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Optimization of the operation of a flywheel to support stability and reduce generation costs using a Multi-Contingency TSCOPF with nonlinear loads

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ABSTRACT

Multi-Contingency Transient Stability Constrained Optimal Power Flow (MC-TSCOPF) models optimize the economic dispatch of power systems while ensuring their stability after a series of reference incidents. This paper proposes a MC-TSCOPF model that represents the power balance at each node of the system and at each sample time. The proposed model includes non-linear loads, synchronous generators, a windfarm, and a Flywheel Energy Storage system (FESS). The model is written on GAMS and solved using a standard Interior Point algorithm. This study focuses on the Fuerteventura-Lanzarote insular grid in Spain, where stability problems and load shedding cause high additional costs due to the low inertia of the system. A FESS has been recently installed in the system to improve its stability, taking advantage of its high-power capacity and rapid response. The proposed TSCOPF model has been applied to optimize the operation of the FESS to support stability in the event of a contingency. The results of the study show that 1) a proper model of non-linear loads is essential in TSCOPF studies; 2) the proposed MC-TSCOPF provides a tool for minimizing the generation costs while ensuring transient and frequency stability; and 3) it is possible to further reduce the generation costs by using the proposed model to calculate an optimal dynamic response of the FESS.

1. Introduction

Ensuring stability and reducing generation costs are essential issues in modern power systems. Transient Stability Constrained Optimal Power Flow (TSCOPF) models have emerged over the last decade as a tool to combine the economic and secure operation requirements. The TSCOPF studies include a time-domain representation of the system dynamics in the optimization problem to account for the effects that dynamic constraints have on the optimal operation.

During the last few years various approaches have been proposed to address TSCOPF [1–4]. On the one hand, evolutionary algorithm methods that use stochastic optimization algorithms [5–7] and direct methods that rely on simplified models [8,9] have been applied to reduce the size and complexity of the problem in large power systems. Other approaches have recently included the uncertainty of the renewable generation for transient stability assessment using probabilistic techniques [10,11]. On the other hand, direct discretization methods, which discretize the differential equations representing the dynamics of the system and include them in the optimization model as algebraic equations, have been applied to smaller systems [12–15].

Direct discretization methods have the advantages of including the dynamics of all the synchronous machines and using standard nonlinear programming solvers, but they are difficult to apply to large. The two main problems associated with the direct discretization TSCOPF studies is the large number of restrictions and variables and the high non-linearity of the electromechanical oscillations between synchronous generators. The size of the model has been reduced in previous studies by representing the grid and the loads as a linear circuit and applying the Kron reduction method [12–15]. This approach has the disadvantage of representing loads as constant impedances. It is also a common practice to represent synchronous generators by using the classical model instead of a standard dynamic model in the dq-axes reference frame [12–14].

The object of this study is the insular power system of Fuerteventura-Lanzarote in Spain. The small size and low inertia of the system, which contains two conventional power plants and a wind farm, make it prone to transient and frequency stability problems. Flywheel Energy Storage Systems (FESS) have received growing interest in practical studies as a tool for increasing the stability, especially in small and isolated power systems where stability and frequency problems are major concerns. High power capacity, short access time, high efficiency, and small environmental impact make flywheels suitable for this purpose [16]. A FESS has been installed in the island of Lanzarote. This device has proven to be a useful resource to improve the

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Nomenclature

Indices and Sets

i, j	Index of nodes, running from 1 to $\mathscr{N}$
t	Time periods, running from 1 to $\mathscr{T}$
$\mathscr{N}$	Set of buses
$\mathscr{T}$	Set of time periods

Control variables

E_{fd}	Field voltage [p.u.]
K_{WF}	Binary variable that is equal to 1 if wind farm is connected, and 0 otherwise
P_{injFW}, P_{absFW}	Injected/absorbed active power by the FESS [p.u.]
P_G, Q_g	Generator active and reactive power [p.u.]
P_{wp}, Q_{wp}	Active/reactive power injected by a wind farm [p.u.]
Q_{injFW}, Q_{absFW}	Injected/absorbed reactive power by the FESS [p.u.]
ΔP	Turbine governor output [p.u.]

