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FUNDAMENTALS OF DYNAMIC POWER GRID MODELLING FOR ENGINEERING EDUCATION OF SYNTHETIC INERTIA

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ABSTRACT

Smart energy transition has significantly changed electric energy systems in many countries. Shares of wind power and solar electricity are already commonly prominent and still growing quickly. From power grid point of view, the change has culminated in replacing traditional synchronous generator-based production with power converter interfaced technology. Consequently, the general sensitivity of power grids to different disturbances has increased. The decrease of inertia is significant from frequency control point of view, but in addition, other issues related to abnormal voltage behaviour have also appeared. In order to support power grids in such situations, new technical solutions are required. Synthetic inertia is a topic covering different actions that aim to support power grids against such new disturbances by means of converter interfaced sources, usually battery energy storages. To understand the root causes of disturbances and requirements of synthetic inertia, dynamic modelling of electric energy system needs to be used. In this paper we build a dynamic model to reveal different disturbances in power grids and also the necessary engineering substance to understand these phenomena. From engineering education viewpoint this means that more emphasis should be put on understanding the physical and mathematical fundamentals. In this paper we show, what kind of knowledge becomes emphasized in understanding the fundamentals of supporting the power grid with synthetic inertia. We suggest that from engineering education point of view, the topic requires special attention.

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1 INTRODUCTION

1.1 Addressing Modern Power Grid Challenges

During the latest decades, smart energy transition has significantly changed electric energy systems in many countries. From environmental perspective, the positive and certainly necessary change has culminated in reducing CO_2 emissions by replacing fossil-based production with renewable energy. However, from power grid point of view several challenges have also appeared. Most of these challenges are related to a significant technical change in electric energy production. As traditional synchronous generator-based power plants are replaced with power converter interfaced weather-dependent production, inherent tolerance of electric energy systems to disturbances has significantly decreased due to the decrease of inertia. (Ratnam et al., 2020)

In traditional production technologies (nuclear, hydro, combined heat & power) the steady rotational speed of synchronous generators produces electric power with just the right nominal frequency. This means that nearly steady rotational speed of massive generators is directly connected to the frequency of the power grid. This is the origin of inertia, which provides inherent frequency stability to electric energy systems. In addition to frequency stability, inertia also has significant role in other power quality issues. For example, when sudden changes of consumption take place in the grid, the quality of voltage tends to decrease. The shapes of sine waves typically get distorted, which easily result in practical challenges. A large amount of inertia in the system helps to maintain high power quality against such transients. (Hatziargyriou et al., 2021)

Due to strong growth of renewable energy, nowadays a big share of production capacity is weather-dependent in many countries. As wind power and solar electricity are connected to the grid via power converters, they don’t provide any inertia to the system. Thus, as the share of weather-dependent production has increased, also the inertia of the system has become weather-dependent. When the shares of wind and solar are high, inertia of the system is typically decreased significantly. The loss of inertia easily results in power quality issues. For example in Finland, the national power grid system operator Fingrid has reported that many new phenomena, such as dynamic voltage disturbances, have been confronted in the grid during the high production shares of converter interfaced production (Fingrid, n.d.). Theme is highly topical, since according to many specialist views, also the recent blackout in Iberian Peninsula was partly caused by the lack of inertia (Entso-e, 2025). However, although converter interfaced sources do not provide natural inertia, they can still be utilized to support power grids in many ways. Such actions, in which the stability of power grid is supported with power converter interfaced sources, are included under the concept of virtual or synthetic inertia (Leelaruji & Bollen, 2015).

Maybe surprisingly, two main topics of this paper, synthetic inertia and engineering education, are inherently interconnected. The foundations of synthetic inertia lay in the fundamental physics of electrical engineering. In order to promote the educational development of synthetic inertia, certain fundamentals need to be underlined. In this paper we point out these details of engineering substances required to achieve the fundamental understanding of the synthetic inertia related grid dynamics.

1.2 Research aim and requirements for engineering education

As smart energy transition has proceeded, related topics have been generally included in curricula of engineering education. These include for example renewable energy technologies, effects of smart energy transition on energy systems and topics of digitalisation and automation. However, at the same time a general trend in engineering education has been to decrease the role of profound scientific understanding (Keeling & Hersh, 2011). The balance between immediate and long-term engineering skills is eternal dilemma in engineering education, and during the ongoing millennium, engineering education has had a tendency to excessively tilt towards the immediate engineering skills (Korpela et al., 2016). This is significant from synthetic inertia point of view, since the understanding of dynamic disturbances in power grid requires quite profound fundamental understanding of electrical engineering and related mathematical concepts.

