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Maximum loadability of an isolated system considering steady-state and dynamic constraints

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ABSTRACT

An optimization model to calculate the maximum loadability of a system when subjected to a severe fault is proposed. The model simultaneously considers steady-state and dynamic constraints, with the dynamics of the generators explicitly included in the formulation. The armature current and the field current heating limits of the synchronous generators are also taken into account. The model is solved using a conventional solver based on the primal–dual interior point algorithm, and tested in a real system with three generators. The results show that the dynamic constraints can significantly affect the maximum loadability of the system. The effect on the solution of the maximum allowed rotor angle deviation is studied over a wide range of angle limits. Finally, the effect on the loadability of increasing the generation capability of certain plants is studied.

1. Introduction

The continuous increase in the demand and the difficulty of constructing new lines, together with the liberalization of energy markets, has increased significantly the stress in power systems. As a result, the determination of the maximum possible loadability has become an important issue, and studies using optimization algorithms are often executed to determine the maximum loading point of a system.

Frequently the loadability is calculated considering only steady-state restrictions such as voltage limits at buses, current limits at lines and transformers, and generation limits at power plants [1–10]. The strong relationship that sometimes arises between voltage stability and loadability is also studied in some of these works [3–10]. The limits found in these cases can be associated with static bifurcation points, such as saddle-node bifurcations (in which the state Jacobian matrix of the equilibrium equations becomes singular) or with the generation reactive power limits [2,12–14]. In some cases, the loading limit can be described as the limit of the voltage stability of the system [4,15]. In [5–8], the maximum loadability limit is calculated using genetic and other innovative algorithms, developed to update power flow variables considering the power mismatches. In [11] a Chaotic Local Search (CLS) is included in the genetic algorithm to overcome possible local optima and reach the global optimum.

Alternatively, the Transient Stability Constrained–Optimal Power Flow (TSC–OPF) is an optimization tool that explicitly includes both steady-state and dynamic constraints in the formulation, and that has received increasing attention over the last years [16]. The TSC–OPF usually includes large numbers of equations and variables, resulting from the addition to the conventional steady-state equations of the dynamic equations representing the electromechanical oscillations at all the discretization points of the time domain simulation. Synchronous generators are usually represented in TSC–OPF by the classical generator model [17–22], consisting of a voltage source of constant magnitude behind a transient reactance [23]. Although this model offers a limited accuracy in the representation of the electromechanical transients, it is frequently used to reduce the computational burden of the model. Some approaches handle the size and complexity of the problem by the reduction of the multimachine system to a scheme of two machines (a "single-machine equivalent" strategy) [17,24], or the modification of the discretization method [25]. Multicontingency cases are also addressed in [18,22].

In [26,27], an optimization problem considering the effects of both steady-state and dynamic security constraints in the loadability of a system is proposed. In this case, the problem is solved using a mathematical programming method comprising an iterative scheme of two kernels. The first kernel evaluates the security of the operation, and the second one adjusts the generation dispatch. The algorithm requires iterative loops to achieve the optimal values. This work and the work presented in this paper are similar in that they calculate the maximum load considering dynamic

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Nomenclature

Parameters:

D_i	damping coefficient of the *i*th generator in p.u.
H_i	inertia constant of the *i*th generator in s
P_{Di}	active power demand at bus *i* in p.u.
Q_{Di}	reactive power demand at bus *i* in p.u.
Δt	time step in s
x'_{Di}	transient reactance of the *i*th generator in p.u.
Y_{Bmn}	branch admittance between buses *m* and *n* in p.u.
Y_{in}	magnitude of the element (*i*, *n*) of the bus admittance matrix
Y_{REDij}	magnitude of the element (*i*, *j*) of the reduced admittance matrix
θ_{in}	phase of the element (*i*, *n*) of the bus admittance matrix in radians
θ_{REDij}	phase of the element (*i, j) of the reduced admittance matrix* in radians
ω_0	frequency reference in radians/s

Variables:

E'_i	internal voltage of the *i*th generator in p.u.
I_{mn}	current between buses *m* and *n* in p.u.
I_{Gi}	output current of the *i*th generator in p.u.
P^t_{Ei}	active power output of the *i*th generator at time step *t*, in p.u.
P_{Gi}	active power generation at bus *i* in p.u.
Q_{Gi}	reactive power generation at bus *i* in p.u.
V_i	voltage magnitude at bus *i* in p.u.
δ^t_i	angular deviation of the *i*th generator at time step *t*, in radians
δ^t_{COI}	angle of the center of inertia at time step *t*, in radians
ϕ_i	voltage angle at bus *i* in radians
λ	load scale factor
$\Delta\omega^t_i$	frequency deviation of the *i*th generator at time step *t*, in p.u.

