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Short Communication

An efficient starting process for calculating interval power flow solutions at maximum loading point under load and line data uncertainties

L.E.S. Pereira [a,1], V.M. da Costa [b,*]

[a] Department of Electrical Engineering, Federal Institute of Minas Gerais, Rua Padre Alberico, 440, São Luiz, 35570-000 Formiga, MG, Brazil
[b] Department of Electrical Engineering, Federal University of Juiz de Fora, Campus Universitário – Bairro Martelos, 36036-33 Juiz de Fora, MG, Brazil

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ABSTRACT

This letter proposes a simple and efficient starting process to be used in the interval power flow current injection at the maximum loading point. Load and line data uncertainties are considered. The proposed method is implemented in the Matlab environment using the Intlab toolbox. The main variables associated with the power flow problem are yielded in an interval form. Results are compared with those obtainable by Monte Carlo simulations. A large scale South–southeastern Brazilian network is used to validate the proposed starting process.

Introduction

Power flow [1,2] is the most frequently performed study in electric power systems, and deals with the calculation of voltages and line flows, in a large sparse electrical network, for a given load and generation schedule. In practice, however, input data are subject to uncertainty. Remarkable technical resources have been published in literature taking into account data uncertainties in different electric power system areas [3–7].

Ref. [8] presents a power flow method under uncertainty by incorporating interval arithmetic into the current injection formulation. No control devices are considered in the power flow problem and the interval solutions refer to the nominal operating point. Ref. [9] extends the methodology developed in [8] in order to calculate in an interval form, under load data uncertainty, not only the maximum loading point, but also the main variables corresponding to this point, such as voltage magnitudes, phase angles, active and reactive power generations, active and reactive line flows and losses. Reactive power generation limits at PV buses and voltage magnitudes limits at PQ buses are considered in Ref. [9].

The main objectives of this letter are twofold. Firstly, to improve the convergence characteristics of the interval power flow algorithm presented in [9], whose notation will be IPFS-MLP throughout this letter. To do this, this letter proposes a new and simple method to initialize interval bus voltages corresponding to step 4 of IPFS-MLP. Secondly, to include line data uncertainties in the interval current injection power flow formulation.

The notations adopted in the letter are the conventional ones whenever possible. Matrices are shown in bold. The over scripts *d* and *i* refer to deterministic and interval quantities, respectively.

Proposed initialization of interval voltages

The power flow problem is modeled through current injections expressed in voltage rectangular coordinates. This letter not only proposes a new interval bus voltage initialization method, but also considers load and line data uncertainties. Therefore, the step 2 of IPFS-MLP must be extended as follows:

$$P^i_{d_k} = [P^d_{d_k}(1-\alpha_{P_k}), P^d_{d_k}(1+\alpha_{P_k})] \quad (1)$$
$$Q^i_{d_k} = [Q^d_{d_k}(1-\alpha_{Q_k}), Q^d_{d_k}(1+\alpha_{Q_k})] \quad (2)$$
$$R^i_{k-m} = [R^d_{k-m}(1-\alpha_{R_{k-m}}), R^d_{k-m}(1+\alpha_{R_{k-m}})] \quad (3)$$
$$X^i_{k-m} = [X^d_{k-m}(1-\alpha_{X_{k-m}}), X^d_{k-m}(1+\alpha_{X_{k-m}})] \quad (4)$$
$$B^i_k = [B^d_k(1-\alpha_{B_k}), B^d_k(1+\alpha_{B_k})] \quad (5)$$

where α_{P_k} and α_{Q_k} factors which denote active and reactive load variations. In addition, $\alpha_{R_{k-m}}$, $\alpha_{X_{k-m}}$ and α_{B_k} are factors which denote line variations regarding series resistance, series reactance and shunt susceptance, respectively.

* Corresponding author. Tel.: +55 32 21023461; fax: +55 32 21023442.
E-mail addresses: eduardo.pereira@ifmg.edu.br (L.E.S. Pereira), vander.costa@ufjf.edu.br (V.M. da Costa).
[1] Tel.: +55 37 91048816.

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As in [9], interval bus voltages are initialized by using the deterministic voltage profile at MLP as midpoint. All deterministic variables associated with MLP are calculated through PSAT (Power System Analysis Toolbox) [10]. To improve the performance of IPFS-MLP, this letter proposes the following starting process:

$$\begin{bmatrix} \Delta \underline{V}_r^i \\ \Delta \underline{V}_m^i \\ \Delta \gamma^i \end{bmatrix} = \begin{bmatrix} & \mathbf{J^d} & \frac{\partial \underline{I}_r}{\partial \gamma} \\ & & \frac{\partial \underline{I}_m}{\partial \gamma} \\ 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 0 \\ \Delta \gamma^i \end{bmatrix} \tag{6}$$

Eq. (6) is based on predictor step of continuation current injection power flow. $\mathbf{J^d}$ is the deterministic current injection Jacobian matrix calculated at MLP. The variable γ is employed to simulate load and generation changes. For a generic bus k, the partial derivatives presented in (6) are given by

$$\frac{\partial I_{r_k}}{\partial \gamma} = \frac{P_k^d V_{r_k}^d + Q_k^d V_{m_k}^d}{(V_{r_k}^d)^2 + (V_{m_k}^d)^2} \tag{7}$$

$$\frac{\partial I_{m_k}}{\partial \gamma} = \frac{P_k^d V_{m_k}^d - Q_k^d V_{r_k}^d}{(V_{r_k}^d)^2 + (V_{m_k}^d)^2} \tag{8}$$

