ | battery degradation coefficient related to depth of discharge of the *x*th BESS |
| $\eta_x^{\mathrm{BESS,P}}$ | battery degradation coefficient related to charging power of the *x*th BESS |
| $\eta_x^{\mathrm{BESS,SOC}}$ | battery degradation coefficient related to SOC of the *x*th BESS |
| $\eta_x^{\mathrm{B}}$ | round-trip efficiency of the *x*th BESS. It is the multiplication of $\eta_x^{\mathrm{CH}}$ and $\eta_x^{\mathrm{DCH}}$ |
| $\eta_x^{\mathrm{CH}}$ | charging efficiency of the *x*th BESS |
| $\eta_x^{\mathrm{DCH}}$ | discharging efficiency of the *x*th BESS |
| $\eta_x^{\mathrm{PLoss,0}}$ | coefficient of the zeroth-order from fitting the values of $P_t^{\mathrm{loss}}$ to $V_{\mathrm{x,t}}$ and $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{PLoss,Q1}}$ | coefficient of the first-order $Q_{x,t}^{\mathrm{PV}}$ from fitting the values of $P_t^{\mathrm{loss}}$ to $V_{\mathrm{x,t}}$ and $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{PLoss,Q2}}$ | coefficient of the second-order $Q_{x,t}^{\mathrm{PV}}$ from fitting the values of $P_t^{\mathrm{loss}}$ to $V_{x,t}$ and $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{PLoss,V1}}$ | coefficient of the first-order $V_{x,t}$ from fitting the values of $P_t^{\mathrm{loss}}$ to $V_{x,t}$ and $Q_{x,t}^{PV}$ |

| | |
|---|---|
| $\eta_x^{\mathrm{PLoss,V2}}$ | coefficient of the second-order $V_{x,t}$ from fitting the values of $P_t^{\mathrm{loss}}$ to $V_{x,t}$ and $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{QLoss,0}}$ | coefficient of the zeroth-order from fitting the values of $Q_t^{\mathrm{loss}}$ to $V_{x,t}$ and $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{QLoss,Q1}}$ | coefficient of the first-order $Q_{x,t}^{\mathrm{PV}}$ from fitting the values of $Q_t^{\mathrm{loss}}$ to $V_{x,t}$ and $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{QLoss,Q2}}$ | coefficient of the second-order $Q_{x,t}^{\mathrm{PV}}$ from fitting the values of $Q_t^{\mathrm{loss}}$ to $V_{x,t}$ and $Q_{x,t}^{PV}$ |
| $\eta_x^{\mathrm{QLoss,V1}}$ | coefficient of the first-order $V_{x,t}$ from fitting the values of $Q_t^{\mathrm{loss}}$ to $V_{x,t}$ and $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{QLoss,V2}}$ | coefficient of the second-order $V_{x,t}$ from fitting the values of $Q_t^{\mathrm{loss}}$ to $V_{x,t}$ and $Q_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{V,P1}}$ | coefficient of the first-order $P_{x,t}^{\mathrm{PV}}$ relating $V_{x,t}$ to $P_{x,t}^{\mathrm{PV}}$ |
| $\eta_x^{\mathrm{V,Q1}}$ | coefficient of the first-order $Q_{x,t}^{\mathrm{PV}}$ relating $V_{x,t}$ to $Q_{x,t}^{\mathrm{PV}}$ |
| $\gamma$ | irradiance correction factor of $V_t^{\mathrm{PV,OC}}$ |
| $\phi$ | phase angle between voltage and current in an AC circuit or system |
| $\mathrm{SOC}_{x,\max}$ | maximum SOC of the $x$th BESS |
| $\mathrm{SOC}_{x,\min}$ | minimum SOC of the $x$th BESS |
| $\mathrm{SOC}_{x,t}$ | SOC of the $x$th BESS |
| $\tilde{P}^{\mathrm{loss,init}}$ | approximate total initial active power loss in a system before adding any DER into the system |
| $\tilde{P}^{\mathrm{loss}}$ | approximate total active power loss in a system |
| $\tilde{P}_i^{\mathrm{loss}}$ | approximate active power loss on the line from sending node $i$ |
