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A demand power factor-based approach for finding the maximum loading point

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ABSTRACT

This paper presents a demand power factor-based approach (DPFA) for finding the maximum loading point (MLP) of a power system using the optimal power flow (OPF). In almost all the presented models in the literature two major drawbacks are obvious: (1) the active and reactive power demands increase equally, constantly, or at the same rate, while in the real world, this hardly ever occurs, and (2) the lack of consideration or misinterpretation of the demand power factor (DPF). This paper addresses the existing drawbacks by proposing a model based on a desired DPF, a threshold predefined by the independent system operator (ISO) that each consumer must maintain to prevent a surcharge. In the proposed DPFA, the active and reactive demands may increase differently resulting in: (1) providing a flexible loading pattern to find the best possible MLP, (2) keeping the desired DPFs at all load buses, and (3) improving the computational efficiency. To verify the DPFA, which is solvable via commercial solvers, several cases such as IEEE 14-, 30-, modified 30-, and 118-bus systems, and a large-scale 2338-bus system are conducted. Results confirm the potential, effectiveness, and superiority of the DPFA compared to the models in the literature.

1. Introduction

From an operational standpoint, the maximum loading point (MLP), is the maximum load that a power system can serve without violating generation, transmission, and operation constraints [1]. MLP-based analysis is an efficient way to evaluate a power system in a steady state and provides a more practical sense of a security margin for system operators [2].

In deregulated environments, power systems work under stress and, as a consequence, a heavily loaded power system has a higher tendency toward instability [3]. Testing a power system under the MLP condition can identify the critical buses, branches, or the weakest areas, which play an essential role in power system operation. The application of the MLP is not only limited to operation-based problems, but also provides useful information for planning-, scheduling-, and market-based problems, e.g. transmission expansion planning, tie-line planning, FACTS placement, unit commitment, distributed generation sizing, etc. [4–6]. In the technical literature, one of the most important issues to consider is the maximum demand of a system, especially for planning problems [7–9].

In order to find the MLP of a system, various mathematical models and optimization techniques, such as classical, heuristic-based, and hybrid methods have been proposed [10]. A simple method to find the MLP is the use of conventional power flow tools to gradually increase the demands until convergence no longer exists [11]. The drawback of this method is not only the need for manual intervention but also the uncertainty of knowing where the limits are. Although finding the MLP using power flow tools is well established problem and some of the existing drawbacks have been addressed [12,13], in today's competitive world precise information is the keystone of decision-making based problems, and this cannot be obtained via a simple economic dispatch or conventional power flow tools. Another obstacle in this area of research is that the enhancements to power flow-based approaches cannot be properly applied to OPF-based approaches, which consider more practical network constraints [14]. In recent years, in order to find the appropriate MLP, OPF-based models have been widely used, which play an important role in the operating-based, decision-making-based, and market-driven problems [7,15–17]. Note that the OPF-based model has been presented in Refs. [18,19] as an extension of the power flow-based model in Refs. [20,21].

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Nomenclature

Sets

Ω_b	Set of buses, $\{1, 2, \ldots, N_b\}$
Ω_{PQ}	Set of PQ buses, $\{1, 2, \ldots, N_{PQ}\}$, $\Omega_{PQ} \subseteq \Omega_b$
Ω_{PV}	Set of PV buses, $\{1, 2, \ldots, N_{PV}\}$, $\Omega_{PV} \subseteq \Omega_b$
Ω_g	Set of generating units, $\{1, 2, \ldots, N_g\}$, $\Omega_g \subseteq \Omega_b$
Ω_l	Set of transmission elements, $\{1, 2, \ldots, N_l\}$

Indices

i, j	Bus indices; $i, j \in \Omega_b$
l	Transmission element indices; $l \in \Omega_l$

Variables and functions

a_{ij}^l, φ_{ij}^l	Adjustable magnitude and phase shifting of transformer taps at line l, corridor ij
fl_{ij}^l	Power flow of line l, corridor ij
F_T	Objective function
$pf_{D_i}^v$	Adjustable demand power factor at each PQ bus i
P_{g_i}	Active power generation of unit i
$P_{D_i}^{new}$	Active power demand under the MLP condition at bus i
$P_{D_i}^v$	Adjustable active power demand at bus i
p_{ij}^l, p_{ji}^l	Direct and reverse active power injections of line l, corridor ij
q_{ij}^l, q_{ji}^l	Direct and reverse reactive power injections of line l, corridor ij
Q_{g_i}	Reactive power generation of unit i
$Q_{D_i}^{new}$	Reactive power demand under the MLP condition at bus i
$Q_{D_i}^v$	Adjustable reactive power demand at bus i
$S_{D_i}^v$	Adjustable apparent power demand at PQ bus i
tp_{ij}^l	Transformer tap of line l, corridor ij
V_i	Voltage magnitude at bus i
λ	Common loading factor for all demand buses
λ_i	Loading factor of demand bus i
δ_i	Phase angle at bus i
θ_{ij}^l	Voltage angle difference between bus i and j, $\theta_{ij}^l = \delta_i - \delta_j$, along with line l
ρ_i	Reactive demand ratio at bus i

