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A probabilistic approach for power system injection shift factor estimation

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ABSTRACT

The data-based power system injection shift factor (ISF) estimation approaches can automatically adapt to the changes of power system operating situation and provide more accurate ISF estimation results. However, because of the linearization assumption and the measurement errors, the data-based ISF estimation approaches still have significant estimation errors, which may degenerate the usefulness of the estimated ISFs. For this reason, predicting the deviation of the ISF estimation error is necessary for developing robust power system operational analysis and control approaches. In this paper, a novel probabilistic approach for ISF estimation is proposed. Using the samples obtained from the online measurements, the posterior probability distribution estimation model of ISFs is established according to the Bayesian linear regression (BLR) rules. Additionally, a numerical method named Gibbs sampling is adopted to solve the posterior probability distribution model and to avoid complicated analytical derivation. The proposed approach has the following distinguished features: (1) The proposed approach makes use of the measurement data, rather than the element parameters, to estimate the ISFs. Therefore, the estimation errors resulting from possible inaccurate element parameters are avoided, and the approach can adapt to the system topology and operating point changes automatically; (2) It is not necessary to set a reference node in the estimation process, and this avoids the estimation error from the inconsistency of the reference node setting between the theoretical calculation and the practical operational situation; (3) The approach can provide probabilistic ISF estimation results, which can quantify the degree of ISF deviation caused by the linearization assumption and the random measurement errors. Tests on a real transmission network in central China demonstrate the feasibility and effectiveness of the proposed approach.

Introduction

In the high-voltage transmission network, the injection shift factor (ISF) is a key linear distribution factor that quantifies the branch power redistribution with respect to a change in generation or load on a particular node in the network [1,2]. Several other important distribution factors, *i.e.*, the power transfer distribution factor (PTDF), line outage distribution factor (LODF), and outage transfer distribution factor (OTDF), can be calculated directly from the ISFs. Therefore, ISF is widely used in power system operational analysis and control procedures, *e.g.*, the optimal power flow [3], congestion management [4,5], power system security evaluation [6,7] and power system equivalents [8], to quickly estimate the active power flow distribution among the transmission networks. Obviously, the estimation accuracy of ISF is crucial for these applications, and the research to obtain a more accurate ISF has great practical significance.

ISFs are conventionally estimated by using an approximation approach based on the DC power flow model [2,9,10]. A set of fixed ISFs is derived directly from the branch admittance matrix according to the approach. These derived ISFs have concise mathematical expressions so the approach is easy for programming. However, this model-based approach has the following inherent drawbacks: (1) The calculation of ISFs in the DC approximation approach relies on the branch parameters. However, in practice, it is usually difficult to obtain accurate branch parameters because of the ubiquitously poor element parameter maintenance. Additionally, the climate change and long operating hours may also lead to branch parameter shifting. The inaccurate branch parameters may influence the ISF estimation accuracy dramatically [11]; (2) In the DC approximation approach, a reference node must be specified to balance the power flow. However, the reference node setting may be inconsistent with the actual power system balance

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strategies, which may also influence the estimation accuracy; (3) The deterministic estimation result cannot reflect the estimation error caused by an improper estimation model or imprecise parameters [12]. In summary, because of the above-mentioned inherent drawbacks, the DC approximation estimation approach may result in inaccurate estimations of the ISFs, and the approach lacks the flexibility to reflect the power system topology and operating situation changes.

With the development of power system measurement technologies [13,14], the system operators can acquire large amounts of measurement data from the supervisory control and data acquisition system (SCADA) and the wide area measurement system (WAMS) continuously. The values of the active branch power flow and the corresponding nodal injections can be screened out from the sequential measurements easily. In this context, it becomes possible to estimate the ISFs by using the measurement data. According to the approximate linear relationship between the active branch power flow and the nodal injections, Refs. [15–17] proposed several data-based estimation approaches by using least-squares estimation (LSE). Because the massive sequential measurements can closely reflect the system operational situation and topology changes [18,19], the data-based estimation approaches exhibit superiority on the estimation accuracy against the DC approximation approach [15]. These studies verify the feasibility of the data-based ISF estimation and conform to the large data trend of modern power systems.

