PROBLEM SOLVING THROUGH LIMIT-CASE ANALYSIS: EXPERIENCE IN TEACHING ELECTRICAL ENGINEERING PROGRAMMES

Federico Milano

University College Dublin (IRELAND)

Abstract

The paper describes an effective approach to solve complex power system engineering problems through an inductive approach based on limit-case analysis. The paper presents and discusses a variety of examples based on the experience of the author in teaching nonlinear system control and stability analysis to undergraduate students of electrical engineering programmes. The examples illustrate the effectiveness of using limit-case scenarios to improve the understanding of the dynamic response and coupling of most important power system devices and theirs primary regulation. The students' feedback as well as an example of lab activity are also discussed in the paper.

Keywords: Electrical energy systems; electrical engineering education; limit-case analysis; computer-based laboratory.

1 INTRODUCTION

Engineering problems tend to be described by a complex set of nonlinear equations, typically with several variables and parameters. This is particularly true in power system engineering. High voltage transmission systems, in fact, consist of hundreds of devices, such as transmission lines, transformers, generators, loads and controllers. It is argued by many that high-voltage transmission systems are the most complex systems ever built by mankind [1]. Even didactic examples taught in undergraduate modules, result complex to the students, despite these examples contains only few units of the devices mentioned above. The main difficulty is to understand the underlying interactions among devices, which typically involve nonlinear dynamic couplings. Any technique able to simplify the understanding of such interactions is thus particularly relevant for teaching purposes.

A powerful, although relatively simple and highly didactic approach based on limit-case analysis can partially overcome the difficulties above. This approach has been adopted by the author in his modules “Power system Modelling and Control” and “Power System Stability Analysis” taught since 2013 at the UCD School of Electric and Electronic Engineering and is utilized to clarify some basic concepts of power system control and stability analysis. The idea is to illustrate the behaviour of regulators and power system devices by means of limit-case values of key parameters and/or operating conditions. In the experience of the author, this approach is generally considered useful by the students and speeds up their learning curve. The limit-case approach also helps the students complete computer-based lab activities as it helps define sensible parameter values and reduce the need to solve not-meaningful simulations.

The contributions of the paper are as follows.

- A discussion on the didactic challenges of teaching nonlinear dynamic systems to students of engineering modules. This discussion is particularly focused to electric power systems, but main concepts can be applied to any engineering area involving sets of nonlinear differential equations.
- A variety of examples that illustrate the effectiveness of using limit-case scenarios to improve the understanding of the dynamic response of principal power system devices as well as primary regulation. These examples are also presented during the lectures, hence, the discussions are based on students' feedback whenever relevant.

The remainder of the paper is organized as follows. Section 2 outlines the content of the modules “Power system Modelling and Control” and “Power System Stability Analysis” and discusses the main challenges that students face while attending such modules and studying the dynamic behaviour of high voltage transmission systems. The context is the 4th year of BE and ME students of Electric Energy Systems at UCD, Ireland. Section 3 discusses the proposed approach based on the limit-case analysis and presents a set of relevant examples. Finally, Section 5 duly draws conclusions and discusses the didactic value of the proposed approach.

2 OUTLINES OF THE MODULES

The examples discussed in this paper are based on the modules Power System Modelling and Control and Power System Stability Analysis taught at during the academic years from 2013 to 2016 at the University College Dublin. These are 4^{th}-stage modules of the ME in Electrical Energy Systems programme that was implemented in 2013. This programme has received the accreditation from Engineering Ireland in 2014. Reference books of the modules described in this section are [2-5]. A brief description of the programme of each module is given below. An example of lab assignment of the module Power System Modelling and Control is given in the Appendix.

2.1 Power System Modelling and Control

The module introduces the main control requirements of most important devices that compose a HV transmission system. The focus of the module is on the dynamic behaviour of power systems. This includes frequency control, voltage control and auxiliary controllers aimed to improve the stability of the network. All topics are explained both theoretically and with simulation-based examples.

The module is divided into three parts.