In order to model any dynamic phenomena in power grid, a differential equation-based approach has to be adopted. In electrical engineering, differential equations originate from dynamic current-voltage characteristics of resistive, inductive and capacitive circuit elements. In this paper we show, how the modelling of dynamic synthetic inertia can be implemented by means of circuit analysis. As long as the basic understanding of dynamic modelling is still included in curricula, presented way of modelling can be utilized as such to promote synthetic inertia related phenomena in electrical engineering education.

The aim of the research is to suggest relevant choices to be made in engineering education by emphasizing the relevance of simulation in understanding fast time domain change phenomena. The research question is: what pedagogical choices should be made in engineering education to promote the fundamental understanding of synthetic inertia through dynamic modelling and simulation?

Previous research has introduced a substantial amount of dynamic time-domain modelling and simulation related to synthetic inertia, as demonstrated, for example by Kerdegarbakhsh (2020), Taczi & Vokony (2016), and AEMO (2024). These types of publications have thoroughly described the mathematical principles and simulation results. Research with a clear educational context includes works like Birchfield et al. (2019) and Hu et al. (2015). However, no study has been identified by the authors that directly addresses the educational implications of synthetic inertia.

In this study, Copilot AI (Microsoft, 2025) was used to assist in formulating the ideas written by authors in more concise manner and refining the language of the manuscript. Prompts were provided to Copilot, and the generated text was reviewed and edited by the authors.

2 COMPUTATIONAL DYNAMIC MODEL FOR SYNTHETIC INERTIA

This section presents the time-domain model, which aims to reveal the dynamic phenomena taking place in the power grid. To promote understanding of aspects related to synthetic inertia, we developed the model from scratch using Matlab

In order to model a dynamic behaviour of voltages and currents in the power grid, a dynamic circuit model is required. And as the grid frequency is tightly connected to

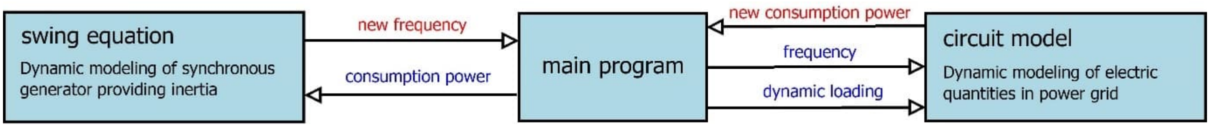


Fig. 1. Simple block diagram of synthetic inertia modelling

the dynamic behaviour of synchronous generators, a dynamic generator model is also required. Thus, two separate models are needed to study power grid dynamics, as can be seen from the simplified block diagram of Figure 1.

The swing equation (on the left of Figure 1) is the differential equation modelling the dynamic behaviour of synchronous generators. Its input is the power imbalance between production and consumption. Once the generators' rotational speed has been solved as the solution of the swing equation, the new frequency of the grid can be determined.

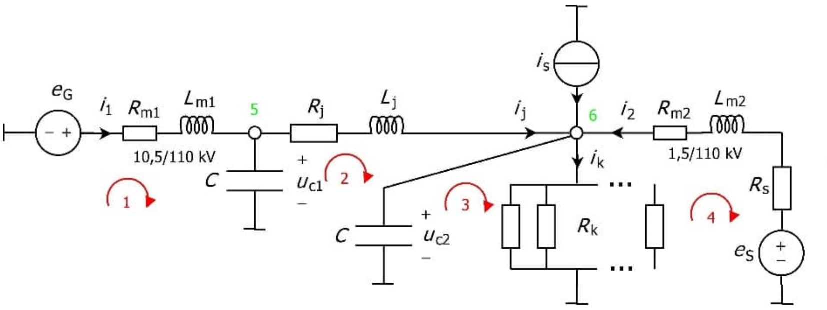
The circuit model solves the dynamic behaviour of voltages and currents in the grid. Once the grid frequency has been solved from the swing equation, dynamic behaviour of voltages and currents can be solved from the system of differential equations describing the grid. And when voltages and currents are known, the new active power of consumption can be determined as the output of the circuit model.