However, even the data-based estimation approaches are more accurate, they still suffer from the estimation errors caused by the measurement noises and the linearization assumption. The ISF estimation errors may cause undesired overestimation or underestimation of the branch power flows and degenerate the usefulness of the ISFs in power system security analysis and control. Therefore, the deviation information of the ISF estimation errors is very desirable for making robust branch power flow estimations and power system operation decisions [20]. Unfortunately, in the existing literature, this information is totally ignored not only in the model-based estimation approaches but also in the data-based estimation approaches.

In this paper, along with the research line of [15–17], a novel probabilistic ISF estimation approach based on Bayesian linear regression (BLR) [21–23] is proposed. Under the assumption of the linearization conditions for high-voltage transmission networks, a linear regression model of active branch power flow regarding each active nodal injection is established in which the ISFs are the regression coefficients. Then, with the sample observations screened out from the sequential measurements, the posterior probability distribution estimation model of ISFs is established according to the BLR rules. To avoid a complicated analytical derivation of the posterior probability distribution, a numerical solution named Gibbs sampling [24,25] is adopted to obtain the posterior probability distribution of the ISFs. The data collected from a real transmission network are used to test the performance of the proposed approach, and the test results illustrate the feasibility and effectiveness of the proposed approach.

The advantages of the proposed approach are as follows:

1. The approach makes use of the measurement data rather than the power system element parameters to estimate the ISFs. So, the estimation errors resulting from possible inaccurate element parameters are avoided.
2. There is no need to set a reference node in the estimation process, which avoids the estimation error coming from the inconsistency of the reference node setting between the theoretical calculation and the practical operation.
3. The approach can provide probabilistic ISF estimation results, which quantify the degree of the ISF deviation caused by the linearization assumption and random measurement errors.

The rest of the paper is organized as follows. Section 'Principles of ISF probabilistic estimation' introduces the linear regression model of ISFs and describes the principles of BLR and Gibbs sampling. Section 'Numerical solution to the ISF posterior distribution' exhibits the test results of a real transmission network. Section 'Case studies' concludes the proposed approach.

Principles of ISF probabilistic estimation

Linear regression model containing ISFs

As is well known, the active nodal power injection and branch power flow will have an approximately linear relationship if the following conditions are satisfied [2]:

(a) The branch resistance is considerably smaller than the reactance.
(b) The voltage phase-angle difference between the two ends of each branch is small enough to be ignored.
(c) The voltage magnitude of each node is close to its nominal value.
(d) The influence of the grounding branches is disregarded.

These conditions are usually satisfied in the high-voltage transmission networks. Therefore, the active branch power flow has an approximate linear relationship with regard to each active nodal injection, namely, the active branch power flow can be approximately represented as a linear combination of the nodal power injections [15]:

$$P_{Branch,k} = \boldsymbol{P}_{Node}^{T} \cdot \boldsymbol{M}_k \tag{1}$$

where $P_{Branch,k}$ stands for the active power flow of branch k, $\boldsymbol{P}_{Node}$ is an N-dimensional column vector that stands for the injected power on N nodes, and $\boldsymbol{M}_k$ is the N-dimensional ISF vector corresponding to the kth branch, which quantifies the respective influence of the N nodes' active power injection change on the active power flow of branch k.

With the development of the advanced power system measurement technologies, the branch power flow and nodal injection can be obtained from the sequential measurements of the SCADA and WAMS systems. These measurements provide sufficient data to estimate the ISFs using a regression method. Considering the existence of the residual term in the regression equation, the linear regression model that contains ISFs can be established as (2):

$$P_{Branch,k} = \boldsymbol{P}_{Node}^{T} \cdot \boldsymbol{M}_k + \varepsilon_k \tag{2}$$

where ε_k is the residual variable following a normal distribution $N(0, \sigma_k^2)$.

BLR model for ISF probabilistic estimation

BLR is an approach for linear regression under the context of Bayesian inference. It can provide probabilistic estimation results for the unknown regression coefficients. For this reason, BLR is adopted here to estimate the ISFs in (2) and catch their uncertain features.

According to BLR, the ISF vector $\boldsymbol{M}_k$ and the variance scalar σ_k^2 in (2) are all regarded as mutually independent random variables. Their joint posterior probability density function can be obtained according to Bayes' rule as: