

Probabilistic Power-Flow Analysis of Distribution Networks Using Advanced Source-Load Models and Time-Varying Drawable Vine Copulas

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DESCRIPTION

Distribution networks are becoming increasingly dynamic as renewable generation, electric vehicles, flexible loads, battery storage and other distributed energy resources become more widely integrated. These changes introduce substantial uncertainty into both electricity production and consumption. Conventional deterministic load-flow calculations generally use fixed operating conditions and therefore provide only one network state for a selected set of inputs. Such an approach may be insufficient when photovoltaic output, wind generation, demand and other variables fluctuate over time. Probabilistic load flow provides a broader framework by representing uncertain inputs through probability distributions and evaluating their combined effects on voltages, branch currents, active power and reactive power. Accurate probabilistic analysis depends strongly on how source and load behavior are represented. Renewable sources are influenced by environmental variables such as solar irradiance and wind speed, while electricity demand follows daily, weekly and seasonal patterns. These variables may also exhibit correlations that cannot be adequately described by treating every input as independent.

Photovoltaic generation is related to solar conditions, while residential demand may vary according to temperature, occupancy and time of day. An advanced source-load model can therefore provide a more realistic representation of the changing conditions within a distribution. The Drawable Vine D-vine copula offers a flexible mathematical framework for describing dependence among multiple uncertain variables. Unlike conventional correlation-based approaches, a copula separates the marginal probability behavior of individual variables from their dependence structure. This makes it possible to model variables with different probability distributions while preserving important relationships among them. A D-vine structure decomposes a multivariable dependence model into a sequence of pairwise relationships, allowing complex interactions to be represented in a systematic manner.

Introducing time variation into the D-vine framework is particularly valuable for distribution networks because dependence patterns are rarely constant throughout the day. The relationship between renewable generation and electrical demand during midday may differ considerably from that observed during evening hours. Similarly, correlations among different photovoltaic units can change with weather conditions and geographical effects. A time-varying D-vine copula can adapt the dependence structure to different periods, providing a more realistic representation of the changing statistical behavior of source and load variables. Once suitable marginal distributions and dependence relationships have been established, correlated source-load scenarios can be generated for probabilistic load-flow calculations. Each scenario represents a possible combination of renewable generation and demand conditions. These scenarios are then supplied to a network power-flow model to determine the corresponding electrical state. Repeating this process across many scenarios produces probability distributions for important network quantities rather than a single deterministic result.

Voltage magnitude is one of the most important outputs because high penetration of distributed generation can cause voltage fluctuations and local overvoltage. Probabilistic results can indicate the likelihood that a bus voltage will exceed an operational limit. Similarly, branch loading distributions can reveal the probability of thermal overload under changing source and demand conditions. Such information is useful for identifying vulnerable sections of a network and assessing whether existing infrastructure can accommodate additional distributed resources. The combination of advanced source-load modeling and time-varying dependence analysis can also improve planning decisions. Network operators may use probabilistic information to evaluate reinforcement requirements, voltage-control strategies, energy-storage placement and distributed-generation capacity. Instead of designing a network solely for one extreme operating condition, planners can consider the frequency and probability of different conditions. This can support more economical decisions while maintaining acceptable reliability.

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Computational efficiency remains an important consideration because detailed probabilistic calculations can require large numbers of scenarios. Efficient sampling methods, adaptive scenario selection, parallel computation and suitable numerical power-flow algorithms can reduce processing requirements. The D-vine structure can also provide a manageable way to represent high-dimensional dependence without constructing one excessively complex multivariate distribution. Another advantage of the approach is its adaptability to changing network conditions. As new renewable generators, electric vehicles, storage systems or flexible loads are introduced, their

statistical characteristics can be incorporated into the source-load framework. Updated observations can also be used to modify marginal distributions and time-dependent dependence parameters. This adaptability is increasingly important as distribution systems move toward more decentralized and active operating structures. Nevertheless, the quality of probabilistic results depends on the quality of the underlying data and assumptions. Insufficient historical information, inaccurate marginal distributions or poorly estimated dependence parameters can affect the resulting network probability distributions.