The swing equation and the circuit model are solved in turns. For synthetic inertia purposes it is important to be able to model the phenomena taking place in milliseconds, which is why we need to use much smaller time step for the dynamic model. At the moment, a time step of 2 μs is used.

2.1 Dynamic circuit model

The network for the circuit model is presented in Figure 2. The chosen network is quite simple but still complicated enough to include all the necessary features of more complex grids. All the variables of the circuit model are not determined here due to lack of space, but the most important ones are:

- The voltage source e_G (V) in the left of the figure represents the synchronous generator providing inertia to the system.
- The parallel resistances R_k (Ω) represent the dynamic load giving rise to the varying active power of consumption in the grid.
- Two power sources on the right of the figure (i_s (A) and e_s (V)) represent the converter interfaced sources utilized to provide synthetic inertia to the system.



$$\begin{cases}
\frac{di_1(t)}{dt} = \frac{e_G(t)-R_{m1}i_1(t)-u_{c1}(t)}{L_{m1}} \\
\frac{di_j(t)}{dt} = \frac{u_{c1}(t)-u_{c2}(t)-R_j i_j(t)}{L_j} \\
\frac{di_2(t)}{dt} = \frac{e_s(t)-(R_{m1}+R_s)i_2(t)-u_{c2}(t)}{L_{m2}} \\
\frac{du_{c1}(t)}{dt} = \frac{i_1(t)-i_j(t)}{C} \\
\frac{du_{c2}(t)}{dt} = \frac{i_j(t)+i_s(t)+i_2(t)-u_{c2}(t)/R_k}{C}
\end{cases}$$

Fig. 2. Network for the circuit model and the system of differential equations describing its dynamic behaviour.

The goal of the dynamic circuit model is to solve the instantaneous values of voltages and currents presented in Figure 2. This is of essential importance, since in order to investigate the opportunities of synthetic inertia, the main purpose of dynamic circuit modelling is to reveal millisecond-scale transients and disturbances.

By writing Kirchhoff's laws to the circuit model of Figure 2, we get the system of differential equations, which is also included in Figure 2. The presented format for the system of equations has been chosen, since it enables the direct utilization of numerical solution methods. After the instantaneous values for all the currents and voltages have been solved, instantaneous powers can be calculated. And after solving instantaneous powers, we possess the required information to solve active and reactive powers. The active power of consumption is the input for the swing equation as presented in Figure 1. (Nilsson & Riedel, 2019)

2.2 Swing equation

After the active power of consumption has been solved, dynamic behaviour of frequency can be described by the swing equation

$$P_{\text{gen}} - P_{\text{load}} = J\omega(t)\frac{d\omega(t)}{dt} + D[\omega(t)]^2, \qquad (1)$$

where P_{gen} is the mechanical power of production (W), P_{load} is the active power of consumption (W), J is the inertia (kgm^2), D is the damping constant (Nms) and ω is the angular velocity of synchronous generator (rad/s), which is connected to grid frequency f (Hz) by $\omega = 2\pi f$. (Linbin et al., 2021)

2.3 Other computational concepts in grid model implementation

This section points out a few key concepts that have arisen in the implementation work of the aforementioned grid model. These include a numerically feasible computation of active power for each simulation time step, the computation of dynamic reactive power directly from the instantaneous power, as well as computing continuous phase differences from dynamic voltages and currents. All these are needed to control the shares of active and reactive power supplied to the grid with converter interfaced sources. Unfortunately, further mathematical details of these subjects had to be excluded from this paper and will be published later elsewhere.

3 RESULTS OF MODELLING

Figure 3 presents the dynamic behaviour of grid variables in one example run of modelling with each model variable solved from the system of differential equations. For simplicity, in this 0.06 s example run the converter interfaced sources i_s and e_s are not connected at all to the grid. Thus, voltage source e_g is the only input to the system, and dynamic load R_k has been used to cause sudden changes of active consumption power to the grid.

