AI-STABLEPOWER

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Executive summary

Energy sustainability is a key challenge of the 21st century. To effectively address the negative impacts of climate change without making sacrifices in terms of our quality of life, a transition towards renewable energy sources (RES) must take place. However, this transition poses a new challenge to the transmission system operators (TSO) around the globe as most technologies used to extract energy from renewable sources (solar panels, wind turbines etc.) substantially decrease the stability of conventional power systems, increasing the risks of blackouts and raising the overall costs of electricity. A key concept related to the transient stability of a power network is inertia: this is a feature which, like its mechanical counterpart, ensures that the system does not undergo sudden and radical changes in its equilibrium state.

To efficiently manage a power grid and prevent undesired events such as blackouts and interruptions of service, the operators must constantly estimate the level of inertia of a power system, which is not directly measurable. Some estimation methods have already been developed, however most of them are lacking either in terms of efficiency or accuracy. For example, mathematical methods are extremely sensitive to noise in measurements, while data-driven approaches work well in simulations but require information which is sometimes hard to collect in the real world without modifying the existing equipment.

In our project we developed a new estimation method which tries to combine the best of both worlds: using a brand new convolutional neural network (CNN) architecture of our own making, named "StepNet", which takes as input variables that can easily be measured by most TSOs, and outputs the estimate of global inertia of the power grid. More specifically, we decided to feed the model with the power spectral density estimated from real-time measurements of the rotational speed of generators. Our model works by comparing the state of the power system, in terms of spectral densities, before and after a modification of the inertial properties of specific devices (CIG, inverters) that make up the electrical system connecting the renewable energy production plant to the rest of the network.

Key Words

Artificial intelligence, power systems, renewable energy sources

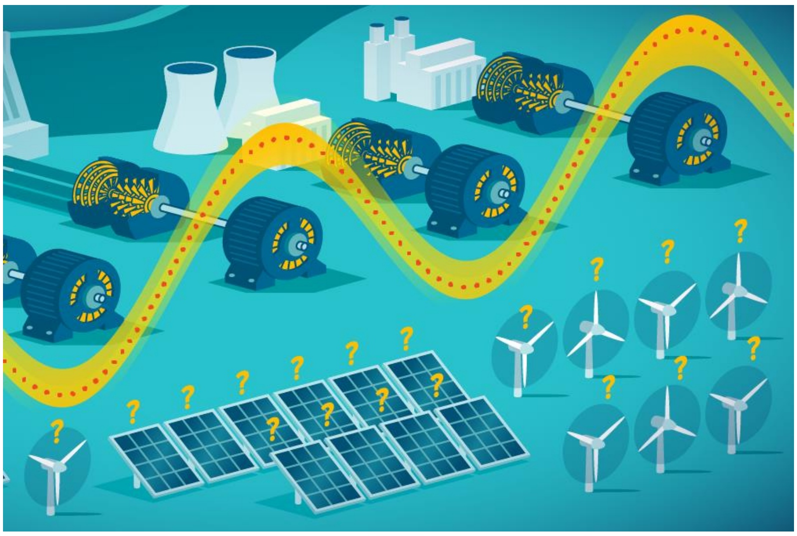
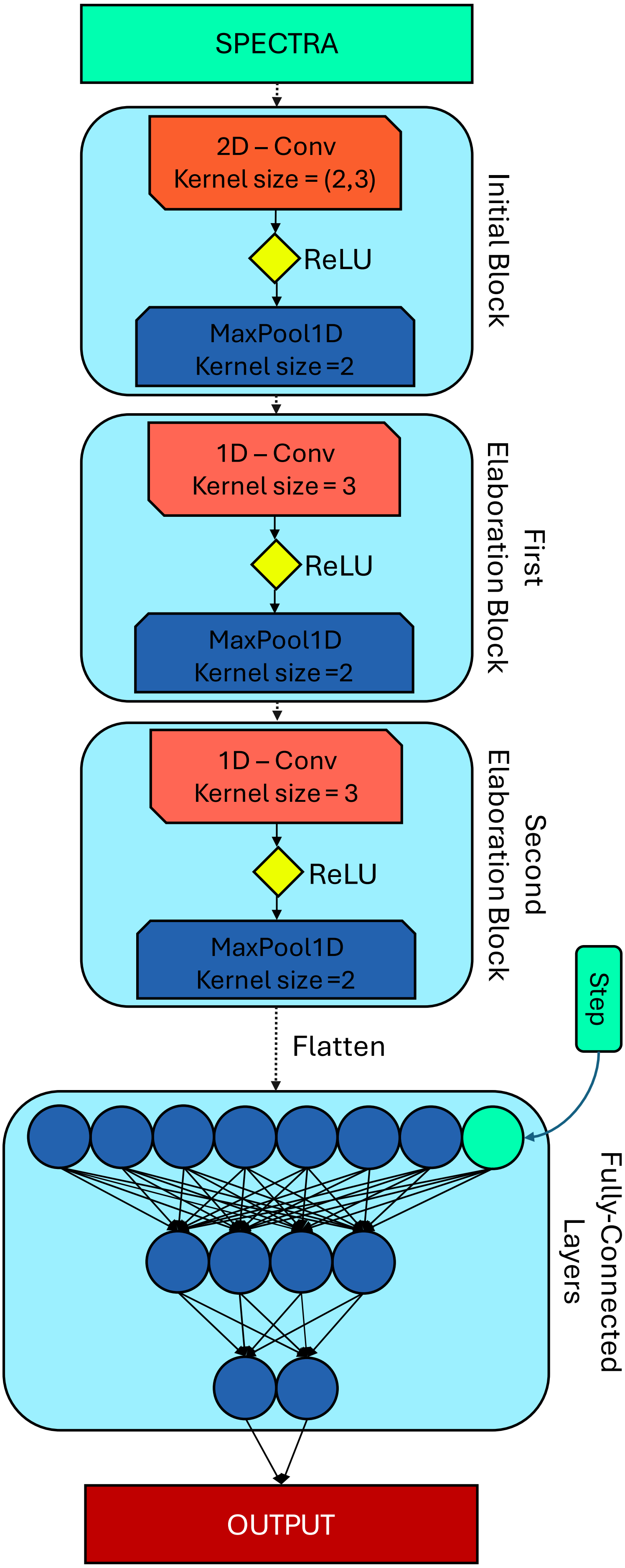


