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Development of PSS tuning rules using multi-objective optimization

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ABSTRACT

This paper explores the process of tuning controllers for conditions that better reflect realistic operating conditions, such as input signals of different shapes. In this study, controllers are tuned simultaneously for input signals of different shapes, using the tools of double objective optimization. For this purpose, a novel performance index is proposed to evaluate a system's ramp response. At the same time, a novel method is proposed for faster and more efficient generation of Pareto plots and Pareto frontiers. The proposed method retrieves the dominant Pareto solutions only, and produces the Pareto frontier directly. The study is applied on the tuning of a Power System Stabilizer (PSS) of a simple power system, at several operating points of the synchronous machine. Finally, a relation between the optimum PSS parameters and the operating points is sought. A linear regression model is used for this purpose, and the tuning rules are tested in an application study. Finally, the optimization technique is applied on a multiple machine system. The results show significant improvement, while maintaining fault resilience.

1. Introduction

The current demand for electric power pressures power system operators to maximize the system's efficiency, security, and reliability. Power systems are required to respond as quickly as possible to external stimulus and to adapt to changes in their operating set point in a timely manner. Accordingly, fixed controllers that have the same tuning and/or the same set of parameters, and that navigate the system through all operating conditions cannot meet the high standards of efficiency. Dynamic controllers, those that constantly change parameters based on the current operating point, exhibit better performance and adapt to large changes in demand.

For objective evaluation of system's performance, a quantitative indicator is useful, and to optimize controllers, a popular class of performance indices is time integrals of certain system states or parameters. The most commonly used index is the Integral of Time & Absolute Error criterion (ITAE). These methods were introduced in the 1970s by [1]. The error signal (e) from the control system ($e(t) = r(t)-y(t)$) is used to evaluate this integral. The mathematical expression of this criterion is illustrated by (1).

$$J_{(ITAE)} = \int_0^t t\cdot|e(t)|dt \tag{1}$$

If a parametric model of the system's dynamics is available with reasonable accuracy, it is possible to predict the best controller parameters that optimize the system's performance. In fact, a plethora of literature and tuning rules exists already, for the optimum parameters of various types of controllers. O'Dwyer's study [2] exhibits numerous tuning rules for PID controllers, for different performance criteria and plant models. Jin et al. [3] proposed tuning rules for the PID controller, for optimum operation of the power system. The step input test is the only signal used for testing and evaluation of systems' performance. However, a set-point change in real life applications can happen in any shape. In such scenarios, the controllers' performance will not be optimal. As a consequence, engineers often discard the recommended settings and tune the controllers manually.

Despite that the ramp-response test and harmonic frequencies are known in optimization, they are rarely used for testing [1]. Tuning rules developed for controllers have not yet considered combining multiple integral performance criteria into one objective function. Secondly, the concept of optimizing a system's response to different input signals simultaneously has not yet been investigated. This study intends to address these two issues simultaneously. Although generation units have well understood dynamics and constraints, such as ramping limits, work on optimizing a generator's response to a ramp change in set point is scarce.

2. Literature review

The work in [4] proposed a linearized model of the synchronous

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Nomenclature

P	real power in per-unit (W)
Q	reactive power in per-unit (VAr)
J	numerical value of an objective/cost function
PSS	power system stabilizer
K_1-K_6	constants of the linearized model of synchronous machine
τ_i	adjustable parameters of the lead-lag compensator part of a PSS
τ_w	adjustable parameter of the washout filter part of a PSS
$ITAE$	integral of time – absolute error
$IAEUS$	integral of absolute error until settling

machine. The linearized model is accurate only around a certain operating point of the machine, where a machine's operating point is defined by the machine's active power (P) and reactive power (Q) outputs. The linearized model has parameters (i.e., gains K_1-K_6) that are calculated as functions of the machine's operating point (P) & (Q), and the machine's physical parameters. This linearized model facilitates tuning PSSs for synchronous machines.

Power systems are dynamic, and synchronous machines are expected to maintain their stability and good performance under different operating points (i.e., P & Q). Hence, proper design of a PSS must consider multiple operating points within the range of the machine's limits (i.e., P_{min}, P_{max}, Q_{min}, Q_{max}). Because the linearized model is accurate only around its operating point, tuning and testing performance of PSSs should be carried out for multiple versions of the linearized machine model that correspond to the operating points of concern.

The need for PSSs in the control loop of a synchronous machine was illustrated in [5]. PSSs provide the damping necessary for machine stability by manipulating the machine's excitation voltage [6]. Different versions of the PSS exist, which differ in their order, in which signal is used as an input, and in the number of input signals. The problem of tuning power system stabilizers is not new. However, current research on the topic proposes utilizing different control methods, optimization algorithms, or novel objective functions.