| $\tilde{Q}^{\mathrm{loss,init}}$ | approximate total initial reactive power loss in a system before adding any DER into the system |
| $\tilde{Q}^{\mathrm{loss}}$ | approximate total reactive power loss in a system |
| $\tilde{Q}_i^{\mathrm{loss}}$ | approximate reactive power loss on the line from sending node $i$ |
| $B$ | number of BESS in a system |
| $c_{x,t}^{\mathrm{BESS,deg}}$ | battery degradation cost of the $x$th BESS |
| $c_t^{\mathrm{Pgrid}}$ | cost of active power from the grid |
| $c_x^{\mathrm{PPV}}$ | cost of active power from the $x$th PV system. It is equivalent to LCOE of the PV system, and is assumed to be fixed for the lifetime of the PV system |
| $c_{x,t}^{\mathrm{QBESS}}$ | cost of reactive power from the $x$th BESS |
| $c_{x,t}^{\mathrm{QEV}}$ | cost of reactive power from the $x$th EV parking lot |
| $c^{\mathrm{Qgrid}}$ | cost of reactive power from the grid |
| $c_{x,t}^{\mathrm{QPV}}$ | cost of reactive power from the $x$th PV system |

| | |
|---|---|
| $c_{x,t}^{\mathrm{QPV,invloss}}$ | inverter power loss component of the reactive power cost from the $x$th PV system |
| $c_{x,t}^{\mathrm{QPV,LR}}$ | inverter lifetime reduction component of the reactive power cost from the $x$th PV system |
| $c_{x,t}^{\mathrm{QSC}}$ | cost of reactive power from the $x$th SC |
| $c_{x}^{\mathrm{BESS,R}}$ | current-dependent loss coefficient of the inverter of the $x$th BESS |
| $c_{x}^{\mathrm{BESS,self}}$ | standby loss coefficient of the inverter of the $x$th BESS |
| $c_{x}^{\mathrm{BESS,V}}$ | voltage-dependent loss coefficient of the inverter of the $x$th BESS |
| $c_{x}^{\mathrm{PV,R}}$ | current-dependent loss coefficient of the inverter of the $x$th PV system |
| $c_{x}^{\mathrm{PV,self}}$ | standby loss coefficient of the inverter of the $x$th PV system |
| $c_{x}^{\mathrm{PV,V}}$ | voltage-dependent loss coefficient of the inverter of the $x$th PV system |
| $E$ | number of EV parking lots in a system |
| $E_{x}^{\mathrm{BESS}}$ | energy capacity of the $x$th BESS |
| $G_{x,t}^{70}$ | upper limit of forecasted irradiance falling on the $x$th PV system in a distribution system at 70% confidence level |
| $G_{t}^{\mathrm{clear}}$ | clear sky irradiance |
| $G_{x,t}$ | irradiance falling on the $x$th PV system in a distribution system. In this book, the irradiance is assumed to be uniform within a particular distribution system for simplicity, such that the value of $G_{x,t}$ is the same for all $x$ |
| $H$ | length of time period in [hour] |
| $i$ | index for bus/node in a system |
| $I_{t}^{\mathrm{CAP,ACrms}}$ | RMS AC current flowing through the DC-link capacitors in a PV inverter |
| $I_{t}^{\mathrm{CAP,ripple}}$ | ripple current flowing through the DC-link capacitors in a PV inverter |
| $I_{t}^{\mathrm{PV,SC}}$ | PV module short circuit current |
| $I_{t}^{\mathrm{PV}}$ | PV module current |
| $I_{\max}$ | upper bound current magnitude across the line in a system |
| $I_{i,t}$ | current flowing from sending node $i$ |
| $j$ | index for bus/node in a system |
| $k$ | index for bus/node in a system |
| $L^{\mathrm{CAP,P}}$ | lifetime of the DC link capacitors, and hence the inverter, when it is only used for $P^{\mathrm{PV}}$ |
| $L^{\mathrm{CAP,Q}}$ | lifetime of the DC link capacitors, and hence the inverter, when it is used for both $P^{\mathrm{PV}}$ and $Q^{\mathrm{PV}}$ |