Parameters

$b_{ij}^{l,ch}$	Charging susceptance of line l, corridor ij
$b_i^{b,sh}$	Shunt susceptance of bus i (℧)
b_{ij}^l	Susceptance (℧) of line l, corridor ij
$\overline{fl_{ij}^l}$	Maximum power flow of line l, corridor ij
g_{ij}^l	Conductance (Ω) of line l, corridor ij
$g_i^{b,sh}$	Shunt conductance of bus i (Ω)
$P_{D_i}^0$	Initial active power demand at bus i
$\underline{P_{g_i}}$, $\overline{P_{g_i}}$	Minimum and maximum active power generation limits of unit i
$Q_{D_i}^0$	Initial reactive power demand at bus i
$\underline{Q_{g_i}}$, $\overline{Q_{g_i}}$	Minimum and maximum reactive power generation limits of unit i
$\underline{tp_{ij}^l}$, $\overline{tp_{ij}^l}$	Minimum and maximum limits of transformer tap of line l, corridor ij
$\underline{V_i}$, $\overline{V_i}$	Minimum and maximum voltage magnitude limits of bus i
ΔP_{D_i}	Pre-specified rate of increase of active demand at bus i
ΔQ_{D_i}	Pre-specified rate of increase of reactive demand at bus i
$\cos\phi_i$	Constant demand power factor at bus i
η_i	Predefined multipliers to designate the rate of loading at bus i

Until now, to the best of our knowledge, in most OPF-based works the reactive power demand increases with a predefined and usually incorrect relationship with the active power demand in order to find the MLP [22,23]. In general, for such mathematical formulations, the demands increase until either the limited induced bifurcation (LIB) or saddle-node bifurcation (SNB) limits are reached [24]. This does not mean that the system is below the MLP, which is a physical limit, it shows the divergence of the power flow calculation, which is a mathematical failure [25]. In order to consider the advantages and shortcomings of the existing models and their evolution to be more applicable, we classify the mathematical models in three groups, such as common loading factor-, different loading rate-, and individual loading factor-based models. These models are shown in detail as follows.

1.1. Common loading factor-based model

In some works, to find the MLP of a system using an OPF-based model, the loading factors at all buses are considered equal, this is called the common loading factor (CLF), which is a widely-used model in power system studies [15,26–28]. The general OPF-based model presented in these works is shown in Eqs. (1)–(8).

$$\max \lambda \tag{1}$$

subject to:

$$P_{g_i} - P_{D_i}^{new} - g_i^{b,sh} V_i^2 - \sum_{ij \in \Omega_l} p_{ij}^l - \sum_{ji \in \Omega_l} p_{ji}^l = 0; \forall i \in \Omega_b \tag{2}$$

$$Q_{g_i} - Q_{D_i}^{new} + b_i^{b,sh} V_i^2 - \sum_{ij \in \Omega_l} q_{ij}^l - \sum_{ji \in \Omega_l} q_{ji}^l = 0; \forall i \in \Omega_b \tag{3}$$

$$|f_{ij}^l(V, \delta, tp)| \le \overline{f_{ij}^l}; \forall ij, l \in \Omega_l \tag{4}$$

$$\underline{V_i} \le V_i \le \overline{V_i}; \forall i \in \Omega_b \tag{5}$$

$$\underline{P_{g_i}} \le P_{g_i} \le \overline{P_{g_i}}; \forall i \in \Omega_g \tag{6}$$

$$\underline{Q_{g_i}} \le Q_{g_i} \le \overline{Q_{g_i}}; \forall i \in \Omega_g \tag{7}$$

$$\underline{tp_{ij}^l} \le |tp_{ij}^l| \le \overline{tp_{ij}^l}; \forall ij, l \in \Omega_l \tag{8}$$

where the active and reactive power demands under the MLP condition in Eqs. (2) and (3) are defined in Eqs. (9) and (10), respectively. The direct and reverse active and reactive power flows are defined in Section 2 of Ref. [14].

$$P_{D_i}^{new} = (1 + \lambda) \cdot P_{D_i}^0 \tag{9}$$

$$Q_{D_i}^{new} = (1 + \lambda) \cdot Q_{D_i}^0 \tag{10}$$

In this formulation, for all PQ buses, the one that reaches its maximum loading capacity before the others defines the MLP of the system. Therefore, the loading factor of the system is the loading factor corresponding to the bus which has the lowest value. This