Upper and lower limits of the variables are marked with the subscripts MAX and MIN, respectively

constraints, but differ in some important aspects. In the present work: (a) the solution is obtained using a single application of a conventional solver, (b) reactive power constraints are applied, and (c) the dynamic equations are solved using the trapezoidal rule, which has better stability properties than explicit integration methods.

The restrictions that ensure that the solution is transiently stable usually assume the form of a limitation in the rotor angle deviations. A wide range of rotor angle limits have been used in previous works [18,20–22,28–31]. However, an assessment on the effect of the rotor angle limit on the results, which can help the operator to select a suitable value, has not been found in the literature.

The aim of this study is to extend the later developments of the TSC–OPF tools to the problem of the maximum loadability. This is done by establishing the following objectives:

- To propose an optimization model to calculate the maximum loadability of a small system (15 buses, 3 generators) that allows it to retain transient stability after a severe fault. For a given fault, the solution must be obtained by the single solution of the optimization model, without any further iteration.
- To analyze the effect of the rotor angle deviation limit on the solution of the maximum loadability of a system.

The first objective is accomplished through an optimization model that includes the static and the dynamic constraints in a unique formulation, and an objective function that accounts for the load. The second objective is studied by means of a systematic solution of the optimization model using different rotor angle limits, and the discussion of the results. The model is applied to a network of 15 buses and 3 generators that represents the power system of two islands in the western Mediterranean Sea. The feasibility of the model is shown by the variety of the situations analyzed, the good convergence obtained in all the cases using a conventional solver and the consistence of the solutions.

2. Formulation

2.1. Maximum loadability in the optimization model

The model is based on the following assumptions:

- After a severe fault, the transient stability of the system can be ensured if the rotor angle deviation of each generator with respect to the Center of Inertia (COI) does not exceed a certain limit.
- The dynamics of the synchronous generators are represented using the classical model.
- During the electromechanical oscillations the loads are modeled as constant admittances.
- In the search for the maximum load, all loads increase proportionally and the power factor remains constant in each of the loads.

The model imposes restrictions on the bus voltages, the branch currents, the field current, output current and output power of the generators and on the rotor angle deviation with respect to the COI during the electromechanical oscillations. The dynamic equations are integrated using the trapezoidal rule, and the resulting equations are included in the optimization model as equality restrictions.

The objective of the model is to maximize the load scale factor λ. When λ is one, the load at each bus *i* is the load at the base case, P_{Di}, Q_{Di}; as λ increases, the active and reactive load at each bus increases to $\lambda P_{Di}, \lambda Q_{Di}$. The load is supposed to increase proportionally at every node of the system, although this formulation can be easily modified to scale the load only at some selected buses.

The complete formulation of the model is as follows; the explanation of the equations is presented below.

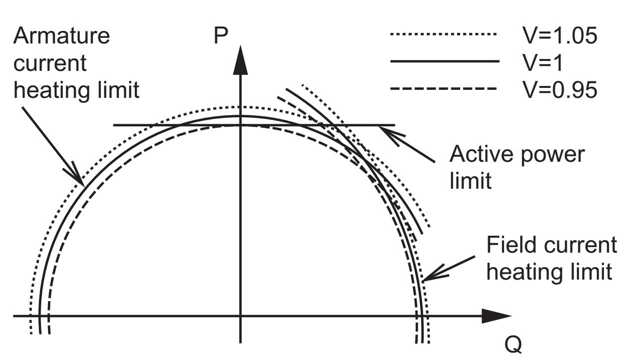

Fig. 1. Capability limits of the generators.