Eqs. (25) and (26) in [9] must be extended in order to include line data uncertainties. Therefore, for a generic PQ bus k,

$$\gamma^i = \frac{(V_k^d)^2 I_{m_k}^i}{Q_{d_k}^i V_{r_k}^d - P_{d_k}^i V_{m_k}^d} - 1 \tag{9}$$

or

$$\gamma^i = \frac{(V_k^d)^2 I_{r_k}^i}{-P_{d_k}^i V_{r_k}^d - Q_{d_k}^i V_{m_k}^d} - 1 \tag{10}$$

For only load data uncertainty, $I_{r_k}^i$ and $I_{m_k}^i$ have null radii. On the other hand, for only line data uncertainty, $P_{d_k}^i$ and $Q_{d_k}^i$ have null radii. The most suitable equation to be used for calculating γ^i is one which consists of an addition operation into the denominator [9]. Alternatively, this letter proposes to use (9) and (10) and adopts the smallest radius. It can be observed that both the real and imaginary current components injected at bus k are now interval variables given by

$$I_{r_k}^i + jI_{m_k}^i = Y^i \cdot V^d \tag{11}$$

where Y^i is the interval bus admittance matrix calculated considering all line data uncertainties.

Since the deterministic maximum loading point γ^d is evaluated from PSAT, the only nonzero component of vector in (6) is given by

$$\Delta \gamma^i = \gamma^d - \gamma^i \tag{12}$$

Finally, the initial guess for interval voltage at bus k is given by

$$V_{r_k}^i = V_{r_k}^d + \Delta V_{r_k}^i \tag{13}$$

$$V_{m_k}^i = V_{m_k}^d + \Delta V_{m_k}^i \tag{14}$$

Additionally, it can be observed that the interval maximum loading point γ^i is now calculated during the interval bus voltage initialization. On the other hand, it is calculated only at the end of iterative process regarding the IPFS-MLP algorithm. This new algorithm is very interesting if the goal is to calculate only γ^i. The proposition of a new interval bus voltage initialization leads to a new interval current injection power flow which will be denoted by IPFS- MLP-NEW throughout this letter.

Results

Initial considerations

In order to perform this study, some simulations were accomplished by using a Brazilian system with 1768 buses, composed of 2527 branches, 96 generation buses and 1003 bus shunt susceptances. The tolerance adopted for convergence of the iterative process, related to both deterministic and interval power flow methods, is 10^{-4} pu. The radius of an interval associated with any input and output variable is defined around its respective deterministic value. In this paper, radius of 2% is considered for all active and reactive loads. Radii of 1% and 5% are assumed for all active power generations and for all line data, respectively.

The Monte Carlo simulation (MCS) method validates the proposed methodology. One million and one hundred thousand of

Table 1
Voltage magnitudes and phase angles.

Bus	Method	V (pu)	D (%)	θ (°)	D (%)
493	Deterministic	0.92546	–	−12.58673	–
	IPFS-MLP	[0.90000; 0.95009]	[0.00000; 1.21413]	[−9.47900; −14.73160]	[3.25981; 4.22684]
	IPFS-MLP-NEW	[0.90000; 0.94548]	[0.00000; 1.27166]	[−9.33506; −14.71411]	[4.72888; 4.10314]
	MCS	[0.90000; 0.94806]	–	[−9.79841; −14.13417]	–
443	Deterministic	0.93748	–	−13.83321	–
	IPFS-MLP	[0.90836; 0.96964]	[0.33023; 1.17739]	[−10.94795; −16.75271]	[0.24060; 4.15552]
	IPFS-MLP-NEW	[0.90122; 0.96941]	[1.11451; 1.15339]	[−10.99135; −16.58819]	[0.63790; 3.13267]
	MCS	[0.91137; 0.96792]	–	[−10.92168; −16.08432]	–
1673	Deterministic	0.90000	–	−31.47459	–
	IPFS-MLP	[0.90000; 0.95633]	[0.00000; 1.43489]	[−27.31998; −36.12137]	[2.10706; 2.29356]
	IPFS-MLP-NEW	[0.90000; 0.95538]	[0.00000; 1.33519]	[−27.15862; −36.05533]	[2.68524; 2.10655]
	MCS	[0.90000; 0.95219]	–	[−27.90802; −35.31148]	–
1103	Deterministic	0.94684	–	10.58755	–
	IPFS-MLP	[0.91026; 0.98468]	[0.33927; 1.65976]	[7.78816; 13.82179]	[0.86230; 5.28921]
	IPFS-MLP-NEW	[0.90092; 0.98359]	[1.36140; 1.54825]	[7.76510; 13.75675]	[1.15580; 4.79373]
	MCS	[0.91335; 0.97823]	–	[7.85590; 13.12745]	–
353	Deterministic	0.94835	–	−46.38757	–
	IPFS-MLP	[0.91242; 0.98412]	[0.84028; 1.44948]	[−51.43451; −43.28600]	[2.26245; 3.55327]
	IPFS-MLP-NEW	[0.91065; 0.98326]	[1.03287; 1.36082]	[−51.24184; −43.45419]	[1.87938; 3.17853]
	MCS	[0.92016; 0.97972]	–	[−50.29657; −44.88074]	–