State variables

E'_d, E'_q	Generator internal transient voltages [p.u.]
E_{FW}	Stored energy in the FESS [p.u.]
I'_d, I'_q	Generator output current components [p.u.]
I_L	Current between nodes (i,j) [p.u.]
I_{ph}	Current through IGBT converters [p.u.]
P_e	Electrical power in the rotor of the generator [p.u.]
V	Bus voltage magnitude [p.u.]
V_r, V_{ref}, R_f	IEEE1 excitation system inputs [p.u.]
α	Bus voltage phase [rad]
$\Delta\omega$	Generator speed deviation [rad/s]
δ	Rotor angle [rad].
δ_{COI}	Rotor angle of the center of inertia [rad]
φ	Bus angle between current and voltage [rad]
ω_{FW}	Flywheel angular velocity [rad/s]

Parameters

a, b, c	Fuel cost coefficients of thermal plants
A_p, b_b, c_p	Active power coefficients of the ZIP load model
A_q, b_q, c_q	Reactive power parameters of the ZIP load model
As, Bs	Excitation system saturation coefficients
D	Damping coefficient [p.u.]
H	Inertia constant [s].
K_A, K_F, K_E	Excitation system gains [p.u.]
K_{TG}	Turbine governor gain [s]
J	Flywheel inertia constant [kg·m^2]
P_{D0}, Q_{D0}	Active, reactive nominal load [p.u.]
P_{WF}^{REF}	Available wind resource p.u.]
Q_{WF}^{REF}	Wind farm reactive power reference [p.u.]
r_a	Armature resistance [p.u.]
T_A, T_F, T_E	Excitation system time constants [s]
T'_{d0}, T'_{q0}	Generator transient time constants [s]
T_{TG}	Turbine governor time constant [s]
x_d, x_q	Synchronous reactances [p.u.]
x'_d, x'_q	Transient synchronous reactances [p.u.]
Y_{ij}	Magnitude of the element (i, j) of the bus admittance matrix [p.u.]
Δt	Time step [s]
$\eta_{iny,abs}$	Performance of the synchronous machine of the FESS
θ_{ij}	Phase of the element (i,j) of the bus admittance matrix [rad]
ω_{FW}^{ref}	Steady state FESS speed [rad/s]
ω_0	Frequency reference [rad/s]

Abbreviations and Acronyms

COI	Centre of Inertia
FESS	Flywheel Energy Storage System
MC	Multi-contingency
MR	Multiple Responses
OPF	Optimal Power Flow
SR	Single Response
TSCOPF	Transient Stability Constrained Optimal Power Flow

frequency stability in small systems [17–19]. However, the calculation of its optimal response to a contingency has not been clearly determined in the literature.

This paper proposes a novel Multi-Contingency TSCOPF (MC-TSCOPF) model based on the direct discretization method. The aim of the study is to minimize the generation costs while ensuring stability. Instead of representing the grid as a linear passive circuit, the proposed model represents the active and reactive power injected at each node and at each sample time as independent variables. Therefore, this approach allows modelling loads as standard ZIP models instead of assuming constant impedances. Furthermore, it enables the integration of variable-speed wind farms and FESSs, represented as devices that inject power according to their control systems and independent of the magnitude of the voltage at the connection point. In the study, the synchronous generators are represented by the transient, 4th-order generator model, that provides an accurate representation for transient stability studies as stated in [9,20].

The main contributions of this paper are as follows:

- A direct discretization MC-TSCOPF model that includes non-linear loads and combines frequency and transient stability constraints.
- The integration of a FESS model into the TSCOPF problem.
- The optimization of the dynamic response of the FESS to reduce generation costs while ensuring both frequency and transient stability.

The optimization algorithm is applied to a real system in the Canary archipelago (Spain), where a FESS has been put in operation. The method proposed here is used to optimize the generation costs while ensuring stability in the event of any critical contingency. The results are compared with those obtained with the conventional operation of the FESS.

The rest of paper is organized as follows: Section 2 describes the proposed TSCOPF model, including the FESS; Section 3 describes the case study; Section 4 shows and discusses the results obtained when solving the proposed MC-TSCOPF; and Section 5 concludes the paper.

2. Description of the model

The TSCOPF models based on direct discretization are composed of two parts: the steady-state and the time-domain period. The steady-state or pre-fault stage corresponds to the normal operation of the system, and the time-domain period simulates the behaviour of the system during and after a contingency. The time-domain period is subdivided into fault and post-fault stages. All periods are included as equality and inequality constraints and solved in the same optimization problem. This section gives a complete account of the steady-state and time-domain equations of the proposed TSCOPF model, organized according to the parts and components that compose the power system.