Figure 1: Artwork by James Provost


SPECTRA
2D – Conv
Kernel size = (2,3)
ReLU
MaxPool1D
Kernel size =2
Initial Block
1D – Conv
Kernel size = 3
ReLU
MaxPool1D
Kernel size =2
First
Elaboration Block
1D – Conv
Kernel size = 3
ReLU
MaxPool1D
Kernel size =2
Second
Elaboration Block
Flatten
Step
Fully-Connected
Layers
OUTPUT

Project description written by the Principal Academic Tutor

AI-STABLEPOWER aims at developing methodologies for the analysis of power system stability by means of state-of-the-art artificial intelligence (AI) techniques. Indeed, monitoring stability is a major concern for Transmission System Operators (TSOs), as the ongoing displacement of conventional generators by renewable generation technologies has reduced system inertia, thus affecting system stability. We employed AI-based techniques to estimate the inertia of the system. More specifically, we used a recently developed approach for inertia estimation based on Convolutional Neural Networks (CNNs) to continuously estimate the inertia of the system. This is in contrast with most existing algorithms, which rely on disturbances (such as load trips or line faults), and are therefore difficult to apply during normal operating conditions.

This project is inherently multidisciplinary since it involves fields of research as diverse as electrical engineering, computer science, computational data analysis, and mathematics.

A successful project outcome would prove beneficial for TSOs to assess stability indices in real time and take appropriate countermeasures, such as the activation of conventional generators in one or more areas of the network. Terna S.p.A., the Italian TSO and external partner of this project, is regularly active in the research and development of algorithms and methodologies for monitoring both system stability and inertia. It will bring its years-long expertise on system operations, providing needs and specifications, and guidance to assure soundness and applicability of the project approach.

Team description by skill

The project required a multidisciplinary approach, combining advanced competences in Electric Engineering, Computer Science and Mathematics. In this section, the group division and method of work will be explained, showing how the constructive collaboration of our diverse backgrounds resulted in the success of the project.

Alessio Brunamonti and Matteo Zampieri are respectively students in Biomedical Engineering and Electrical Engineering. They planned and executed all the simulations. Zampieri used his background to list all the possible scenarios and efficiently organize the generation of synthetic data that was required. Brunamonti focused on the automatization of the generation algorithm and explored the diverse ways for the computation of the spectra.

