GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA

FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2025

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FACULTY OF ELECTRICAL ENGINEERING

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PREFACE

The Third International Conference “Electrical Engineering, Technology, Informatics, Mechanical Engineering and Automation – Technical Sciences in the Service of the Economy, Education and Industry” (ETIMA’25), organized by the Faculty of Electrical Engineering at the “Goce Delchev” University – Shtip, represents a significant scientific event that enables interdisciplinary exchange of knowledge and experience among researchers, professors, and experts in the field of technical sciences. The conference was held in an online format and brought together 78 authors from five different countries.

The ETIMA conference aims to establish a forum for scientific communication, encouraging multidisciplinary collaboration and promoting technological innovations with direct impact on modern life. Through the presentation of scientific papers, participants shared the results of their research and development activities, contributing to the advancement of knowledge and practice in relevant fields.
The first ETIMA conference was organized four years ago, featuring 40 scientific papers. The second conference took place in 2023 and included over 30 papers. ETIMA’25 continued this scientific tradition, presenting more than 40 papers that reflect the latest achievements in electrical engineering, technology, informatics, mechanical engineering, and automation.

At ETIMA’25, papers were presented that addressed current topics in technical sciences, with particular emphasis on their application in industry, education, and the economy. The conference facilitated fruitful discussions among participants, encouraging new ideas and initiatives for future research and projects.

ETIMA’25 reaffirmed its role as an important platform for scientific exchange and international cooperation. The organizing committee extends sincere gratitude to all participants for their contribution to the successful realization of the conference and its scientific value.

We extend our sincerest gratitude to all colleagues who, through the presentation of their papers, ideas, and active engagement in discussions, contributed to the success and scientific significance of ETIMA’25.

The Organizing Committee of the Conference

ПРЕДГОВОР

Третата меѓународна конференција „Електротехника, Технологија, Информатика, Машинство и Автоматика – технички науки во служба на економијата, образованието и индустријата" (ЕТИМА'25), организирана од Електротехничкиот факултет при Универзитетот „Гоце Делчев" – Штип, претставува значаен научен настан кој овозможува интердисциплинарна размена на знаења и искуства меѓу истражувачи, професори и експерти од техничките науки. Конференцијата се одржа во онлајн формат и обедини 78 автори од пет различни земји.

Конференцијата ЕТИМА има за цел да создаде форум за научна комуникација, поттикнувајќи мултидисциплинарна соработка и промовирајќи технолошки иновации со директно влијание врз современото живеење. Преку презентација на научни трудови, учесниците ги споделуваат резултатите од своите истражувања и развојни активности, придонесувајќи кон унапредување на знаењето и практиката во релевантните области.

Првата конференција ЕТИМА беше организирана пред четири години, при што беа презентирани 40 научни трудови. Втората конференција се одржа во 2023 година и вклучи над 30 трудови. ЕТИМА'25 продолжи со истата научна традиција, презентирајќи повеќе од 40 трудови кои ги отсликуваат најновите достигнувања во областа на електротехниката, технологијата, информатиката, машинството и автоматиката.

На ЕТИМА'25 беа презентирани трудови кои обработуваат актуелни теми од техничките науки, со посебен акцент на нивната примена во индустријата, образованието и економијата. Конференцијата овозможи плодна дискусија меѓу учесниците, поттикнувајќи нови идеи и иницијативи за идни истражувања и проекти.

ЕТИМА'25 ја потврди својата улога како значајна платформа за научна размена и интернационална соработка. Организациониот одбор упатува искрена благодарност до сите учесници за нивниот придонес кон успешната реализација на конференцијата и нејзината научна вредност. Конференцијата се одржа онлајн и обедини седумдесет и осум автори од пет различни земји.

Изразуваме голема благодарност до сите колеги кои со презентирање на своите трудови, идеи и активна вклученост во дискусиите придонесоа за успехот на ЕТИМА'25 и нејзината научна вредност.

Организационен одбор на конференцијата

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TRANSIENT PHENOMENA IN BLACK START

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Abstract

System restoration following a blackout event involves complex electrical and operational challenges that must comply with Commission Regulation (EU) 2017/2196 and following TSOs' restoration codes as mandated by that Regulation. It is also mandated that TSOs review the measures of their restoration plan, including the energising restoration path from restoration service providers with black start or island operation capabilities. This paper presents a simulation-based analysis of electromagnetic and wave transients during the energisation of a hypothetical restoration route between a hydroelectric power plant (HPP) providing black-start service and a nuclear power plant (NPP) requiring auxiliary power for its systems. The study evaluates sequential and simultaneous energisation strategies using various EMTP models for the transformers. Results reveal significant insights regarding transient voltages, inrush currents, and harmonic content critical and highlight the importance of precise route modelling.