- Part I: Park-Concordia model of the synchronous machine. Control of the synchronous machine, as follows. Primary and secondary controls including automatic voltage regulators, turbine and turbine governors, under and over-excitation limiters, and power system stabilizers. Synchronous machine secondary controls including automatic generator controllers and secondary voltage regulators. Tertiary frequency control.
- Part II: Transformer and FACTS device controllers, including under-load tap changers and phase shifters. VSC model and controls. Control of shunt and series FACTS devices. Basic models of VSC-based HVDC connections.
- Part III: Distributed energy sources control with particular emphasis on models and controllers of wind turbines and photovoltaic panels (MPPT, voltage control, frequency control, etc.). Basic control schemes of VSC-based distributed energy resources, e.g., PV power plants and battery energy storage devices.

The learning outcomes of the module are: basic concepts of power system frequency and voltage control; knowledge of control systems of all principal devices for high voltage transmission systems; and practical examples based on numerical simulations.

2.2 Power System Stability Analysis

The module explains the mathematical background of the phenomena that lead to power system instability, studying numerical methods to tackle such phenomena. The module is divided into four parts.

- Part I: long term voltage stability. Bifurcation theory (saddle-node, limit-induced and singularity-induced bifurcations) and the voltage collapse phenomenon. Continuation power flow analysis. Direct methods. Voltage stability constrained OPF. Voltage stability indexes. Cascade line tripping phenomenon.
- Part II: large perturbation angle stability (transient stability). Lyapunov theory. Direct methods. Time domain analysis methods. Hybrid methods (e.g. SIME [6]). Transient stability constrained OPF. Multi-swing phenomenon.
- Part III: small-signal angle stability analysis. Hopf bifurcations and limit cycles. Monodromy matrix. Routes to chaos, Poincaré maps and Lyapunov exponents. Small-signal stability constrained OPF. Effect of delays and analytical methods to assess the stability of delayed DAEs.
- Part IV: frequency stability. Load shedding problem. Frequency stability with renewable energy sources. Effect of thermostatically controlled loads.

Each part is completed by real-world examples (large scale blackouts), practical remedial actions and several computer-based simulation examples to support theoretical aspects.

The learning outcomes of the module are: basic principles of stability analysis of nonlinear differential-algebraic equation systems; definitions, causes and concepts of voltage, transient, angle and frequency stability; applied numerical methods to assess power system stability of large power systems; and practical control and protection strategies to avoid power system instabilities and blackouts.

2.3 Challenges in Teaching Nonlinear Systems

The two modules described in the previous subsections focus on nonlinear dynamic equations that describe the behaviour of power systems. Main sources of nonlinearity are the power flow equations, which are basically quadratic expressions, synchronous machine mechanical equations, control limits and saturations, discrete variables (e.g., tap positions of under-load tap changer transformers) and discrete events (e.g., line outages). In the module Power System Stability Analysis, delays and chaotic motions are also considered.

The inherent complexity of power systems as well as their nonlinearity is the source of the difficulties of the students. Teaching nonlinear systems to undergraduate students poses several challenges. In the experience of the author, the following aspects are relevant.

- The response of a system is hard to predict due to its nonlinearity. The superposition principle cannot be applied to nonlinear systems and, as a matter of fact, the effect of each device cannot be studied separately. The system has thus to be studied as a whole and each case study is different. A typical example of such unpredictability is the well-known transient stability analysis, that studies the effect of short circuit and large perturbations on the stability of synchronous machines. This topic is so relevant and, at the same time, hard to solve, that a vast literature has been dedicated to its study (see for example the literature review in [6]). Several techniques have been proposed to study such a problem, including direct methods based on Lyapunov and/or transient energy functions [7-9]. However, brute-force time domain integration (which consists in *observing* the behaviour of the system rather than *understanding* it) is still the tool to define the transient stability used in industry-grade applications.
- The behaviour of the system can show substantial qualitative changes depending on the perturbation. These phenomena are typically tackled by means of bifurcation theory which provides a taxonomy of "special" points, namely bifurcation points, at which the structure of the system changes qualitatively. A well-known example is the saddle-node bifurcation that is used to explain the voltage collapse [10].
- The dynamic coupling of continuous and discrete variables is particularly hard to understand. This is often due to the effects of saturations and control limits. If a control limit becomes binding, in fact, the control is effectively disabled. Recent studies on grazing bifurcations have attempted to study the role of discontinuities and control limits [11].
- Nonlinearity can lead to unexpected changes in the global dynamic behaviour of the system. This can be due, for example, to the birth of strange attractors that leads to chaotic motions [12]. Another relevant example is the multi-swing instability which is similar to the transient instability described above but occurs unexpectedly and cannot be detected through direct methods [13]. It has also been conjectured that multi-swing instability is a special case of short-terms chaotic motion [14].