As can be seen from Figure 3 (a), there is a sudden change in loading of the grid at 0,02 s. The original load represents the balanced situation between the mechanical power of production and the active power of consumption, since the frequency in

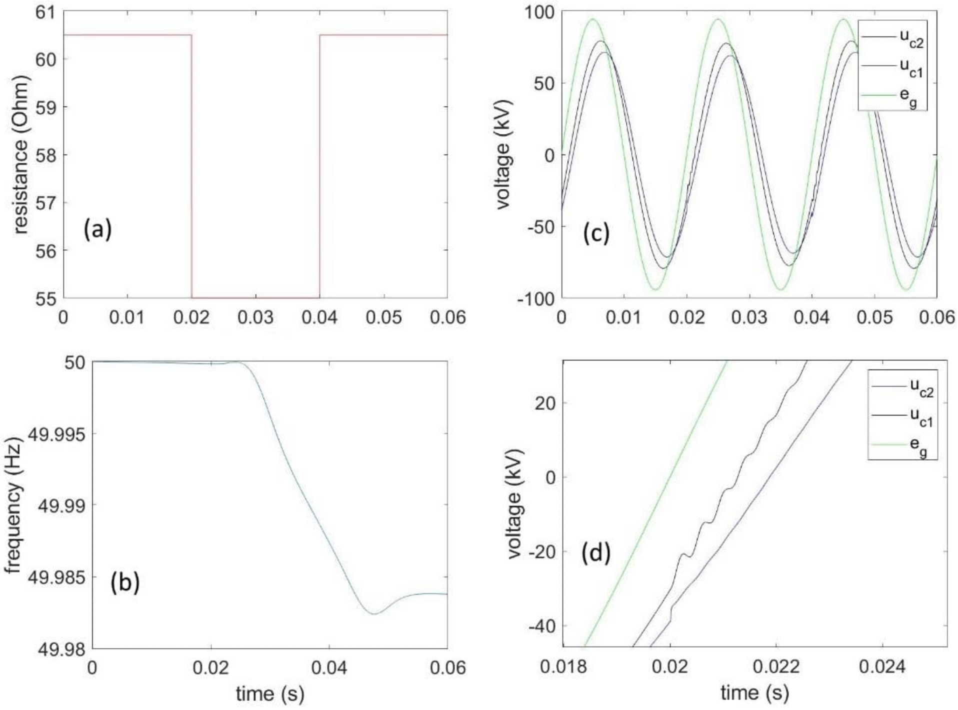


Fig. 3. Dynamic behaviour of (a) load R_k, (b) frequency, and (c) & (d) voltages

Figure 3 (b) remains originally at 50 Hz. After the load change at 0.02 s, there is a shortage of mechanical power of production, due to which the frequency starts to decrease. At 0.04 s the load is restored to its original value, after which the frequency levels out due to the balance between the mechanical power of production and the active power of consumption.

Figure 3 (c) and (d) present the dynamic behaviour of voltages in the grid. The green curve is the input of the system (e_g), but black and blue ones represent the dynamic behaviour of voltages solved from the system of differential equations presented in Figure 2. The blue curve is marked as u_{c2} in Figure 3 (c) and (d), but as can be seen from Figure 2, it is also the voltage of the dynamic load. If watched closely, sudden changes can be seen in u_{c2} at 0.02 and 0.04 s due to load change. Figure 3 (d) is a zoomed picture of the same voltages in the vicinity of 0.02 s. As can be seen, the curves of u_{c1} and u_{c2} deviate strongly from steady-state sinusoidal behaviour after the load change.

Revealing the dynamic disturbances like the ones presented in Figure 3 (d) have a key role in supporting the power grid by means of synthetic inertia. For example, as voltages are disturbed from their steady-state sinusoidal form, sudden phase differences typically take place. From the system control viewpoint, these are problematic and may easily cause challenges. However, such disturbances can be smoothened by well-timed supply of active and reactive power to the grid by means of converter interfaced sources which is in the core of synthetic inertia.

4 DISCUSSION

Vast majority of both the educational and industrial modelling of electric power engineering is based on phasors. It means that time-dependent variables of power grids are modelled in steady-state time harmonic manner. This way of grid modelling is very efficient and broadly useful, but it has one significant drawback: it cannot reveal any transients. In addition, although the phasor-based circuit analysis is highly necessary and very effective, it easily hides more profound understanding of related electromagnetic phenomena. However, we are not suggesting that the role of phasor-based analysis should be challenged in engineering education. Due to its effectiveness, it deserves to have its lead role also in the future of engineering education. Nevertheless, in order to promote the understanding of new phenomena taking place in power grids due to smart energy transition, the fundamentals of dynamic modelling should also be preserved and even emphasized in electrical engineering curricula.