| $L^{\mathrm{CAP}}$ | estimated lifetime of the DC link capacitors, and hence the inverter of a particular PV system |
| $L_{\mathrm{ref}}^{\mathrm{CAP}}$ | reference lifetime of the DC-link capacitors in a PV inverter |

| | |
|---|---|
| $L_t^{\mathrm{CAP}}$ | expected lifetime of the DC-link capacitors in a PV inverter for a particular operating condition. The lifetime of all the DC-link capacitors in an inverter is assumed to be the same for simplicity |
| $L^{\mathrm{PV}}$ | lifetime of a PV system |
| $M$ | number of PV systems in a system |
| $M_t$ | modulation index of a PV inverter |
| $N^{\mathrm{PV,par}}$ | number of PV strings connected in parallel for a PV system |
| $N^{\mathrm{PV,ser}}$ | number of PV modules connected in series in a string |
| $P'_i$ | active power flowing across the line from sending node *i* before the addition of any DER into the system |
| $P_{x,t}^{\mathrm{BESS}}$ | charging (positive)/discharging (negative) power of the *x*th BESS |
| $P_{x,t}^{\mathrm{EV}}$ | total charging (positive)/discharging (negative) power of the *x*th EV parking lot |
| $P_t^{\mathrm{grid}}$ | active power from the grid |
| $P_{i,t}^{\mathrm{load}}$ | active power load at node *i* |
| $P_{i,t}^{\mathrm{loss}}$ | active power loss on the line from sending node *i* |
| $P_t^{\mathrm{loss}}$ | total active power loss in the system |
| $P_{x,t}^{\mathrm{PV70}}$ | upper limit of forecasted active power from the *x*th PV system at 70% confidence level |
| $P_{x,t}^{\mathrm{PV}}$ | active power from the *x*th PV system |
| $P_{\mathrm{ave}}^{\mathrm{PV}}$ | average active power generated by a PV system at each period *t* over the lifetime of the system, taking into account the reduction of PR in later years |
| $P_i$ | active power flowing across the line from sending node *i* |
| $P_{x,\mathrm{max}}^{\mathrm{BESS}}$ | maximum charging power of the *x*th BESS |
| $P_{x,\mathrm{max}}^{\mathrm{EV}}$ | maximum charging power of the *x*th EV parking lot |
| $P_{x,\mathrm{max}}^{\mathrm{PV,invloss}}$ | maximum power loss in the inverter of the *x*th PV system |
| $P_{x,\mathrm{min}}^{\mathrm{BESS}}$ | maximum discharging power of the *x*th BESS |
| $P_{x,\mathrm{rated}}^{\mathrm{PV}}$ | power rating at STC of the *x*th PV system |
| $P_{x,t}^{\mathrm{BESS,invloss}}$ | power loss in the inverter of the *x*th BESS |
| $P_{x,t}^{\mathrm{PV,invloss}}$ | power loss in the inverter of the *x*th PV system |
| $PR'$ | performance ratio of a PV system before taking into account the inverter losses |
| $Q'_i$ | reactive power flowing across the line from sending node *i* before the addition of any DER into the system |
| $Q_{x,t}^{\mathrm{BESS}}$ | reactive power from the *x*th BESS |
| $Q_{x,t}^{\mathrm{EV}}$ | total reactive power from the *x*th EV parking lot |
| $Q_t^{\mathrm{grid}}$ | reactive power from the grid |
| $Q_{i,t}^{\mathrm{load}}$ | reactive power load at node *i* |

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| $Q_{i,t}^{\mathrm{loss}}$ | reactive power loss on the line from sending node $i$ |
| $Q_t^{\mathrm{loss}}$ | total reactive power loss in the system |
| $Q_{x,t}^{\mathrm{PV}}$ | reactive power from the $x$th PV system |
| $Q_i$ | reactive power flowing across the line from sending node $i$ |
