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Heuristic optimization based approach for identification of power system dynamic equivalents

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ABSTRACT

This paper introduces an approach for identification of dynamic equivalent parameters from measured operational dynamic responses associated to different disturbances. To tackle challenges related to optimization problem complexity (i.e., non-linearity of time-domain simulation based fitness calculation, discontinuity, non-convexity, and multimodality), the approach adopts a novel variant of the mean-variance mapping optimization algorithm to pursue efficient and fast search capability. This variant bases on swarm intelligence precepts and employs a multi-parent crossover criterion for offspring creation. Numerical tests performed on the Ecuadorian–Colombian interconnected system, including performance comparisons with other heuristic optimization tools, support the potential of the proposal to provide accurate estimates within a fast convergence rate.

Introduction

The operation of modern power systems is being subjected to several technical challenges associated to increasing complexities in utility planning and management policies as well as in important structural changes. On operational planning and management side, the spare operating margins have been dramatically reduced due to slow grid infrastructure expansion and market-oriented pressures [1]. On the structural side, wide scale participation of new generation sources with intermittent behavior along with increasing interconnections are significantly altering the typical power flow patterns [2]. In this context, the systems are more frequently operated very near to their security limits, which entails a higher risk of occurrence of disturbances and cascading events that may lead to major consequences, including widespread disruptions or even blackouts, whose root causes could be occasionally attributed to different stability problems [3,4].

New technological solutions are therefore required to improve the monitoring, and control tasks while maximizing the utilization of renewable energy, energy storage, and demand side response schemes. With the remarkable progress of power electronic and the telecommunication technologies, the main premise is to make efficient use of sensory information to enhance overall power system performance through timely detection of undesirable operating conditions and execution of optimal remedial actions (i.e., self-healing grid) as well.

So far, the utilities rely on model based dynamic simulation studies to conceive appropriate strategies for dynamic security improvement. Despite of the availability of powerful simulation engines and the widespread use of modern high-performance computing techniques (e.g., parallel or distributed processing), performing dynamic security analysis of detailed complex interconnected systems in real-time is still unfeasible. Nevertheless, considering that system vulnerability begins to develop in a specific zone, where the triggering event occurs, it is usual to divide the system into zones to speed up the vulnerability assessment computation time [5]. Broadly speaking, the system portion of interest (i.e., study area) is modeled with enough detail whereas the remaining interconnected portions (i.e., external or neighbor areas) are replaced by dynamic equivalents, which should allow reproducing the influence of the neighbour zone on the study zone [6].

Dynamic equivalents are also relevant for controller design studies, which require smaller system models. Moreover, their use is motivated by other factors such as, for instance, lack of information about dynamic models and control structures belonging to the external areas due to confidentiality. These equivalents are usually modeled considering the following precepts [7]: (i)

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adequate representation of the dynamic phenomena under study (e.g., transient stability); (ii) use of generic models, which provide the required simplicity and accuracy to properly recreate the joint interaction between the elements composing system portion to be replaced and the study area; and (iii) contribute significantly to decrease the computational memory and time that is expended to run system security studies in near real-time.

Preliminary stages of dynamic equivalence comprise identification, grouping and aggregation of those elements exhibiting coherent dynamics [8]. Well-established solutions exist in literature to accomplish these tasks based on different control theory and structure preserving criteria [8,9]. Recently, several approaches have been proposed to overcome the limited availability of data of external zones as well as to perform the reduction in real time using phasor measurement unit (PMU) signal records [9,10]. Once the structure of the equivalent is defined, measurement data can further be utilized to estimate its parameters. Such an identification problem has been tackled in pioneering studies using neural networks [11] as well as trajectory sensitivities and parameter correlation analysis [12]. Due to the complex nature of power system dynamics, the optimization problem of dynamic equivalent parameter identification possesses a discontinuous multimodal and non-convex landscape, which does not lend itself to solution by classical optimization methods. Thus, other alternative solution approaches have been proposed based on different heuristic optimization algorithms [13,14]. Nevertheless, a thorough analysis of the solution quality and computing efficiency that can be achieved with these tools is needed, since their searching performance is sensitive to algorithm's parameter settings.

Motivated by results on application of the mean-variance mapping optimization algorithm (MVMO) to several power system problems [15–20], including a preliminary study on identification of dynamic equivalent parameters [16], the research work presented in this paper concerns the development of an alternative solution approach based on a novel variant of MVMO, which apart from being a swarm intelligence based procedure, incorporates a multi-parent crossover, aiming at enhanced search capability. The proposed variant of MVMO is hereafter referred to as MVMO-SM. Following this introduction, Section 'Proposed approach' discusses key aspects related to definition of the identification problem and implementation of the MVMO-SM based optimization procedure. Section 'Test case study' provides a case study on the Ecuadorian–Colombian interconnected system, including performance comparisons with classical MVMO and other heuristic optimization tools. Finally, conclusions and outline for future research are given in Section 'Conclusion'.