Key words

Power system restoration, black-start capability, EU 2017/2196, restoration plan, wave transients, transformer inrush.

Introduction

The European Union's electricity system restoration procedures are governed by Commission Regulation (EU) 2017/2196, which establishes a network code on electricity emergency and restoration. This regulation mandates that each Transmission System Operator (TSO) must have had designed and implemented a restoration plan by December 18, 2018, containing specific technical and organisational measures [1].
According to Article 23(4) of the regulation, the restoration plan must include:

- A list of substations essential for restoration procedures
- The number of power sources with black-start capability, quick re-synchronisation capability (through houseload operation), and island operation capability
- High-priority significant grid users and terms for their disconnection and re-energisation
- Implementation deadlines for each listed measure

The regulation specifies in Article 26 that restoration procedures must contain measures for both top-down and bottom-up re-energisation strategies. For bottom-up strategies, specific requirements include managing voltage and frequency deviations due to re-energisation, monitoring island operation, and resynchronizing island operation areas.

While the regulatory framework provides clear requirements for restoration plan structure, the actual implementation presents significant technical challenges. Article 51 mandates that TSOs review restoration plan measures using computer simulation tests at least every five years, covering:

- The energizing restoration path from black-start capable units
- Supply of power generating module auxiliaries
- The demand reconnection process
- The process for resynchronisation of networks in island operation

This study addresses these requirements by examining the transient behaviour during the critical first phase of restoration: establishing an energisation path from a black-start capable power plant (Hydroelectric Power Plant i.c.) to another power plant needing external power for its' auxiliary systems (Nuclear Power Plant i.c.). The analysis focuses on electromagnetic transients that could compromise equipment safety or trigger protection systems, potentially disrupting the restoration process.

2. Restoration route design

Some Hydroelectric Power Plants can provide primary black-start service due to their ability to self-energize auxiliary their systems without external power supply and provide power to the electrical grid [2], [3]. The NPP auxiliary systems represent a possible high-priority significant grid user as defined in Article 23(4)(d), requiring rapid re-energisation following a blackout event. The restoration route examined in this study therefore aligns with requirements for power sources with black-start capability.

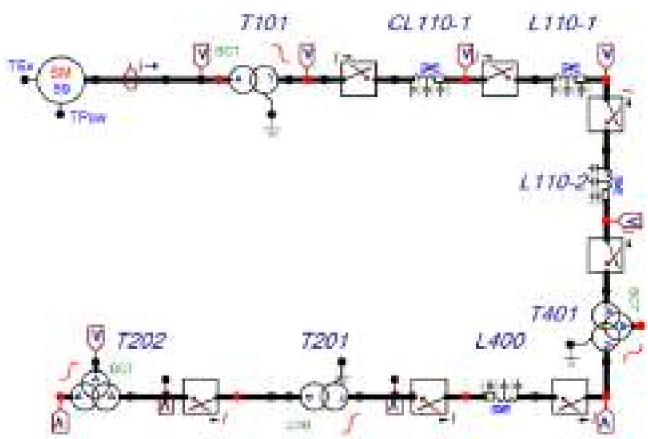

Fig. 1 Restoration path model

The selected route follows a predefined chain from HPP to NPP through:

- HPP Substation (transformer T101)
- Distribution system interconnection
- Substation A (transformer T401)
- Transmission system path
- NPP Substation (transformers T201 and T202)

The HPP, as a restoration service provider delivering black-start service, must execute black-start capability testing at least every three years according to Article 44(1), following the methodology in Article 45(5) of Regulation (EU) 2016/631.
Two energisation approaches are evaluated in compliance with Article 27, which requires TSOs to select re-energisation strategies based on available power sources, expected duration and risks, and system conditions:

- Sequential Energisation - Each element is energized individually with verification steps between operations.
- Simultaneous Energisation - All breakers along the route are pre-closed in de-energized state, then energized with a single command. This method reduces total restoration time but subjects all equipment to one combined transient event.

3. Simulation methodology

A simple EMTP model was developed in ATPDraw software environment. Such or similar simulation model is needed for real restoration plan as per Article 51 requirement for computer simulation testing of restoration plans. The model includes:

- HPP synchronous generator (ATP-EMTP Type 59) without active voltage regulation, representing early black-start conditions
- 110 kV transmission lines with distributed parameters
- Transformers modelled with both linear and nonlinear magnetisation characteristics

No active loads are included to assess worst-case overvoltages and ferroresonance potential.

