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# Continuation power flow considering area net interchange constraint

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ABSTRACT

Interconnected power systems not only allow to the areas to provide mutual assistance, but also import or export energy with respect to optimize energy resources assessment where, a cost reduction involved in the generation of power required to meet its demand. To determine the required control actions, in the planning and operation stages, it is important to verify the loading margins for both the normal operation and the different conditions of contingencies that may eventually occur. In this paper a continuation power flow that allows obtaining the loading margin and maximum active power transfer considering the area interchange control is proposed. From the results of the IEEE systems (9 and 118 buses), a difference of up to twelve percent in the active power transfer capacity is verified compared to the cases without area interchange control. The method also highlights the effects of the loop flow which occur as a consequence of the existence of parallel paths in the interconnected network.



## Introduction

Modern electric power systems are comprised the control of the interconnected areas through tie lines (interconnecting lines). In Brazil, the system is composed predominantly by hydropower plants and some thermal power plants. Although the generation cost of hydros is lower than the thermals, they are much more far away from the consumers. Interconnected power systems allows, among other advantages, a better use of available generation resources, reduction in the required total installed capacity and generating reserve needed to ensure continuity of service, and greater operating flexibility to meet the energy demand, and consequently increasing the reliability and quality of electricity supply is obtained [1–4]. They also enable the areas to import (buy) or export (sell) power from each other. So, each area can increase/decrease the power generation of respective generators in order to meet the increases/decreases of its own demands, or of other areas. Despite these advantages, due to the increase in demand and a greater utilization of power transfer capability of existing transmission lines, at these systems blackouts and energy rationing are still occurring [1]. Consequently, it is important to perform the assessment of the available power transfer limits of these interconnected systems for various energy scenarios, load conditions and network configurations, so that sufficient transmission capacity is assured. Under certain conditions the limits are restricted by voltage instability problems. In this case, it is necessary to verify that, if the system is not close to an operating condition in which a small increase in the load or in the active power transfer and an occurrence of a simple contingency causes the voltage collapse.

In studies related to static voltage stability, the continuation power flow is commonly used for tracing the system *P–V* curves because it allows to obtain the maximum loading point (MLP) and thereby determining the accurate system loading margin, without numerical problems related to Jacobian matrix singularity [5–9]. To determine the power transfer capacity of an interconnected power system, the amount of active power to be transferred between two regions, at the same area, or areas must be defined. For that purpose, the generation in a particular region (or area), which is considered as the source region (or area), and the load on another region (or area), considered as the sink region (or area), are increased [2–4]. The net interchange of each area is defined as the algebraic sum of the active power flowing over all the tie-lines of a given area; the active power flowing to a given area is considered negative and flowing away from a given area, positive [10–12]. The net interchange of each area must be kept in its respective scheduled value, which requires the addition of one equality constraint equation for each area, in solving process of the problem of load flow [10,11]. So, each area must have at least one generation bus (*PV*) that will be used to regulate its net interchange.

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To keep the net interchange of area in its respective scheduled value, the injected active power of the regulating bus is adjusted. So, this bus is nominated by area interchange control (AIC) regulating bus and classified as V type, its active power generation is not specified, but only the voltage magnitude [11]. Note that if one or more areas do not have regulating bus, the net interchange cannot be controlled in this area. In a system with n areas only $n-1$ can be controlled because one of the net interchange is determined by specification of the rest and so, one area must be a reference area. One generator bus of the reference area is used as the reference bus and others angles of the system buses are adjusted based on this reference. It is classified as a $V\theta$ type. As the losses are not known in advance of the load flow solution, it bus is also used as slack (or swing) bus to balance the active and reactive power in the system.

The maximum active power that could be transferred between regions of the same area through the internal transmission lines, or between areas across the tie-lines, without any problems related to the voltage stability, should be assessed maintaining the correct interchange values among the areas [12–15]. Nevertheless, in [12] the maximum power interchange is calculated by the sum of active power flowing over all the tie lines, at the maximum loading point. The loading is performed by considering the system as a single area with a single slack bus, i.e., it does not include the areas' interchange constraint equations. In [11], a method for inclusion of the AIC in the conventional power flow was proposed. The method stands out, when compared to others, because it considers the generated powers at the regulating buses as state variables and allows the use of multiple AIC regulating buses per area. Based on this method, in Section 'Proposed continuation power flow' the contribution of the paper that is the inclusion of AIC in continuation power flow is considered in detail. This inclusion provides greater flexibility since now, which makes it possible to determine the available transfer capacity of different areas considering the inclusion of multiple AIC regulating buses per area. Each area acts as an independent system that controls its interchange during all the procedure of system loading. In Sections 'Loop flow, an illustrative example and Performance of the proposed CPF for the modified 118-bus IEEE test system', the proposed continuation power flow (PCPF) is applied to the IEEE systems of 9 and 118 buses. The systems were divided into several areas with the aim of highlighting the differences between the loading and power transfer margins obtained with the method with and without considering the constraints imposed by the net interchange. Two different load change scenarios are considered: (1) with a constant power factor, i.e. the active and reactive loads are increased proportionally to the base case and (2) only the active loads are increased.

Moreover, in Section 'Loop flow, an illustrative example', the results demonstrate the effects of the loop flows (parallel path flows, inadvertent flows or circulating flows), which occur due to the existence of parallel paths in the interconnected network [16–18]. As a consequence of the net interchange is the difference between the input and output power of the area, the power transfer across an affected area will not appear in it. On the order hand, as a consequence, an area that is not participating in the exchange of power has to cover the losses incurred by these unscheduled power flows and the power transfer capacity between two regions of its network will be restricted. Moreover, the AIC regulating buses will be increase or decrease their generations in order to provide the loss variations. In Section 'Performance of the proposed CPF for the modified 118-bus IEEE test system', some critical contingencies of IEEE-118 considering the restrictions imposed by the AIC are also evaluated. From the results it causes a difference up to 12% in the available active power transfer capacity.

