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Application of game theoretic approaches for identification of critical parameters affecting power system small-disturbance stability

Kazi Nazmul Hasan*, Robin Preece, Jovica Milanović

School of Electrical and Electronic Engineering, The University of Manchester, M13 9PL, Manchester, UK.

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ABSTRACT

This paper evaluates a number of game theoretic (GT) approaches with the aim of assessing their suitability to identify the most influential parameters affecting the small-disturbance stability of a power system. Identification of the most influential parameters affecting system stability will facilitate cost-effective operation and control of a power system in general as it would require limited network monitoring, control and modelling effort by system operators and stakeholders. After identifying the most influential parameters the financial and human resources could be adequately prioritised and deployed to solve or prevent power system stability problems. A priority ranking procedure based on a GT approach has the advantage, compared to other techniques, of considering simultaneously the effect of individual and all possible combinatorial effects of the uncertain parameters (or players in a game context). In this study, the most influential players have been identified through a multi-level approach considering the power flow in the network (by optimal power flow), small disturbance stability aspects (by modal analysis), rational behavior of individual players (by a sensitivity technique) and formation of groups between players (by cooperative game theory). Various GT approaches have been considered namely Shapley Value, Aumann Shapley, Nucleolus, and τ-value approach in order to compare and assess their suitability for power system applications. The results are illustrated using two test networks and considering several approaches of sensitivity analysis and different degrees of variability in the considered uncertainties.

1. Introduction

Power System operation and control are becoming more uncertain and their analysis more complex due to the proliferation of new types of generation and loads. The number of uncertainties has been constantly increasing, and it is likely that this might require frequent changes in dispatch and operational scheduling in the future [1]. A wide range of scenarios affected by numerous uncertainties cannot be appropriately assessed through the traditional deterministic approaches to predict the system stability and security [2].

A probabilistic approach, on the other hand, can consider uncertain parameters in the system and can predict more accurately the true system behaviour as affected by changes in system parameters. As the number of uncertain parameters is increasing, the computational requirements grow and it is becoming inefficient to address all uncertain parameters in a realistic system. Moreover, it may not be necessary to model all uncertain parameters as some of them may have a negligible impact on the system phenomenon of interest. Hence, identification of the most influential uncertain parameters in the system will facilitate more cost–effective operation and control of the system requiring less monitoring by system operators and stakeholders [2].

Sensitivity analysis (SA) techniques have been traditionally implemented in power system studies to identify the most influential parameters [3–7]. While simple SA methods considered linear [5], quadratic [6], or trajectory based sampling [7], advanced SA techniques relied on improved sampling procedures by increasing the search space, dimensions and uniformity of sampling [2]. Still, the advanced SA methods only considered a single variable or a set of variables, ignoring the explicit interactions among different combinations of variables. A comprehensive comparative study of a range of frequently used "traditional" sensitivity analysis techniques, has been reported in [8] and their advantages and disadvantages clearly identified.

A game theoretic (GT) approach, on the other hand, has the capability to consider explicitly all possible combinations among all variables considered. Game theory assigns a value to raw sensitivity measures of each combination (i.e. groups) to obtain the game theoretic index. This index captures the cumulative impact of an individual parameter effect and the effects of all mutual (i.e. each and every

* Corresponding author.
E-mail addresses: Kazi.Hasan@manchester.ac.uk (K.N. Hasan), Robin.Preece@manchester.ac.uk (R. Preece), Jovica.Milanovic@manchester.ac.uk (J. Milanović).

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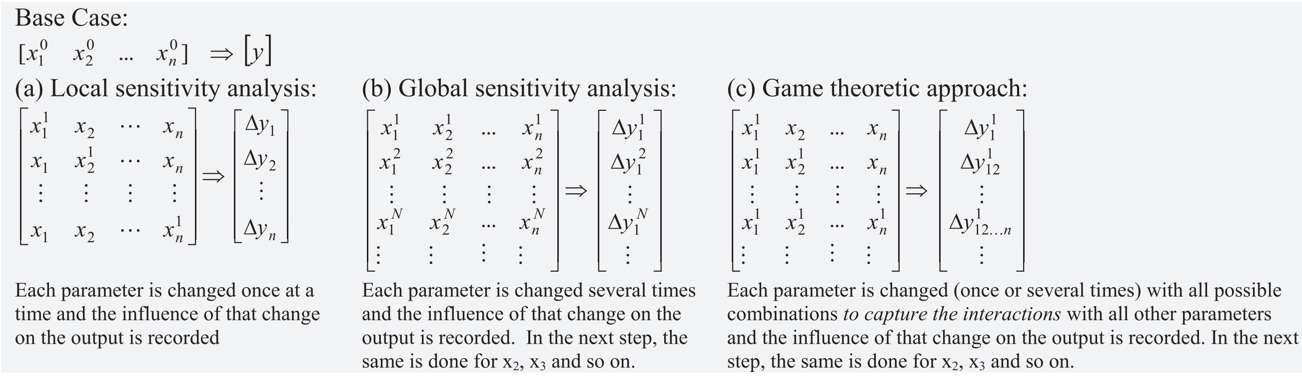

Fig. 1. Comparative representations of interactions among variables in local and Global SA, and GT approaches. In (a) one parameter is changed at a time, (b) one parameter in changed several (in some cases, many) times and (c) one parameter is changed many times with all combinations of that input with other inputs to measure the impact of changes in inputs to the outputs.

combination) interactions. The influence of every possible combinatorial effect of system components on its performance can only be suitably assessed by cooperative GT approach [9,10].