Since all phenomena above can occur in a system and it is impossible, a priori, to know which kind of dynamic response the system under study will actually show, it is not hard to understand how difficult can be for an undergraduate students to master the topic.

To provide a large variety of examples clearly helps, but the examples are not very effective if the students do not understand the inherent causes originated the phenomena that they observe. A big challenge is that the students dealing with nonlinear system dynamics are often overwhelmed by the variety of different models and the large number of parameters of each model. At the beginning, it may seem impossible to be able to understand the effect of each parameter and how each device interact with rest of the system. The limit-case approach discussed in the next section is aimed at simplifying this task and reducing the time required to master the subject.

3 LIMIT-CASE ANALYSIS THROUGH EXAMPLES

In his 15-year long experience in teaching power system modelling, control and stability analysis, the author has found that the best strategy to keep the attention of the students high during the lectures is to challenge them with simple yet tricky problems and questions. Since power systems are described by a set of nonlinear dynamic equations, it is actually relatively easy to set up problems that are counter-intuitive and surprise the students. However, more complicated is to find examples that allow drawing general conclusions or provide insights on a basic property of the systems. This is particularly true for power systems because they are far away from the experience of the students (it would be much simpler, for example, to provide examples related to low-power electronic or digital devices that the students use on a daily basis). The intrinsic nonlinearity of power systems prevents also, quite often, to use the common sense as this can be often misleading. The examples presented in this section are based on an approach that has proven to be useful, at least in the experience of the author, and is based on a limit-case analysis. The approach consists in describing to the students two extreme, contrasting conditions of the same phenomenon. These limit cases are often easier to understand than intermediate (normal) conditions. Once the limit cases are clear, intermediate conditions, which are often those of interest in practical applications, can be properly understood. Limit cases also help the students define the boundaries of the problem and, in most cases, clarify the motivations and the rationale behind the matter under study. This section presents a selection of such problems.

3.1 Blackouts and Maximum Loading Level

One of the very first questions that the author asks to his student in the introductory lecture of the module “Power System Modelling and Control” is why blackouts do happen. There are several ways to answer this question and the purpose is just to make student think. Actually, the whole module “Power System Stability Analysis” is dedicated to discuss the mathematical and physical causes of instability that lead to the system collapse and, ultimately, blackouts. However, there is also a very simple way to tackle this question, which is to consider the blackout as a limit case of a standard operating condition. As such, the only reason why a power system that goes haywire would always end up in a situation where all voltages and currents are null, e.g., the blackout condition, is just because such a condition is *very* stable. This is so because the blackout is also a minimum energy point (the energy involved in the system is actually zero, as the product of voltage and currents are null). Another consequence of the intrinsic *stability* of a blackout condition is that it is relatively difficult to restore – re-energize – the system after a major blackout. Any operating condition will, in fact, show an energy level higher than the blackout.

This example is useful also to explain to the students the meaning of *trivial solution*. This is a mathematical concept that is used to indicate, in the context of nonlinear dynamic equations, solutions that do not carry any *information*. In lay language, one may say that a trivial solution is useless and, as such, must be discarded. For example, when solving the linear eigenvalue problem, the null eigenvector is always a solution but is also useless as it cannot be used as a base for the ortogonalization of the matrix. Similarly a blackout is a trivial solution as, from the practical viewpoint, it is the condition for which no load can be supplied.

The blackout is thus the minimum possible loading level of a power system and, for obvious reasons, is not a sensible operating condition. The maximum loading condition, is the other limit case and is more complicate to study and compute as it is not a trivial solution. From circuit theory, however, is well known to the students that the maximum power that can be delivered by a Thevenin equivalent, which can be used to represent, at least in steady-state, an active network at a point of connection, is obtained when the load impedance is equal to the conjugate of the Thevenin impedance. It is also easy to understand that such a loading condition cannot be, in general, acceptable as the network, to be efficient, has to show a small equivalent impedance. Consequently, the maximum loading condition will also be characterized by an equivalent low impedance of the load, which leads to a relatively low voltage at the point of connection and a high current injected into the load.

