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Flow tracing as a tool set for the analysis of networked large-scale renewable electricity systems

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ABSTRACT

The method of flow tracing follows the power flow from net-generating sources through the network to the net-consuming sinks, which allows to assign the usage of the underlying transmission infrastructure to the system participants. This article presents a reformulation that is applicable to arbitrary compositions of inflow appearing naturally in models of large-scale electricity systems with a high share of renewable power generation. We propose an application which allows to associate power flows on the grid to specific regions or generation technologies, and emphasizes the capability of this technique to disentangle the spatio-temporal patterns of physical imports and exports occurring in such systems. The analytical potential of this method is showcased for a scenario based on the IEEE 118 bus network.

1. Introduction

The electricity system is built up of a complex interwoven network of technologies, which provides the backbone for our modern society. In the past, this network was characterized by power flows from large central power plants downstream through the grid to the consumers, with only very limited interactions between different geographical regions. Today, the rising share of decentralized, fluctuating renewable generation and the increasing inter-dependence of international electricity markets has led to a more dynamical system: the power grid has become the underlying infrastructure for a complex pattern of long-range power flows between a heterogeneous distribution of power generation to consumers, integrating not only dispatchable conventional generation, but also electricity from offshore wind farms, wind and solar parks and roof-top solar panels. In this context, a deeper understanding of the emerging power flow patterns is of paramount importance on different levels: For instance, internationally integrated electricity markets need to incorporate possible network congestion into their market design [1], whereas network expansion plans attempt to minimize this congestion in the long run [2,3]. Also the development of fair and transparent grid usage fee systems, or public discussions concerning the benefit of new infrastructure projects rely strongly on insights concerning the composition and dynamics of the flow pattern in the network [4,5]. In this article we present a reformulation of a well-known method of flow allocation, denoted as average participation or flow tracing, that is well adapted to the challenges of the system analysis of complex modern electricity systems. Different approaches to the problem of flow allocation in power grids are often derived from circuit theory [6,7] or are based on approximations of the complex power flow equations for AC electrical networks [8,9]. For the application of such methods to the problem of flow allocation in large-scale models of electricity systems, one has to factor in the potentially coarse-grained nature of such models. Both the network buses and transmission lines might be aggregated representations of lower level infrastructures, which cannot be included in detail in the model due to computational limitations or lack of data [10–12]. The method of flow tracing can be applied directly to the overall power flow pattern in the system, and thus does not explicitly have to take into account the underlying modeling details. By tracing what we term in-partitions, we show how the known composition of network-injected power generation can be followed through the grid and thus be transferred to the power flows and composition of net consumption at the sink nodes. In this way the location of generation of power flow can be connected to its location of consumption, thus disentangling the complex spatio-temporal patterns of imports and exports inherent to interconnected electricity systems with a high share of renewable generation. We showcase the potential of this methodological tool set by application to the Scenario 2023B of the IEEE 118-bus model adapted by Barrios et al. at RWTH Aachen with renewable generation capacities and hourly availability for a model year as a benchmark for transmission expansion algorithms [13].

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Nomenclature

Indices and labels

n,m,k	index of buses
l,l'	index of lines
α,β,τ	labels of regions and technologies for grouping the power injection and flows

Constants, variables and functions

$P_n(t)$	net power injection at bus n (MW)
$G_n^\tau(t)$	power generation by technology τ at bus n (MW)
$L_n(t)$	load at bus n (MW)
$F_{n\to m}^{out}(t)$	power outflow from bus n in direction of bus m (MW)
$F_{n\to m}^{in}(t)$	power inflow to bus m from bus n (MW)
$F_l(t)$	absolute value of the power flow on line l
$\chi_{n\to m}(t)$	loss in the transmission line between bus n and m (MW)
$q_{n,\alpha}^{in}(t)$	in-partition, the share of the injected power at bus n attributed to component α
$q_{n,\alpha}^{out}(t)$	out-partition, the share of the consumed power at bus n attributed to component α
$q_{l,\alpha}(t)$	line-flow partition, the share of the power flow through line l attributed to component α
$p_l(F_l)$	probability for a flow F_l on line l
$p_l(q_{l,\alpha}\|F_l)$	conditional probability for a share $q_{l,\alpha}$ of component α in case of a flow F_l
$h_{l,\alpha}(F_l)$	average share of owner α on the link l for a flow F_l
$w_{l,\alpha}(\mathscr{K})$	weight for the usage of the capacity increment between $\mathscr{K}$ and $d\mathscr{K}$ attributed to owner α on the link l
$\mathscr{K}^T$	transmission capacity of the network (MW)
$\mathscr{K}_l^T$	transmission capacity of line l (MW)
$\overline{\mathscr{K}}^T$	transmission capacity of the network including length (MW km)
$\overline{L_l}$	length of transmission line l (km)
$\overline{D}_n$	average graph distance of bus n (km)
$\mathscr{M}_{\alpha,\tau}^{(1\ldots4)}$	transmission network usage measures (MW km)

After a short review of flow tracing, Section 2 introduces the reformulated flow tracing technique and a measure of network usage. The subsequent Section 3 showcases two exemplary applications: Firstly the tracing of power flow of different generation types between several regions across a network model based on the IEEE 118 bus case, and secondly a comparison of a statistical transmission capacity usage measure with several alternative allocation mechanisms. Section 4 concludes the paper.