Giulio Merlo and Andrea Ruglioni are Mathematical Engineering students. They designed the architecture of our Neural Network (StepNet). They also evaluated each incremental improvement of the architecture with the datasets produced by Brunamonti and Zampieri. Moreover, they analyzed the experimental results and, with Zampieri's assistance, contextualized them within the framework of existing literature and current solutions.

Giuseppe Boccia and Matteo Forlivesi study Computer Science and Engineering. They improved the StepNet Architecture leveraging on advanced Machine Learning and Deep Learning techniques. Furthermore, they created Python modules to make the testing procedure faster and easily repeatable with different iterations of both the network and datasets.

Goal

AI-STABLEPOWER aims to make a significant step forward in the way TSOs monitor the stability of a power system and enable them to take appropriate countermeasures. So far almost all the algorithms used for this purpose require either a network event or some exogenous perturbation to provide a good estimation. The proposed approach, on the other hand, would exploit the capabilities of deep neural networks to build a statistical model of the dynamics of the power system and allow to accurately estimate its inertia and therefore the onset of potential instabilities.

Our goal is to develop an estimation method for the inertia of the electric grid which:

- **does not require the installation of additional physical equipment**: this represents a significant advantage over traditional inertia estimation methods, which often require additional sensors or dedicated devices to measure the system's response to specific disturbances.
- **must not interfere with the daily operations of the grid**: the method must not create other types of problems for grid management and interfere in any way with the TSOs' control operations.
- **is completely data driven**: the method must be agnostic to the specific system configuration and independent from detailed models of the power system.
- **can capture hidden inertia**: for the new method to be favored over the traditional approach, it must effectively measure the hidden inertia associated with loads, storage, or RES plants that provide synthetic inertia.
- **works within the market session interval**: to meet operational requirements, the method should provide an estimate of the network's global inertia within 15 minutes, aligning with the intervals of the intraday market sessions.

Understanding the problem

Electrical systems for power generation, transmission, and distribution are required to maintain stability by limiting frequency excursions. A classical measure of a power system's capability to counteract frequency changes is its inertia constant, which is related to the kinetic energy stored in the rotating masses of all synchronous generators and turbines. The nature of conventional power plants is such that inertia is approximately constant over time, thus contributing to the overall stability of the power system. In recent years, however, power systems have witnessed an increase in the share of power generation, most notably by RES, that has led to a steady decline and increasing variability of the inertia attributable to conventional generation sources/loads (see Figure 2): this, in turn, has increased the risk of compromising the stability of the power grid.

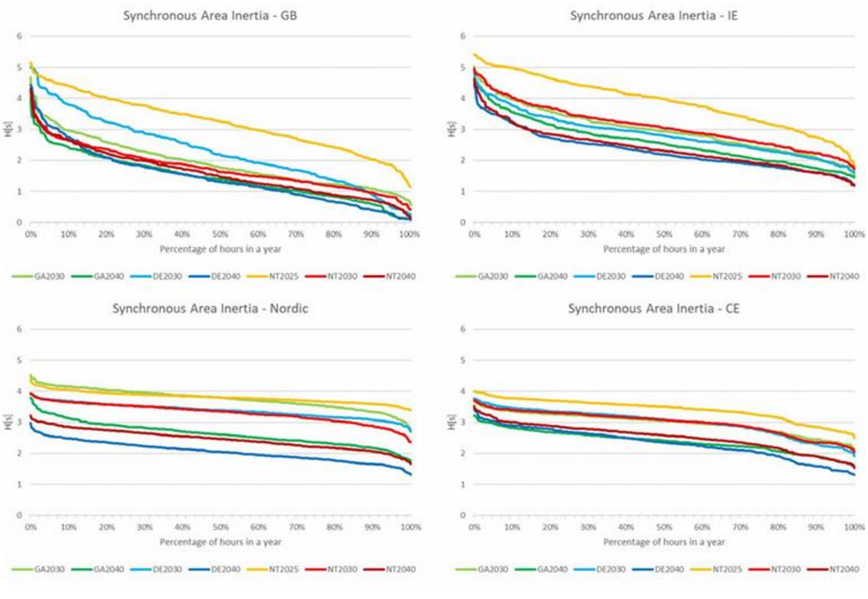


Figure 2: Steady tendency in the reduction of inertia from 2025 to 2040

Therefore, to maintain grid stability, it is vital for TSOs to accurately and continuously estimate the inertia level of the network.

However, current inertia estimation methods—such as summing constants from connected generation, measuring the rate of change of frequency (RoCoF) during significant excursions, and calculating inertia based on annual power events—offer only a limited, retrospective view of grid stability. These approaches lack the ability to provide TSOs with the real-time, precise, and dynamic inertia measurements needed to safely integrate more renewable energy and maintain grid stability.