There are thus two well-defined loading conditions or, using the notation of this paper, limit cases, that are not acceptable in practice. Feasible operating conditions must lie somewhere in the middle, not too close to the blackout (as no power is delivered in this case) and not too close to the maximum loading condition (for security reasons as high currents would increase the temperature of the transmission lines and transformers included in the system).

At the stage at which this example is proposed to the students, they have still no experience of power system modelling and control but the discussion above provides them with the concept that the operation of a power system is a fine balance continuously struggling between the collapse and dangerous overloading. This helps motivate the need for a proper scheduling of the resources (generators, transmission systems and loads) as well as for a proper coordinated control of the system.

3.2 Primary Frequency Control

In recent years, the number of non-synchronous machines (e.g., VSC-based distributed energy resources) has increased considerably mainly because of the increasing penetration of renewables. However, conventional power plants based on fossil fuels, nuclear or water are still the principal and largest suppliers of high voltage transmission systems of developed countries. Conventional power plants are connected to the grid through synchronous generators, which are, thus, the most important devices to produce active power.

While synchronous machines naturally synchronize and maintain a constant synchronous frequency, active power fluctuations due to load variations or contingencies have to be properly regulated to prevent frequency instability and, ultimately, the system collapse. Frequency regulation is indeed a crucial aspect of the operation of high voltage transmission systems. A huge literature has been dedicated to this topic and it is still a hot topic due to the high penetration of non-synchronous generation occurred in the last decade [15]. It is thus extremely important that the students properly understand the main aspects of such a regulation.

For several technical reasons, the standard primary frequency control of synchronous machines in an interconnected system is based on the so-called "droop control". This imposes that every machine responds to frequency variations (or, which is the same, to power imbalances) by varying its power production proportionally to its capacity. In particular, since a reduction of the frequency implies a deficit of generation, the power-frequency control characteristic has to show a negative slope (see Figure 1.c). This strategy makes sure that generators "democratically" share active power imbalances and generally ensures a secure operation. The droop control, however, does not allow a perfect tracking of the frequency and, in fact, after every disturbance, the resulting steady state frequency cannot recover to the synchronous one (e.g., 50 Hz in Europe). Figure 1.c shows that moving the generated power from P_o to P^* also moves the frequency from Ω_o to Ω^*. Hence the need of implementing additional controllers (e.g., the automatic generation control which implements a secondary frequency control).

In the experience of the author, if the primary frequency control is explained to the students as discussed above, there is a substantial risk that they miss the whole point of the frequency regulation. The inevitable steady-state error of the frequency is often perceived as a limitation of the primary frequency control, while it is not. The droop is actually necessary to make the behaviour of synchronous machines both predictable and secure. Why this is so can be properly explained discussing two limit-cases first, i.e., the droop coefficient b_p that tends to infinity and b_p that tends to 0.

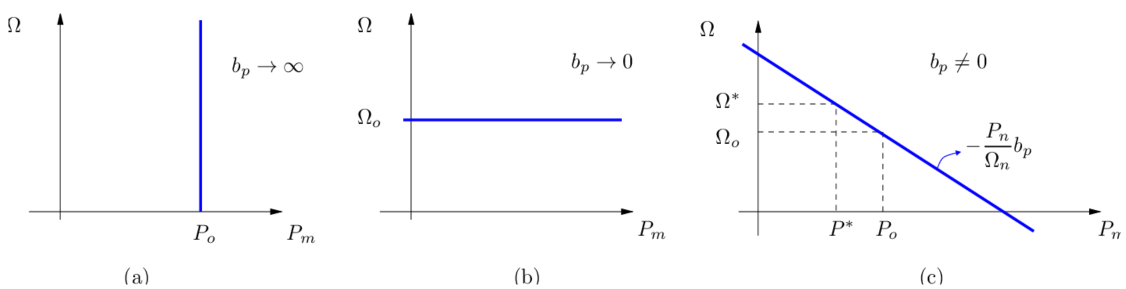

Figure 1: Steady-state generation mechanical power vs. system frequency classified based on the value of the droop coefficient b_p. (a) constant power (frequency control is disabled); (b) constant frequency (isochronous control); and (c) standard primary frequency regulation based on a droop control, i.e., the variations of the active power are proportional to the frequency deviation. The notation is as follows: P is the active power, Ω is the system frequency and indexes *o*, *n, m,* and * indicate current operating point, nominal values, mechanical power, and post-disturbance values, respectively.