As mentioned earlier, synchronous machines must be able to operate at different points (P & Q). A robust PSS design should be capable of stabilizing the system at different operating points within a predefined range. This is achieved by analyzing the system's stability at all operating points, and using different techniques to find a single set of PSS parameters that produce a stable system at all operating points. In linear systems, stability analysis is usually carried out by finding the system's poles in the S-plane, or the eigenvalues of the state-space's model of the system.

For example, the work in [7] obtained a single set of PSS parameters that stabilize the model of a single-machine infinite-bus system, for 140 operating points (P & Q) using Genetic Algorithms. This work was developed further by the same authors in [8], for the machine's actual (non-linear) model and for a multi-machine system. The concept of a robust PSS was further explored by the authors of [9], who extended a single set of parameters of the PSS. The work by [9] depicts each set of PSS parameters as a point in a multidimensional space. The author tests the stability of numerous points in the parameters' space in order to outline a continuous region where all points correspond to a robust PSS design (according to the definition of robust PSS provided above). The work in [9] utilized a model of PSS that has only three terms or variables to reduce the search space.

The work in [9] selects a point in the center of the outlined region that is denoted as the most resilient controller design. Selection of a centrally-located controller – the middle of a stability region – guarantees stability against uncertainty in the model's parameters, which is one of the strengths of this technique. However, unlike the work in [7,8], this choice does not guarantee a minimum value of the system's damping factor at all operating points. Furthermore, visualization of the polytope-of-stability in the parameters' space is possible only for a PSS with three parameters at most. According to [10], some PSS designs have as many as eleven parameters.

The authors in [11] mitigate the problem of communication latency when they examine inter-area oscillations. The study utilized the Grey-Wolf optimization algorithm for PSS tuning. The system's damping factor was improved by shifting critical system modes to the left of the S-plane, with a smaller control gain (K_p). The study also determines accurately the margin of delay and latency of which the system can still maintain its stability.

Sequential linear programming was used in [6] for robust tuning of PSS. The study used a PSS model with two decision variables. Analysis of stability was not based on finding the system's poles at each operating point (P & Q), but by producing the multivariable root locus at each operating point (P & Q). The multivariable root locus plot has multiple branches, and it shows the path of system's poles as a function of PSS parameters. A particular set of PSS parameters is deemed stable if the branches of the multivariable root locus land at satisfactory points in the S-plane. Because the PSS model employed in [6] has two decision variables only, a set of PSS parameters may be visualized as a point in a 2D space. When a particular set of PSS parameters is deemed stable (according to the root locus criterion described above), the set of parameters is represented by a point in a 2D space of PSS parameters. The points in this plot construct a path leading to a point with optimal PSS parameters.

The work in [12] utilizes a PSS model that consists of a linear part (lead-lag compensator), and non-linear part (saturation limits). An analysis of stability using the system's poles in the S-plane can only be used for tuning the linear part of the PSS model. However, the Hessian Matrix optimization algorithm is a method for tuning all system parts.

Advanced and adaptive control methods are used in some studies to tune a PSS in real-time. The work in [13] combines recurrent neural networks (RNN) and adaptive control systems to devise a novel control method denoted as the Recurrent Adaptive Control (RAC). The work notes the difficulty of applying the new algorithm to systems with long delay. Furthermore, the authors in [14] proposed a method to tune PSS in a multi-machine system in real-time, without knowledge of machine's external reactance or infinite bus voltage, but only with the knowledge of the voltage at the HV side of the machine's transformer.

Some work involved multi-objective optimization, such as [15]. The objective of optimization is minimizing both the eigenvalues' damping factor (ξ) and the eigenvalues' real part ($-\alpha$). The paper emphasized the difficulty of solving multi-objective problems analytically despite the fact that a modified artificial immune network was used for optimization. Ross et al. [16] set up a multi-objective optimization model for operating micro-grids. The weighted sum of all objectives was used as the cost function of optimization. The objectives were given different weights, however, the choice of weights was not justified. The magnitude of the weights aimed mainly to scale down objectives whose order of magnitude is very large compared to other objectives. The same approach was adopted in [17] without justification of the weights either.

Furthermore, the work by [18] used Genetic Algorithms to improve damping of several electromechanical modes, where the decision variables included the PSS parameters, the PSS's relative location in the grid, and the rating size of a unified power flow controller (UPFC). Optimization was achieved for several operating conditions, and the work established optimal coordination between PSS and UPFC. This improvement of damping characteristics comes at the cost of reducing other performance qualities, such as quick response towards load variations and adjustment of the machine's output. The findings and