Load Flow with Uncertain Loading and Generation in Future Smart Grids

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Abstract. The growing amount of renewable and fluctuating energy sources for the production of electrical energy increases the volatility and level of uncertainty in the operation of power systems. Whether it is the growing number of photovoltaic installations harnessing solar energy or large-scale wind farms, these new class of environmentally dependent appliances increase the unpredictability of load situations hitherto known only from consumer behavior. One of the mayor concerns in grid operation under increasing feed-in from unpredictable generation and consumption is the detection of peaks in network strain. In order to limit investments into grid infrastructure to a reasonable level node-specific limitations for power injections are introduced to reduce the probability of such peaks that may pose a threat to a stable operation of the power system. In order to support the ongoing integration of renewable generation into the grid, a trade-off has to be found between investment costs and imposed operational constraints. In order to determine the probability of congestions under these unpredictable conditions, mathematical algorithms are employed that are able to estimate the probability of certain line loading levels from the probabilistic data derived from the appliances' behavior.

This chapter will cover a variety of approaches to solve (probabilistic) load flow problems, ranging from currently deployed state-of-the-art procedures to the newest advances in probabilistic load flow calculation and determination. Advantages and drawbacks of those methods are discussed in detail.

1 Introduction

In general, electric network states or congestions are determined and calculated using power flow calculations. The most popular method of solving the non-linear system of power flow equations is the Newton-Raphson (NR) method. The NR method starts from initial and likely guesses of all unknown variables (voltage angles, voltage magnitudes at load and generator buses). Next, a Taylor Series is

K. Gopalakrishnan et al. (Eds.): Soft Comput. in Green & Renew. Ener. Sys., STUDFUZZ 269, pp. 117–156.
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formulated for each of the power balance equations included in the equation system. The resulting linearized system of power flow equations is solved to determine the next iteration (a refined guess) of the voltage angles and magnitudes for which the procedure is repeated. This process continues until a stopping criterion is met, e.g. the difference of two subsequent results for voltage angles and magnitudes being beyond a specified threshold.

With a high amount of renewable – volatile and unpredictable – generation, standard power flow calculations reach their limits when applied to power system planning due to the continuous fluctuation of necessary data from the grid's feed-in nodes making it difficult to guess likely starting points for the initial step of the NR method. Choosing starting points for the NR method that deviate too far from the sought solution may cause the iterative method to diverge [Kornerup and Muller 2006]. Even when choosing appropriate starting values, the iterative method may be insufficient for timely detection of congestions in highly dynamic scenarios due to the number of (possibly computational complex and time consuming) iterations until the algorithm converges. In order to determine the probability – and thus mean time of occurrence – of congestions under these conditions, mathematical algorithms are employed that are able to estimate the probability of certain line loading levels from the probabilistic data derived from the generators' behavior. Hence, the stochastic behavior of (non-deterministic) renewable generation as well as loads is no longer described through clearly defined values, but given as a range of possible states together with their corresponding probability. This representation allows the prediction of the behavior for any given generator or load with a certain amount of probability or "softness". This is a sharp contrast to conventional power flow calculations, which precisely determine the state of the network on the basis of correct data for the (deterministic) behavior of every conventional generator and load connected to the network. Conventional power flow calculation by design is not able to cope with fuzzy input data and is very sensitive to misguesses, in the sense that a poorly chosen value in a scenario-based congestion analysis may lead to false results and ultimately to congestions not being detected [Kornerup and Muller 2006]. Probabilistic load flow calculation can tolerate this up to a certain extend without the result becoming useless. The concept of probabilistic load flow calculation is known for almost 40 years and appropriate research has been conducted in [Borkowska 1974][Dopazo et al. 1975][Allan and Alshakarchi 1976][Allan and Alshakarchi 1977] [Aboytes 1978][Allan et al. 1981][Silva et al. 1985][Silva and Arienti 1990].

In this chapter the authors will introduce the mathematical basis of probabilistic load flow calculations, current reference approaches and algorithms and give an outlook on further developments in this field.

1.1 Structure of Public Power Systems

In order to understand the differences in the mathematical formulation and problem-solving strategies, it is important to first get a basic understanding of the structure and operation of a public electric power system. In general, large power systems are composed of multiple voltage levels that can be distinguished into the *transmission system* and the *distribution system* (see Fig. 1).