These two cases are illustrated through Figures 1.a and 1.b, respectively. An infinite droop coefficient b_p corresponds to the case for which the primary frequency control is deactivated. The generator, in fact, produces the same power independently from the value of the frequency. Clearly, this approach cannot be adopted by all generators connected to the system, otherwise, no frequency control is provided and the power unbalanced cannot be compensated (thus leading to the collapse). The case with null droop coefficient is also called the isochronous regulation as the generator maintains the frequency constant. While this could appear as the required condition this kind of control is not adequate in an interconnected system with multiple generators. In fact, if two or more generators would implement the isochronous control, power variations following a load variation would be unpredictable. Moreover, if only one generator implemented such a perfect tracking control, that generator would take care compensate the whole power variations, which is potentially inadequate (the capacity of one generator might not be sufficient to compensate load fluctuations) and unreliable (the isochronous generator could be disconnected from the system). Since none of the two limit-cases above is acceptable in an interconnected systems, it follows that the conventional situation for which the droop coefficient b_p is finite and non-null is the only feasible condition.

3.3 Load Modelling

One of the most challenging topics of power systems is the modelling of loads. While there is basically one well-accepted dynamic generator model, i.e., the Park-Concordia one [16], and while primary controllers are generally known with a certain accuracy (as these models are provided by suppliers), there is no common agreement on the models of loads. As a matter of fact, several models have been proposed (see, for example, references [17-20]). The main problem is that loads, at least at the high-voltage level, are never single devices or single users, which could be characterized precisely, but rather an aggregation of hundreds or thousands of users. The best approach would thus be to use a statistical model, but, in this case, one should run hundreds of simulations to determine the behaviour of the system.

This, indeed, is an application where the limit-case approach can be of great help to understand the expected dynamic response of a system for which one does not have a perfect knowledge of its parameters. The limit-case load models are, for this application, constant impedances and constant powers. The constant impedances include all simplest static loads (e.g., resistances), while constant power loads implies a dynamic control which can be obtained, in steady-state, through under-load tap changers or power electronics. Most dynamic loads, including induction motors, show intermediate behaviours, i.e., behaviours that are between a constant impedance and a constant power consumption. Since the composition of the loads is not known *a priori*, unless a careful study is carried out, and since load models affect considerably the dynamic response of the overall system, it would be very useful to be able to determine at least the behaviour of the system for limit case models and then deduce, at least qualitatively, the behaviour of more complex load models.

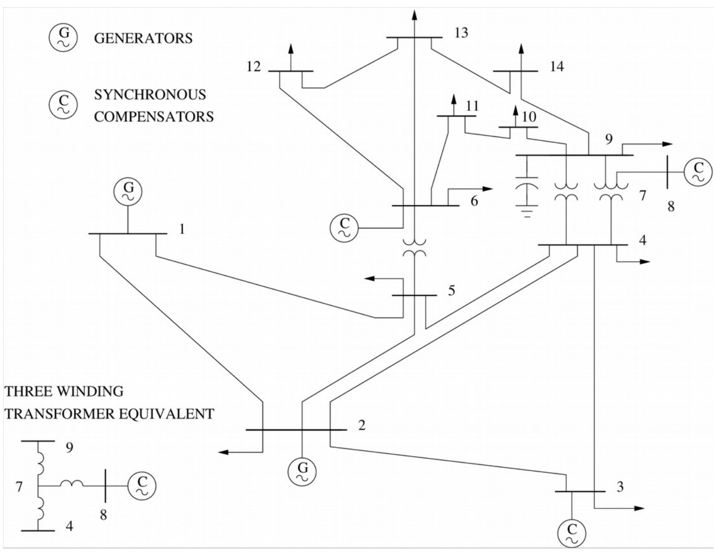

Figure 2: Single-line diagram of the IEEE 14-bus system.

To illustrate the discussion above, we use the following example based on the well-known IEEE 14-bus system (see Figure 2). Let us assume that we want to determine the dynamic response of the system considering that loads are composed of voltage dependent load, i.e., the power consumption is proportional to v^a, where a is a coefficient determined based on the response of the aggregated load and an under-load tap changer transformer. The latter regulates the voltage in such a way that, in steady-state, $v = v^{ref}$. Hence in steady state, the load behaves like a constant power. Since the regulator of the transformer is slow, it has to be expected that, in the initial stage of the transient, the load will depend on the value of a. In this example we assume that $a = 2$, hence, in the first instants after the disturbance, the load will behave like a constant impedance. Clearly, if the software tool allows to model the load as described above, one can run the simulation using the precise model. However, if loads cannot be modelled in details, it is generally always possible to simulate constant impedance and constant power loads.