During the ongoing millennium a general trend has been to include more wide-ranging substances to engineering curricula, and the change has often been carried out at the expense of profundity. For example, in electrical engineering this easily means that time-consuming learning of dynamic fundamentals is replaced with some demonstrations carried out by dynamic commercial simulators. As Birchfield et. al. (2019) point out, the simulators have been used in power systems education for over four decades with increasing amount of features and benefits towards industrial applications and real-time simulations. Not undermining the benefits of the development, we still suggest keeping the careful learning of dynamic fundamentals alongside in the curriculum, recognizing that this involves a chain of prerequisites. If the learning of fundamentals has been omitted, the ability to analyse the results of dynamic modelling becomes also vanished.

Our pedagogical approach focuses on exploring the nature of time-domain effects by emphasizing the understanding of differential equations and utilizing simulation code that solves these equations. This approach is more of a 'back to basics and history' type and is currently directed towards universities of applied sciences. Although this method has been implemented previously, differential equations are often subject to being reduced or omitted either at curriculum-level or due to time and content constraints in engineering mathematics courses.

To address the synthetic inertia requirement to react to millisecond-scale phenomena (Fingrid, 2023), the curricula must enable students to understand differential equations. We want to specifically point out that this is distinct from solving them. Students need to comprehend know what the differential equations describe and how differential equations arise from electric circuits. This also requires a fundamental AC circuit analysis course as a prerequisite. This foundation enables students to understand and alter dynamic models meaningfully. Additionally, curricula should foster code literacy, focusing on interpreting and modifying code rather than creating it. This approach provides contextual understanding, where models and simulations numerically evaluate specific cases of underlying concepts. The relevance and benefits become visible to students when the entire chain of needed knowledge is demonstrated to them utilizing simulations. These demonstrations must be carried out piece by piece. This method is directed at third-year electrical engineering students who have the necessary prerequisites. But note that the path to it starts already during the first year of studies.

This simulation-based teaching approach is not just about using a simulator but involves a comprehensive understanding of all concepts required to make the phenomena relevant for synthetic inertia visible. This promotes the role and use of profound knowledge and the results of engineering sciences. Currently, our plan is to test this simulation-based pedagogical setup within 1-2 years, possibly as a within-subject study, at our university of applied sciences. The most challenging part is likely to be finding enough time for an in-depth understanding of differential equations.

Compared to prior work, the simulation model is not novel per se but its development has highlighted key phenomena essential to understand in teaching and learning of synthetic inertia. This study lays the groundwork for a simulation model to be used and further developed for educational purposes. Future research will include detailing the pedagogical model, innovating educationally relevant simulation cases, and exploring teacher competence requirements and development paths. Both modelling and pedagogical advancements will be published in future papers

5 CONCLUSIONS

This paper laid the foundations of dynamic power grid modelling for synthetic inertia in engineering education. While converter interfaced sources were not yet utilized to support the grid, the groundwork to model the dynamic behaviour of electric energy systems was established. Future studies will address smoothing voltage and current disturbances using synthetic inertia, but this paper focused on building a dynamic model based on bachelor-level electrical engineering curricula.

The smart energy transition has significantly altered electric energy systems, reducing CO_2 emissions but also decreasing inertia as traditional synchronous generators are replaced by converter interfaced, weather-dependent production. This shift makes power grids more sensitive to disturbances, necessitating new solutions like synthetic inertia to maintain high power quality.

Our dynamic power grid model demonstrated the importance of understanding the dynamics behind grid disturbances. Effective synthetic inertia control requires rapid response within milliseconds, highlighting the need for dynamic modelling and understanding of basic electromagnetic behaviour. Preserving these profound topics in engineering curricula is crucial to prevent them from being overshadowed by immediate engineering skills.

Our pedagogical model emphasizes a comprehensive understanding of all concepts required to make synthetic inertia related phenomena visible and controllable. This simulation-based approach will be tested within few years at our university of applied sciences. Further research will develop relevant simulation cases and assess the competence requirements for teachers.

In conclusion, engineering education should should lay greater emphasis on more profound knowledge and role of scientific results to address complex topics like synthetic inertia. As simple tasks are increasingly automated, investing in foundational understanding becomes essential. The need for synthetic inertia, driven by the smart energy transition, exemplifies the importance of mastering such profound concepts.

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