## Proposed continuation power flow

The proposed continuation power flow (PCPF) is developed based on the method presented in [11], which allows the representation of multiple AIC regulating buses per area and represents that the AIC effects is put into the Jacobian matrix. In this method, the equations of generated active power of regulating buses are kept, unlike the proposed method in [10], wherein they are replaced by the net interchange equations. The PCPF is used to determine the successive solutions of a load flow by considering a given load change scenario including the interchange control. The bus voltage profiles (*PV* curves) are traced starting from a base case (a given initial solution) up to the maximum loading point (MLP). The singularity of the Jacobian matrix of the load flow is removed by slightly modification of the power flow equations presented in [11] and by applying a local or a geometric parameterization technique [5–7].

The general power flow equation to be solved including the interchange control, are expressed compactly as:

$$\mathbf{G}(\boldsymbol{\theta}, \mathbf{V}, \mathbf{P_G}, \lambda) = \mathbf{0} \tag{1}$$

that can be rewritten as:

$$\begin{aligned} \Delta\mathbf{P}(\boldsymbol{\theta}, \mathbf{V}, \lambda) &= \mathbf{P^{sp}}(\lambda) - \mathbf{P}(\boldsymbol{\theta}, \mathbf{V}) = \mathbf{0} \\ \Delta\mathbf{Q}(\boldsymbol{\theta}, \mathbf{V}, \lambda) &= \mathbf{Q^{sp}}(\lambda) - \mathbf{Q}(\boldsymbol{\theta}, \mathbf{V}) = \mathbf{0} \\ \Delta\mathbf{PI}(\boldsymbol{\theta}, \mathbf{V}, \lambda) &= \mathbf{PI^{sp}}(\lambda) - \mathbf{PI}(\boldsymbol{\theta}, \mathbf{V}) = \mathbf{0} \\ \Delta\mathbf{g}(\mathbf{P_G}) &= \mathbf{g^{sp}} - \mathbf{g}(\mathbf{P_G}) = \mathbf{0} \end{aligned} \tag{2}$$

where $\mathbf{V}$ and $\boldsymbol{\theta}$ are the vectors of voltage magnitudes and phase angles, respectively. The loading factor ($\lambda$) is used to scale up the loading and generation level. For a given bus, $k$, $\mathbf{P}(\boldsymbol{\theta}, \mathbf{V})$ and $\mathbf{Q}(\boldsymbol{\theta}, \mathbf{V})$ are given by:

$$P_k(\boldsymbol{\theta}, \mathbf{V}) = G_{kk}V_k^2 + V_k\sum_{l\in\Omega_k} V_l(G_{kl}\cos\theta_{kl} + B_{kl}\text{sen}\,\theta_{kl}), \quad k \in PQ, \quad PV$$

$$Q_k(\boldsymbol{\theta}, \mathbf{V}) = -B_{kk}V_k^2 + V_k\sum_{l\in\Omega_k} V_l(G_{kl}\text{sen}\,\theta_{kl} - B_{kl}\cos\theta_{kl}), \quad k \in PQ \tag{3}$$

where $\Omega_k$ is the set of all buses directly connected to the bus $k$, and $G_{kl}$ and $B_{kl}$ terms represent the conductance and susceptance of ($k$, $l$) element in the nodal admittance matrix $\mathbf{Y} = [\mathbf{G}] + j\,[\mathbf{B}]$.

For a given bus, $k$, $P_k^{sp}(\lambda) = (P_{Gk0} + \lambda \text{ger}_{\mathbf{k}}\text{Ptr}_{\mathbf{0}}) - (P_{Lk0} + \lambda C_{Pk}S_{k0}\cos(\varphi_{k0}))$ is the difference between the generated and consumed active powers for load ($PQ$) and generation ($PV$) buses, and $Q_k^{sp}(\lambda) = Q_{Gk} - (Q_{Lk0} + \lambda C_{Qk}S_{k0}\text{sen}(\varphi_{k0}))$ is the difference between the generated and consumed reactive powers for load buses. The subscript "0" is used to indicate the values of respective variables in the initial condition of operation, i.e. in the base case. The constants $C_{Pk}$ and $C_{Qk}$ are used to indicate a specific network loading condition: if $C_{Pk} = 1$ and $C_{Qk} = 1$, a loading with constant power factor is considered; if $C_{Pk} = 1$ and $C_{Qk} = 0$, only active power variations are considered. The symbol $S_{k0}$ is used to designate the apparent power of bus $k$, $\varphi_{k0}$ is the power factor angle of bus $k$. $\text{Ptr}_0 = \sum_{k=1}^{n} C_{Pk}S_{k0}\cos(\varphi_{k0})$ is the power to be transferred. The increase of active power at $PQ$ buses must be supplied by the $PV$ generator buses belonging to the area that will export electric power. The symbol $P_{Gk0}$ represents the active power generated in the base case at bus $k$ and $\text{ger}_k$ is the participation factor of generator $k$, which is calculated from the base case solution as follows.

$$\text{ger}_k = P_{Gk0}\Big/\sum_{j=1}^{\text{nger}} P_{Gj0} \tag{4}$$

For a given area, nger represents the number of generators (regulating buses) that will satisfy the load increase, i.e. the generators that participate in the sharing of load increase. The increase