2. Methodology

Flow tracing was introduced as a loss-allocation scheme by Bialek et al. based on solving linear equations [14] and in parallel by Kirschen et al. as an analytical tool using a graph-based, iterative approach [15].

It was soon after proposed as a transmission-usage allocation scheme [16–19]. Subsequently, the method was discussed to cover concrete supplementary charge schemes for cross-border trades [20,21], in view of the discussion about the mechanism of inter-transmission system operator compensation in Europe [4,22,23].

Of the other network-cost allocation methods – reviewed in [24] or [25], for instance – we only want to highlight marginal participation [26] and the related decomposition method [27], which attribute transmission capacity according to linear sensitivities of network flows to differential bus injections as captured by the power transfer distribution factors (PTDF) [28]. Due to its influence on the PTDF, for this method the choice of the slack bus has to be taken into account explicitly [29], whereas for the flow tracing technique this choice only affects the total power flow but not the allocation mechanism.

2.1. Power flow

The active power flow in an electricity system satisfies Kirchhoff's current law. If the net power injection at bus n from generators and loads is given by P_n, and $F_{n\to m}^{in/out}$ are the power in- and outflows from bus n to m, then the power flow through node n is conserved as

$$P_n^{in} + \sum_m F_{m\to n}^{in} = P_n^{out} + \sum_m F_{n\to m}^{out}. \tag{1}$$

Here we use the positive and negative injections P_n^{in} and P_n^{out} at node n and invoke the convention that all $F_{m\to n}^{out}$ and $F_{m\to n}^{in}$ are positive or zero. Table 1 introduces a particular snapshot in a simple network with four buses with generation G_n, load L_n and im-/exports I_n/X_n with other buses not represented explicitly. In this example, we take the positive injection as the net surplus between generation G_n and demand L_n plus the imports I_n, while the negative injection follows from the deficit and exports X_n, as

$$P_n^{in} = \max\{(G_n - L_n),0\} + I_n,$$
$$P_n^{out} = \max\{-(G_n - L_n),0\} + X_n. \tag{2}$$

The flows and line-losses are illustrated in Fig. 1. The convention means that the line from bus 1 to bus 3 is described by $F_{1\to3}^{out} = 2.2$ GW, $F_{1\to3}^{in} = 1.8$ GW, $F_{3\to1}^{in} = 0$ and $F_{3\to1}^{out} = 0$.

Here and in general the outflow from bus n to m, $F_{n\to m}^{out}$, is larger than the inflow to m, $F_{n\to m}^{in}$ due to losses in the transmission line $n\to m$. We denote them by $\chi_{n\to m} = F_{n\to m}^{out} - F_{n\to m}^{in}$.

2.2. Flow tracing

The flow tracing method by Bialek and Kirschen [14,15] follows the power flow from individual buses through the network and decomposes the flow on the power lines into contributions associated to each bus. Since for large-scale electricity systems, the injection P_n^{in}, in general, already contains several constituents, we introduce an in-partition $q_{n,\alpha}^{in}$ associating the power injection at each bus n to a set of components α. For the power flows of the four bus example, we will use the components $\{1,2,3,4,I\}$ with the in-partition

$$q_{n,\alpha}^{in} = \begin{cases} \frac{\max\{G_n - L_n,0\}}{P_n^{in}} & \text{for } \alpha = n \wedge P_n^{in} > 0, \\ \frac{I_n}{P_n^{in}} & \text{for } \alpha = I \wedge P_n^{in} > 0, \\ 0 & \text{else.} \end{cases} = \begin{pmatrix} \frac{10.5}{11.4} & 0 & 0 & 0 & \frac{0.9}{11.4} \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{3}$$

to differentiate the imports I_n entering at each bus from the power generated there. Note that the component I is associated with injected power throughout the network. Similarly, another in-partition for components {wind, solar, conventional, imports} is able to encode the relative shares of wind, solar and conventional generation sources, for instance.

Flow tracing follows the diffusion of the different components α by assuming conservation of the partial power flows at bus n in analogy to (1)

Table 1
Power generation and consumption of a simple four bus network with im-/exports with external buses in GW.

n	G_n	L_n	$G_n - L_n$	I_n	X_n
1	76.0	65.5	10.5	0.9	5.6
2	20.5	21.1	−0.6	0.9	0.6
3	8.5	8.0	0.5	0.0	1.8
4	7.3	7.5	−0.3	0.0	2.5