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Optimal re-dispatch of an isolated system considering transient stability constraints

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ABSTRACT

In this paper, an algorithm for calculating the optimal operation of a system with different load states and fault clearing times is proposed. The algorithm simultaneously considers both economic and stability constraints. The proposed formulation is evaluated on the Majorca and Minorca islands power system, which is a small, isolated system with low inertia. A conventional optimisation tool is used to solve the optimisation problem. The results show the efficiency of the proposed approach and the advantages of including stability restrictions in the optimisation analysis. The application of the algorithm to different operation points is used to evaluate the cost of assuring the transient stability after a severe fault in the transmission grid. The analysis of different fault clearing times is used to estimate the economic savings of implementing a faster protection system.

1. Introduction

Optimal power flow (OPF) is an important tool for power system operation and planning. The main purpose of an OPF program is calculating the optimal operating point of a power system and setting the variables for the economic and secure operation of the system.

Transient stability studies test the optimal solution obtained from the OPF under credible disturbances to ensure the stability of the system. If the system is transiently unstable under one of the disturbances, the OPF solution must be modified. Heuristic trial-and-error methods, based on engineering experience, are typically used to re-dispatch the system to guarantee the stability of the operation [1,2]. The conventional sequential procedures of dynamical simulation require the same number of equations and variables. Therefore, when the number of variables is greater than the number of equations, the best solution of the system is obtained by successive behaviour simulations to find a reasonable answer [3,4].

Until recently, the dynamic of a power system could not be incorporated into a mathematical OPF formulation through a transient stability model. However, the advance of computing resources and consolidation of optimisation methods for the solution of large-scale problems allow the temporal representation of the dynamical system in the optimisation problems. The main advantage of representing differential equations in optimisation problems is the possibility of giving a preferential direction to the solution of the dynamic equations when the number of variables exceeds the number of equations. In this manner, it is possible to minimise or maximise performance indexes, calculate optimal parameters and make the system more stable or economical. Of course, this integration of static and dynamic studies implies an increase in the dimension of the optimisation problem [5].

The transient stability-constrained OPF (TSC-OPF) aims to integrate economic objectives and both steady-state and stability constraints in one unique formulation. Previous studies on TSC-OPF show different ways to approach this complex problem. In [6] and [7], the infinite-dimensional TSC-OPF problem is converted to a solvable finite-dimensional programming problem using functional transformation techniques. The transformed problem has the same variables as those in the pure OPF problem. In this approach, the temporal behaviour of the dynamic variables cannot be observed. Alternatively, in [8], dynamic equations are transformed into numerically equivalent algebraic equations using the trapezoidal rule and then included in the conventional OPF formulation. For the algorithm to be solved, the OPF constraints, stability equations and objective function must be linearised. The authors of [9] and [10] propose the resolution of a multi-contingency TSC-OPF problem, including the temporal representation of the dynamical equations in the optimisation problem. To obtain the solution, a specifically modified algorithm of the Primal–Dual Interior-Point method is used. This algorithm can accommodate nonlinear equations, but a reduction method is necessary to efficiently handle the inequality constraints. Nonlinear equations are also represented in [11], which considers the algebraic equations (both equality and inequality constraints) that describe the steady-state situation of

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the power system during both the pre-fault and steady-state post-fault periods. In [12], the authors propose a similar approach, reducing the multi-machine model to a scheme of two machines using the "single-machine equivalent" concept.

This study proposes an algorithm that includes all of the simulation period in one formulation: the pre-fault, fault and post-fault stages. The differential equations of the classical model of the generators for dynamical studies are explicitly included in the optimisation problem as nonlinear constraints using the trapezoidal rule. Two different simulation steps, during and after the fault, are used to reduce the computational burden. Using this approach, the most changing stage of the simulation can be represented in more detail.

The algorithm is applied to the interconnected system network of the islands of Majorca and Minorca, consisting of 15 buses and 3 generation machines in isolated operation. The optimal generation dispatch, considering economic parameters and assuring the stability of the system at different load states and after one of the most severe faults, is obtained. The generators must preserve a maximum angle deviation from the grid's centre of inertia (COI). The dynamic behaviours of the three generators are simultaneously calculated in the optimisation solution. At the end of the paper, two fault clearing times are considered to analyse the effect of using faster protections from an economic point of view.

The results show that the proposed algorithm can adequately calculate the optimal behaviour of the system for different load states and fault clearing times in an efficient manner. An initial calculation of the costs associated with the stability constraints for different operation states is performed. In the present system, the reduction of the clearing time of some protections (from 300 to 250 ms) can decrease the operational cost by 8.84% for medium load conditions.