Moreover, in the European grid (see image below) inertia is not limited to individual countries but is a characteristic of the entire interconnected network. All synchronized generators operate at the same nominal frequency (e.g., 50 Hz in Europe). A frequency variation at any point in the grid, due to an imbalance between power supply and demand, propagates rapidly throughout the network. This interconnectedness allows a disturbance in one part of the grid to be mitigated by inertia provided by generators in different countries.

Figure 3: The European transmission grid

For example, when the frequency decreases due to a sudden increase in demand in Northern Italy, the kinetic energy of generators across continental Europe reacts to this change. It is important to remember that electricity transmitted through power lines consists of electromagnetic waves traveling at the speed of light. This means that if a generator in Puglia responds to a frequency drop by supplying kinetic energy, it helps stabilize the frequency across the entire interconnected grid, including Northern Italy, in few seconds.

Exploring the opportunities

Some estimation methods to estimate the level of inertia of a power system, which is not directly measurable, have already been developed, so we started to analyze those.

Most common methods are based on disturbance data. This means that, during transient events such as significant system disturbances, the active power variation and the RoCoF are used to calculate inertia using the swing equation. However, this method is highly subjective to noise, even when using the sliding window method (SWM) to mitigate it, and is dependent on significant disturbance events, which may not occur frequently.

Another class of methods is based on electromechanical oscillations. These methods estimate inertia by exploiting the system's electromechanical oscillations, which are related to inertia and the damping coefficient. They are based on analyzing the system's response to small perturbations and do not require detailed modeling of the entire system. However, these methods may fail in the presence of multiple internal oscillation modes and are sensitive to noise.

Finally, the micro perturbation method (MPM) was developed to overcome the limitations of transient signals. This approach uses multi-sinusoidal signals to perturb the system and improve the signal-to-noise ratio. While this method offers accurate inertia estimation, its complexity increases due to the need for additional probing signals, making it less suitable for interconnected multi-area systems.

Therefore, the need emerged for a new method to estimate system inertia which is resistant to noise, does not require modifications of the grid structure, and does not risk perturbing normal gird operation with probing signals, while at the same time remaining fast, efficient, and accurate.

Generating a solution

Our proposed solution involves the implementation of a deep convolutional network designed to analyze the frequency spectra of a generator. This neural network, which we call StepNet, fully automates the inertia estimation process, ensuring reliable estimation across various scenarios without the necessity of injecting probing signals into the grid.

StepNet is trained to estimate inertia by looking at the spectral properties of the power system. In its final application, the network should be capable of accepting as input the spectra before and after the inertia step (hence the name StepNet), along with the magnitude of the adjustment itself (i.e., the amount by which the inverter inertia constant was temporarily increased) and output a precise estimate of the global inertia.

The development of this model as well as its extensive testing were all done using the Python programming language. This language was chosen for its simplicity and readability, which allows developers to write clear and concise code. Another key feature of this language is its extensive standard library, which provides a vast array of modules and functions that can be readily used without the need for additional installation. This makes Python highly efficient for a wide range of tasks, from web development and data analysis to scientific computing and machine learning. Specifically, we made vast use of the PyTorch library, an extremely popular Python package developed by Meta, which allowed us to easily define the CNN, and provided direct integration with the CUDA modules speeding up the training process thanks to the parallelization capabilities of GPUs.

To train the model efficiently, we needed to realistically simulate the behavior of the transmission system in any configuration we desire. For our purposes, we used PowerFactory by DIgSILENT, a power system analysis software application for analyzing generation, transmission, distribution, and industrial systems. This simulator is widely recognized for its advanced simulation capabilities in power systems. It allows for detailed modeling and analysis of electrical grids, incorporating various components such as generators, transmission lines, and loads. By leveraging synthetic data from PowerFactory, we created a detailed dataset of rotor speed spectra for training our machine learning model, enhancing its ability to predict system behaviors under various conditions.

Finally, to ensure that this approach is a viable real-world solution, we rigorously tested and validated StepNet under various challenging conditions. Starting from noise-free data, we then added noise to the spectral data fed into the network. Then, we also tested it on unseen grid-network configurations, to make sure that it generalized well to new and unseen data. Finally, we tested the network in extreme scenarios, such as the sudden failure of one or more generators.

Main bibliographic references

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