Balancibility: Existence and Uniqueness of Power Flow Solutions under Voltage Balance Requirements

In distribution systems, power injection variability due to growing penetrations of distributed energy resources (DERs) and dispatchable loads can lead to power quality issues such as severe voltage unbalance. To ensure safe operation of phase-balance-sensitive components such as transformers and induction motor loads, the amount of voltage unbalance must be maintained within specified limits for a range of uncertain loading conditions. This paper builds on existing ``solvability conditions" that characterize operating regions for which the power flow equations are guaranteed to have a unique high-voltage solution. We extend these existing solvability conditions to be applicable to distribution systems and augment them with a ``balancibility" condition which quantifies an operating region within which a unique, adequately balanced power flow solution exists. To build this condition, we consider different unbalance definitions and derive closed-form representations through reformulations or safe approximations. Using case studies, we evaluate these closed-form representations and compare the balancibility conditions associated with different unbalance definitions.