Figure 3 shows the results for the IEEE 14-bus system following the outage of line 2-4 and considering three load models, namely, constant impedance, constant power and voltage dependent load with tap changer. As expected, the behaviour of the tap changer-controlled load follows between the other two. It is closer to the constant impedance in the first instants after the contingency and tends to behave as a constant power in steady-state. The simulations obtained for the constant impedance and the constant power models are thus a boundary for all other models, which can be either very complex to implement or not fully known. However, if the response of the system is acceptable for the two limit-case scenarios, there is no need to model with more precision the loads. If one of the two limit cases leads to unacceptable results, and thus further study is required, the limit-case analysis allows indicating what kind of actions are needed to improve the response of the system. It will be sufficient, in fact, to implement control actions that modify the behaviour of the load in such a way that it gets closer to the behaviour of the acceptable limit-case model. Finally, if no further information is available, the best approach will be to assume the worst case scenario and design corrective actions based on the load model that leads to the worst dynamic response of the system.

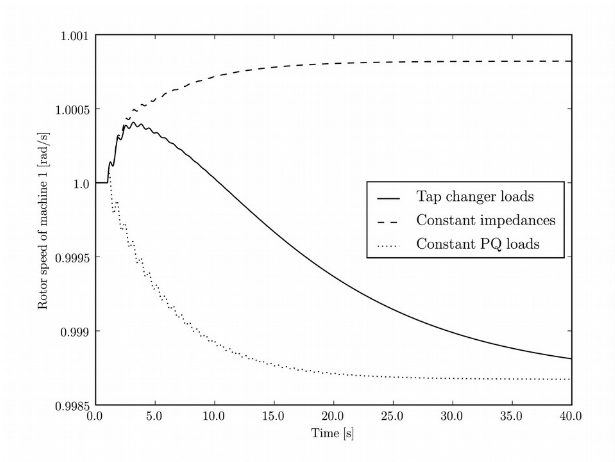

Figure 3: IEEE 14-bus system. Dynamic response following line 2-4 outage for different load models.

3.4 Power System Stabilizers with Delay

An advanced topic of the module “Power System Stability Analysis” is the impact of time delays on power system stability. In the vast majority of the cases, delays reduce the stability and, possibly, drive power systems to instability. The limit-case approach is particularly suited to explain this point. In control loops, a delay that affects a controlled signal causes the controller to postpone its reaction to a variation in the system. If the delay increases the reaction is further postponed and, for an infinite delay, the controller never reacts to the perturbation as the controlled signal is never updated. This is equivalent to opening the control loop and disabling the controller.

During the lectures, the following example based on the IEEE 14-bus system shown in Figure 2 is proposed. It is assumed that generator 1 includes an automatic voltage control (AVR) and a power system stabilizer (PSS). AVRs provide the primary voltage regulation while PSSs are controllers that reduce the oscillations of synchronous machines. If one assumes that the controlled signal of the PSS is not the local speed of the machine but a remote signal of the synchronous frequency of the system, such a signal can be affected by a delay. The IEEE 14-bus system is known to show poorly damped or undamped oscillations for high loading levels [1]. Connecting a properly tuned PSS at the AVR of generator 1 helps damping oscillations. Figure 4 shows the response of the system overloaded by 20% with respect to the base case condition following the outage of line 2-4. The system without the PSS does not have a stable operating point and the trajectories fall on a stable limit cycle. On the other hand if a PSS with no delay is included, the system shows a stable a properly damped operating point.