Considering that the small-disturbance stability is affected by continuous changes in the system load and generation and interactions among these factors and system controllers [11,12], the GT approaches are a logical choice for quantifying the scale of this problem. The possible consideration of interactions of system inputs such as generators and loads in interconnected power systems can be represented as shown in Fig. 1. A system output of interest (y) can be obtained for a set of system inputs (x_1 to x_n) for any input set (e.g. the base case at nominal conditions, as indicated by a superscript zero).

A local SA technique, presented in Fig. 1(a), studies the impact of a small-perturbation in single input parameters on the system output one at a time. That is, x_1 is changed by a certain percentage to a new value x_1^1 whilst keeping all other inputs at their nominal value and the corresponding impact of the change in x_1 on the output is measured as Δy_1. Similarly, the sensitivity of other inputs is measured as Δy_2, Δy_3, and so on. After testing each parameter, the most influential parameter is identified as that with the largest normalized value of $\Delta y_n/\Delta x_n$.

In a global SA technique as presented in Fig. 1(b), a range of variations of inputs to the system output are considered, while one parameter such as x_1 is changed several times (in some case, many times, depending on the complexity of the method). For example, each parameter is changed 4 to 10 times in Morris screening method, or in the range of a few hundred to a few thousand times in Monte Carlo simulation. These methods have been discussed in more detail in Section 4.3. The variations in the values of Δy_1, in this case are calculated from all measured responses of 1(b) to measure the impact of x_1 on the output. This process is repeated for x_2, x_3 and so on. However, the explicit interactions among different combinations of variables are not taken into account.

On the other hand, the game theoretic approaches as presented in Fig. 1(c), explored in this paper, can explicitly model the interactions among different input parameters (considering all possible combinations of x_1 with all other parameters). This is clear advantage of the game theoretic approaches compared to other methods. In this approach the variations in the values of Δy_1 with explicit combinations *to capture the interactions* with all other parameters are calculated from all measured responses of 1(c) to evaluate the impact of x_1 on the output. This process is repeated for x_2, x_3 and so on. It is obvious that the computational burden increases with the complexity and rigor of the methods from (a) to (c) presented in Fig. 1.

By implementing the alternative approaches, as presented in Fig. 1(a)–(c), the most critical parameters can be identified through the measure of the output which is the most affected by an input change.

1.1. Game theory

Game theory is an efficient tool to assess the interactions of multiple participants in a cooperative (or competitive) game. Identification of the most influential parameters affecting the stability of a power system involves interactions among multiple components of the associated system. The huge number of components interacting among themselves contributes a small amount each. The contribution is expected to be proportionate and equitable. Such a situation can be represented as a game with generators, loads and connected components as *'players'* of the game [9].

Typical applications of GT approaches are found in decision-making processes where the individual players can exercise their "strategic behavior" and make decisions over time. However, there are multiple non-conventional uses of GT approaches where these techniques have been successfully used in assessing and quantifying the interactions among different players in different situations. The "strategic behavior" or "bargaining power" is excluded in these types of cooperative GT applications and only the interactions among players are considered and evaluated. This use of GT approaches for the assessment of interaction has been demonstrated in many areas of power system studies, including transmission cost allocation [9,10,13], transmission congestion [14], and reactive power support [15], as well as in broader applications such as telephone billing [16], setting transportation tariffs [17], firm energy right assessment [18], airport usage [19], multi-criteria decision [20], water projects [21], and capital risk assessment [22]. However, these GT techniques have not previously been used in power system stability studies and therefore this paper is attempting to clarify their suitability for this type of application.

1.2. Aim of the study

This paper describes four cooperative GT indices which can be used to assess the sensitivity of a power system output to uncertain inputs and represents the first comparative analysis of a variety of GT techniques to power system applications. This novel application of GT approaches to determine the importance of uncertainties within power networks enables further development of probabilistic system analysis tools.

The techniques applied within this work are illustrated using examples of multiple power systems to demonstrate the applicability of the GT methods under varying problem formulations and constraints. The importance of uncertainties using GT methods is assessed in this work with respect to their effect on system small-disturbance stability. Even though this is the first application of GT methods to power system stability assessment, it must be noted that this represents just one of numerous