| $Q_{x,t,\mathrm{lim}}^{\mathrm{PV}}$ | the maximum reactive power that can be generated by PV without reducing its active power output beyond the additional inverter loss |
| $Q_{x,t,\mathrm{lim}}^{\mathrm{X}}$ | the maximum reactive power that can be generated by the DERs without reducing their active power output |
| $R^{\mathrm{CAP,s}}$ | series resistance of the DC-link capacitors in a PV inverter |
| $R^{\mathrm{CAP,th}}$ | thermal resistance of the DC-link capacitors in a PV inverter |
| $R^{\mathrm{PV,s}}$ | PV module series resistance |
| $R_{ij}$ | effective resistance connecting node $i$ and node $j$ |
| $r_i$ | resistance of the line from sending node $i$ |
| $S^{\mathrm{loss}}$ | total apparent power loss in a system |
| $S_{i,t}^{\mathrm{loss}}$ | apparent power loss on the line from sending node $i$ |
| $S_{x,\mathrm{max}}^{\mathrm{PV}}$ | inverter power rating of the $x$th PV system |
| $S_{x,\mathrm{max}}^{\mathrm{X}}$ | inverter power rating of the $x$th DER |
| $S_{x,t}^{\mathrm{BESS}}$ | apparent power from the $x$th BESS |
| $S_{x,t}^{\mathrm{PV}}$ | apparent power from the $x$th PV system |
| $T$ | number of time periods in a simulation |
| $t$ | index for time period |
| $T_{x,t}^{\mathrm{a70}}$ | upper limit of ambient temperature experienced by the $x$th PV system in a distribution system at 70% confidence level |
| $T_{x,t}^{\mathrm{a}}$ | ambient temperature experienced by the $x$th PV system in a distribution system. In this book, the ambient temperature is assumed to be uniform within a particular distribution system for simplicity, such that the value of $T_{x,t}^{a}$ is the same for all $x$ |
| $T_t^{\mathrm{CAP,P}}$ | operating temperature of the DC link capacitors in a PV inverter, when it is only used for $P^{\mathrm{PV}}$ |
| $T_{\mathrm{ref}}^{\mathrm{CAP}}$ | temperature rating of the DC-link capacitors in a PV inverter |
| $T_t^{\mathrm{CAP}}$ | operating temperature of the DC-link capacitors in a PV inverter |
| $T_{x,t}^{\mathrm{PV}}$ | solar cell temperature of the $x$th PV system. All the solar cells in a PV system is assumed to have the same temperature for simplicity |
| $V_{\mathrm{ref}}^{\mathrm{CAP}}$ | voltage rating of the DC-link capacitors in a PV inverter |
| $V_t^{\mathrm{CAP}}$ | operating voltage of the DC-link capacitors in a PV inverter |
| $V^{\mathrm{INV,AC}}$ | line-to-line RMS AC output voltage of a PV inverte |
| $V^{\mathrm{INV,DC}}$ | rated DC voltage of a PV inverter |
| $V_t^{\mathrm{PV,OC}}$ | PV module open circuit voltage |
| $V_t^{\mathrm{PV}}$ | PV module voltage |

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| $V_{\max}$ | upper bound voltage magnitude of the nodes in a system |
| $V_{\min}$ | lower bound voltage magnitude of the nodes in a system |
| $V_{\text{ref}}$ | reference voltage magnitude in a system, usually taken as 1.0 p.u. |
| $V_{i,t}$ | voltage at node $i$ |
| $V_{x,t}^{\text{meas}}$ | measured voltage at the node where the $x$th PV system is located |
| $V_{x,t}^{\text{pred}}$ | predicted voltage at the node where the $x$th PV system is located |
| $X$ | superscript denoting that the quantity is associated to DERs (either BESS, EV parking lot, PV system, or SC) |
| $x$ | index for PV and other DERs in a system |
| $X_{ij}$ | effective reactance connecting node $i$ and node $j$ |
| $x_i$ | reactance of the line from sending node $i$ |