Proposed approach

The overall procedure of the proposed approach sketched schematically in Fig. 1. It is assumed that the interconnected power system to be reduced has well defined zone coherency, so models of the study area and the dynamic equivalent that suitably represent the external area should be previously defined. A set of multiple disturbances, for which the dynamic equivalent should be identified, are also specified beforehand. Initially, the settings of MVMO-SM are defined and samples of the optimization variables (i.e., parameters of the dynamic equivalent) are randomly generated within their search boundaries for a given number of particles (i.e., population of solutions). Besides, the optimization variables are normalized at this stage, that is, the range of the search space for all variables is transformed from [min, max] to [0, 1]. This is a precondition for the subsequent mutation operation via mapping function; on top of this, it is ensured that the generated offspring will never violate the search boundaries. The optimization variables

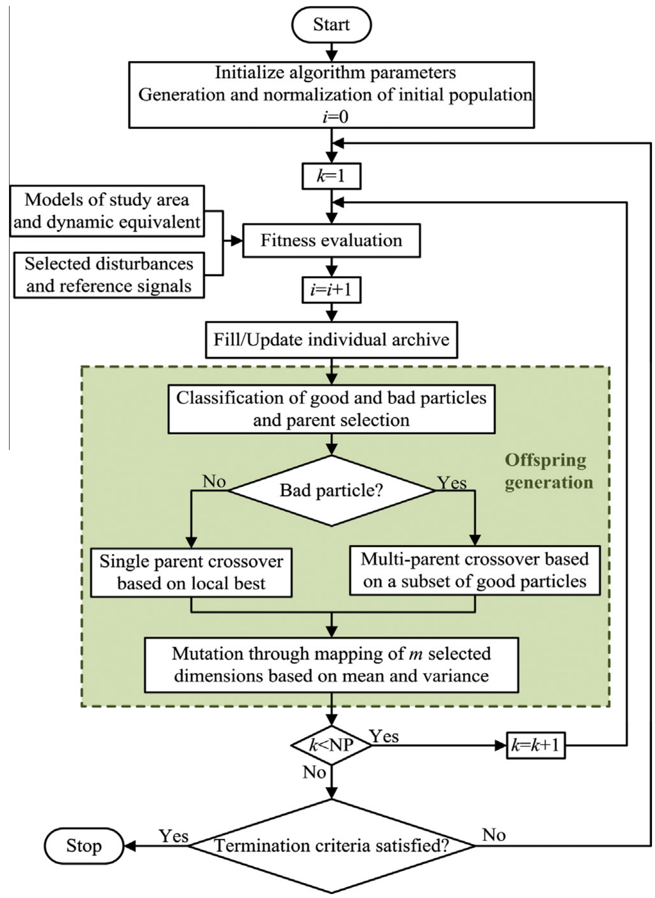

Fig. 1. Framework of the proposed approach. The fitness evaluation and particle counters are denoted by i and k, whereas NP stands for number of particles.

are de-normalized before fitness evaluation stage, in which, the response of the dynamic equivalent, as seen from the border between study and external areas, should fit a given set reference signals obtained through simulation with full system model or from available measurements. Next, for every particle, the optimization search is iteratively performed by considering filling and continuous update of the solution archive (i.e., algorithm's knowledge base) and some steps for creating new potential solutions (i.e., offspring generation) in light of the performance of the previous ones. The procedure is terminated once a predefined termination criterion is satisfied.

Optimization problem statement

Considering the difference between selected reference signals (obtained from simulations or measurement devices) corresponding to measured responses of the external zone at the boundary with the study area (e.g., tie bus voltage, tie line power flows) and those signals obtained by considering the dynamic equivalent, the parameter identification, treated as an optimization problem, can be formulated as follows:

Minimize

$$OF = \sum_{np=1}^{p} \alpha_{np} \int_0^{\tau} \left[w_1 \left(y_1 - y_{1_{\text{ref}}} \right)^2 + \cdots + w_n \left(y_n - y_{n_{\text{ref}}} \right)^2 \right] dt \tag{1}$$

subject to

DAE system

$$\mathbf{x}_{\min} \leqslant \mathbf{x} \leqslant \mathbf{x}_{\max} \tag{2}$$