2. Transient stability model

Analysing the transient stability of power systems involves the computation of their nonlinear dynamic response to large disturbances, typically a fault in the transmission network followed by the isolation of the faulted element by protective relaying. In this section, a mathematical model of the power system dynamics suitable for the TSC-OPF and a criterion for determining whether a case is acceptable with respect to rotor angle stability are proposed.

In this paper, the synchronous generators are represented by the classical generator model [13], which consists of a voltage source E_i' of fixed magnitude behind a transient reactance x'_{d_i}, as shown in Fig. 1. In the classical model, the swing equation provides the two differential equations for each generator as follows:

$$d\delta_i/dt = \omega_0 \Delta\omega_i \tag{1}$$

$$d\Delta\omega_i/dt = (1/2H_i)(P_{m_i} - P_{e_i} - D_i\Delta\omega_i) \tag{2}$$

where δ_i is the angular position of the rotor with respect to a synchronously rotating reference, $\Delta\omega_i$ is the rotor speed deviation,

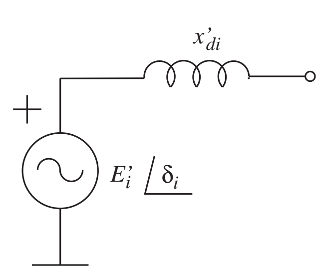

Fig. 1. Equivalent circuit of the synchronous generator.

ω_0 is the reference frequency, H_i is the inertia constant, P_{m_i} and P_{e_i} are the input and output powers, respectively, D_i is the damping constant and d/dt is the derivate of the function with the time.

The mechanical power input is considered to be constant throughout the study period, and the magnetic saturation is not represented. The three more usual static load models in transient stability studies are: constant impedance, constant current and constant power [14]. In this study, the loads are modelled as constant impedances and included in the system's admittance matrix. This representation allows the reduction of the admittance matrix during the transient period, only representing the internal nodes of the synchronous generators. The representation of all loads as passive impedances is one of the common simplifications applied in TSC-OPF [5,9,10,12], because it significantly reduces the number of equations. The output power of the ith generator can then be expressed as

$$P_{e_i} = E_i' \sum_{j=1}^{N_g} E_j' Y_{red,ij} \cos(\delta_i - \delta_j - \theta_{red,ij}) \tag{3}$$

where N_g is the number of generators and the complex number, $Y_{red,ij}|\underline{\theta_{red,ij}}$ is the element in position (i, j) of the reduced admittance matrix.

The classical generator model is commonly used in the state of the art TSC-OPF [8–12]. This model is a compromise between adequate dynamic representation and computational burden. In this study, conservative limits for the determination of the transient stability constraints are adopted, due to the difficulties associated with improving the representation of the generators by including additional differential equations.

The state of the system is considered acceptable for a given disturbance if the maximum rotor angle deviation during the electromechanical oscillations does not exceed a certain value. Here, instead of the maximum deviation between the angles of two machines [12,15–17], the maximum deviation with respect to the COI is constrained [18]. The COI has the advantage of providing a reference that includes the component of the angle deviation due to the acceleration of the system and allowing to identify the component with the larger individual rotor oscillations. The angle of the COI is defined as

$$\delta_{COI} = \sum_{i=1}^{N_g} H_i \delta_i \Bigg/ \sum_{i=1}^{N_g} H_i \tag{4}$$

Differential Eqs. (1) and (2) are solved using the trapezoidal rule, which is an L-stable implicit integration method [19]. The stability of the trapezoidal rule is important because it allows the computational time to be reduced by using larger time steps.

When applied to Eqs. (1) and (2), the trapezoidal rule yields

$$\delta_i^{t+1} = \delta_i^t + (\Delta t/2)\omega_0(\Delta\omega_i^{t+1} + \Delta\omega_i^t) \tag{5}$$

$$\Delta\omega_i^{t+1} = \Delta\omega_i^t + (\Delta t/4H_i)(2P_{m_i} - P_{e_i}^{t+1} - P_{e_i}^t - D_i(\Delta\omega_i^{t+1} + \Delta\omega_i^t)) \tag{6}$$

where t is the iteration step and Δt is the time step. The fact that the trapezoidal rule is an implicit method is not a problem in this study because the optimisation algorithm solves all of the equations simultaneously, obtaining the dynamic positions in all of the simulation periods and the optimal initial conditions at the same time.

3. Formulation of the TSC-OPF problem

The objective of this study is to obtain the optimal operational conditions of the system when the system is affected by a symmetrical three-phase fault to ground with different load levels. The fault