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Optimal Load Shedding in Electricity Grids with Renewable Sources via Message Passing

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Abstract

The increased penetration of volatile and intermittent renewable energy sources challenges existing power-distribution methods as current dispatch methods were not designed to consider high levels of volatility. We suggest a principled algorithm called message passing, which complements existing techniques. It is based on statistical physics methodology and passes probabilistic messages locally to find the approximate global optimal solution for a given objective function. The computational complexity of the algorithm increases linearly with the system size, allowing one to solve large-scale problems. We show how message passing considers fluctuations effectively and prioritise consumers in the event of insufficient resource. We demonstrate the efficacy of the algorithm in managing load-shedding and power-distribution on synthetic benchmark IEEE data and discuss the role of weights in the trade-off between minimising load-shedding and transmission costs.

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Keywords: Electricity distribution; load shedding; message passing; networks; optimisation; power flow; renewable energy; uncertainty

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1. Introduction

Recent EU legislations aims for 20% of all of generated power to be from renewable sources [1] by 2020 in order to limit the use of destructive and unsustainable power sources such as fossil fuels and nuclear plants. While renewable sources such as wind and solar offer a clean, mature and tested technology they are fluctuating and are

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not fully under human control. This, in addition to the fluctuations in demand, results in higher levels of uncertainty in planning power generation and distribution at the economic dispatch stage over the 15-60 min time window. The current distribution method was not designed to consider such high levels of uncertainty and a new method is sought. An effective distribution algorithm must also consider scenarios where generation does not meet demand, especially with the inevitable increased fluctuations in power systems. This paper suggests representing uncertainties as probability distributions and using message passing, which inherently considers probabilistic scenarios to find a global solution at the economic dispatch stage of power distribution.

Power distribution is currently modelled using optimal power flow (OPF) [2]. Assuming initial voltages, the first step to adjust voltages uses Newton Raphson or a fast-decoupled method to satisfy Kirchoff's law. The second step seeks a better solution using steepest descent or similar techniques and the algorithm is repeated until an optimal is found. OPF has been used for a long time with little change, it makes small adjustments and uses linear techniques to consider network fluctuations, but is less effective when considering the large scale fluctuations introduced by renewable sources. Existing alternative methods of optimal power distribution include: chance constrained OPF [3, 4], which builds on previous work [5], suggests that adding probabilities to the hard constraints of OPF is sufficient for considering renewable fluctuations; and the interior point method [6], which uses matrices to solve network constraints and a predictor-corrector technique to improve the solution. The majority of existing methods are heuristic and consider fluctuations superficially.

Message passing (MP) [7, 8] is a principled technique which passes conditional probabilities locally to find an optimal solution with modest computational complexity. This enables the algorithm to inherently consider the probabilistic nature of renewable sources and address very large scale problems. Message passing algorithms have been developed to consider bandwidth [9] and fluctuations [10].

This paper extends previous work on fluctuations to include load shedding when demand exceeds power generation. One aspect of the extension with respect to previous work is the consideration of load shedding in the presence of weighted nodes, where weights indicate the importance of nodes, section 2. We demonstrate the effects of the suggested algorithm on synthetic benchmark IEEE networks and randomly generated random-regular graphs in section 3. Section 4 discusses the advantages of message passing and possible future directions.

2. Methodology

Consider a network of N nodes (consumers/generators/ substations), connected to c others (degree connectivity can be heterogeneous but we keep them uniform within derivations for simplicity), each node j has a capacity Λ_j, which indicates if the node is a consumer (negative) or a generator (positive). In power distribution, generator i sends power y_{ij} to consumer j via power lines (edges) such that $y_{ij} = -y_{ji}$, in order to satisfy the constraint that all nodes need to be satisfied, i.e., have non-negative resource. As mentioned, in some cases there is insufficient power to satisfy all consumers and the algorithm distributes what is available. To model this one adds a *load-shedding* variable ζ_j to the constraint, which should be minimised. Mathematically the constraint can be written as in Eq. (1):

$$\sum_{(ij)} \mathcal{A}_{ij} y_{ij} + \Lambda_j + \zeta_j \geq 0 \tag{1}$$

for each node j, where (ij) describes any pair of nodes, $\mathcal{A}_{ij} = 1$, if nodes i and j are connected by an edge, and 0 otherwise; this is one of many constraints a power flow model must consider (others include bandwidth over edges and keeping generated power between the minimum and maximum capacities). A power distribution algorithm must also minimise functions such as: power loss, load shedding and generation costs; this paper describes the first two. To consider minimising transportation costs we use the equation $\phi = \frac{y_{ij}^2}{2}$ (loosely based on the power loss equation, but other loss functions and models can be considered). To minimise load shedding we minimise the deficit of each node multiplied by some predetermined weight indicating its importance: $\psi = \frac{\alpha_j \zeta_j^2}{2}$, where α_j is the importance weight of the node j. The general energy equation of the network can be written as:

$$\mathrm{E} = \sum_{(ij)} \mathcal{A}_{ij} \phi\left(y_{ij}\right) + \sum_j \psi\left(\zeta_j\right) \tag{2}$$