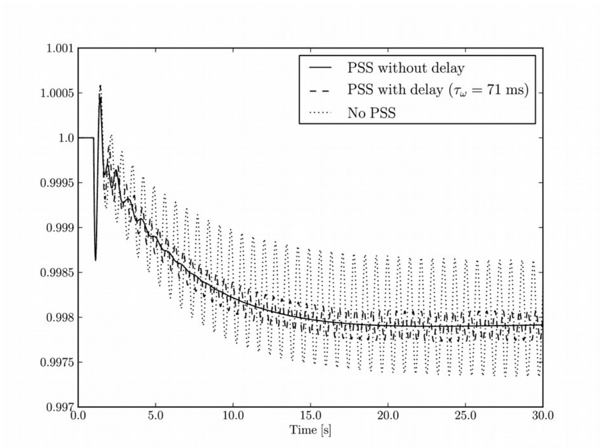

Figure 4: IEEE 14-bus system with a PSS connected to generator 1. Time domain simulation following line 2-4 outage; the case without PSS is equivalent to the case with a PSS with an infinitely delayed input signal [21].

The case with no PSS is equivalent to the case with a PSS with an infinitely delayed input signal. We have thus two limit cases, one stable for a null delay and one unstable with an infinite delay. We can conclude that there is a (finite) value of the delay for which the system becomes unstable. The limit-case approach is only qualitative and, hence, does not allow to determine for which value of the delay the instability occurs. However, it is important to note that the conclusion above can be inferred without the need of any specific quantitative tool to define the stability of delayed differential-algebraic equations (the interested reader can find full details in [21], [22], and [23]). Thus, when applicable, the limit-case approach is a simple yet powerful technique that allow investigating the qualitative properties of complex nonlinear systems.

4 CONCLUDING REMARKS AND STUDENTS' FEEDBACK

This paper discusses an approach based on limit-case analysis to improve the learning process of students of BE and ME Electric Energy system Programmes. This technique is utilized by the author in the modules Power System Modelling and Control and Power System Stability Analysis taught at UCD since 2013. The limit-case approach appears particularly suited to the analysis of the behaviour and the control of power systems as these are described by a set of nonlinear differential-algebraic equations.

The examples provided in this paper show that the limit-case approach is able to provide a qualitative information on the system. Typically such information is simple to understand or, at least, simpler than the general case. Moreover, the limit-case scenarios often prevent the need for complicated models and provide a powerful tool to draw quickly relevant conclusions without the need of detailed and time-consuming and error-prone analysis. The “robustness” with respect to errors is, in fact, another added value of this approach. The author believes that such an approach is particularly suited for engineering programmes as it provides “simple practical solutions to complex problems”, which, ultimately, is the mission of all engineers.

The feedback of the students is generally very positive. The author has noticed that students are generally not used to the limit-case approach as a problem-solving technique. He has also noticed, however, that several students, at the end of the modules, apply such a technique while preparing the reports related to the laboratory activities. Typically they use the conclusions that can be drawn using the limit-case approach to reduce the number of simulations they have to carry out (the Appendix provides an example of assignment) and, ultimately to save time. It is interesting to note, however, that, apart from saving time, the students that utilize the limit-case approach also consistently reduce the source of errors and misunderstanding with respect to students that do not apply such a technique.

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APPENDIX

This appendix reports an example of lab activity of the module "Power System Modelling and Control".

The main objective of this lab activity is to study the transient response of a simple system with inclusion of a wind turbine. Specific goals are:

• To compare the transient behavior of a constant-speed wind turbine (CSWT) with a doubly-fed induction generator wind turbine (DFIG).

• To determine the effect of control parameters of the DFIG wind turbine on its small-signal stability and transient behavior.

• To define the transient response of the CSWT and DFIG with different wind speed inputs.

The assignment requires a detailed sensitivity analysis of the parameters of the devices and their controller. The exercises below can be quite time consuming if the sensitivity analysis is carried out without a proper strategy. The limit-case approach, coupled with the knowledge of the range of feasible variations of the parameters can help to significantly reduce the number of simulation.

Proposed exercise are as follows:

1. Study the effect of varying machine (e.g., inertia, stator and rotor reactances and resistances) and control parameters (e.g., gains and time constants) of both the CSWT and the DFIG on the small signal stability of the system. With this aim, the student has to vary one parameter at a time and draw relevant conclusions. The goal of this exercise is to understand the sensitivity of the models to both machine and control parameters.

2. Using the DFIG and the CSWT models, the student has to simulate and compare the transient response of the system with respect of different non-deterministic wind speed models: (a) Mexican hat model; and (b) Weibull distribution model. The purpose of this exercise is to understand the sensitivity of the models to machine, wind and control parameters.

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