This study has following switching cases:

- Distribution line switching transients
- Substation transformer energisation
- NPP auxiliary transformer connection
- Complete simultaneous energisation

Maximum peak values of voltage are evaluated, and Fast Fourier Transform analysis is performed to assess harmonic content.

4. Results

Distribution Lines Switching Transients

Generator

Energizing an unloaded 110 kV line causes it to draw a steep inrush due to its capacitance. When sequentially energized, each line section produced a peak of approximately 1 kA with linear-core transformer model and 4 kA with the nonlinear-core transformer model. End-of-line voltage reached 1.45 p.u. Simultaneous energisation of all line sections yielded a single 4.5 kA pulse and up to 1.64 p.u. of overvoltage.

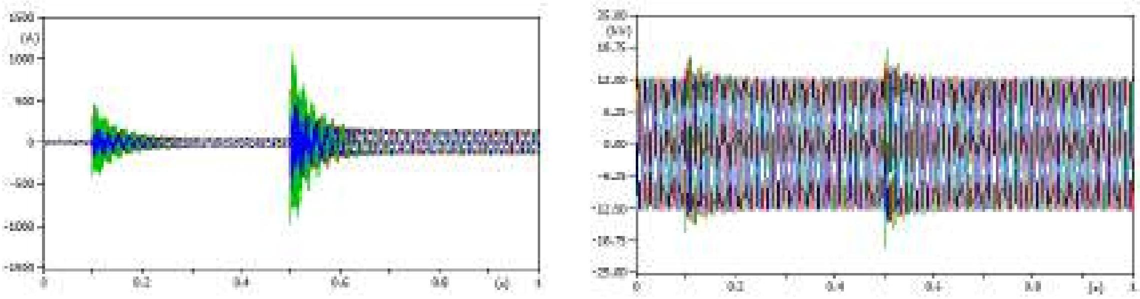

Fig. 2 Generator node current (left) and voltage (right) during distribution lines switching. (linear transformer model)

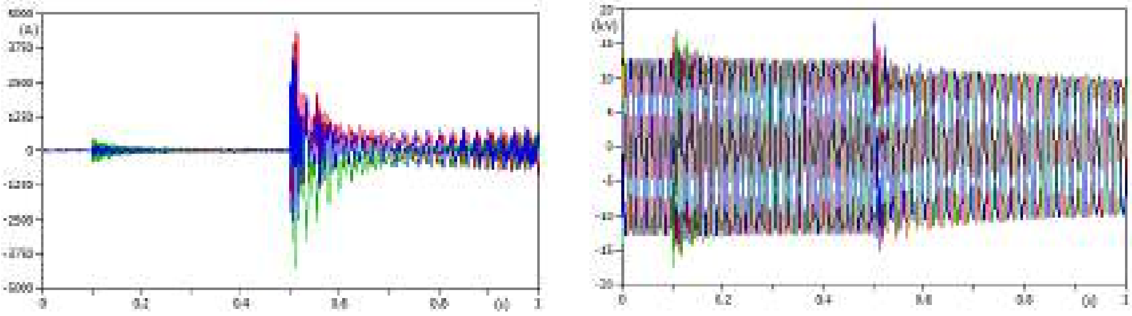

Fig. 3 Generator node current (left) and voltage (right) during distribution line switching. (nonlinear transformer model)

T101 - primary winding

Secondary side voltages' and currents' waveforms mostly retain the shape of waveforms on the generator.

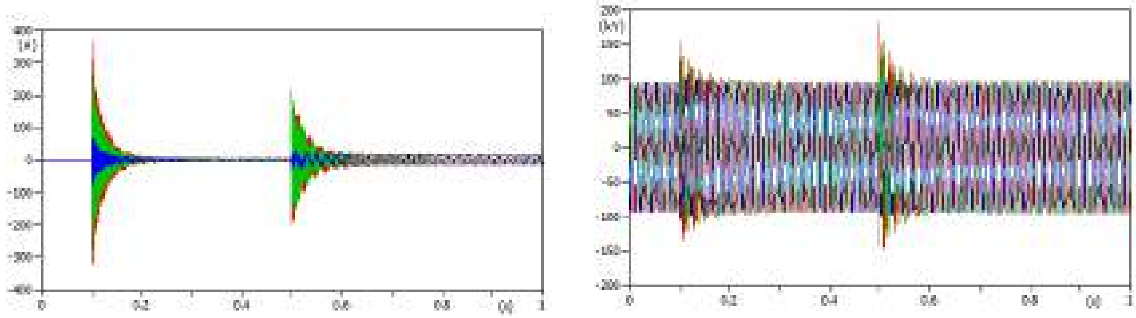

Fig. 4 T101 node current (left) and voltage (right) during distribution line switching. (linear transformer model)

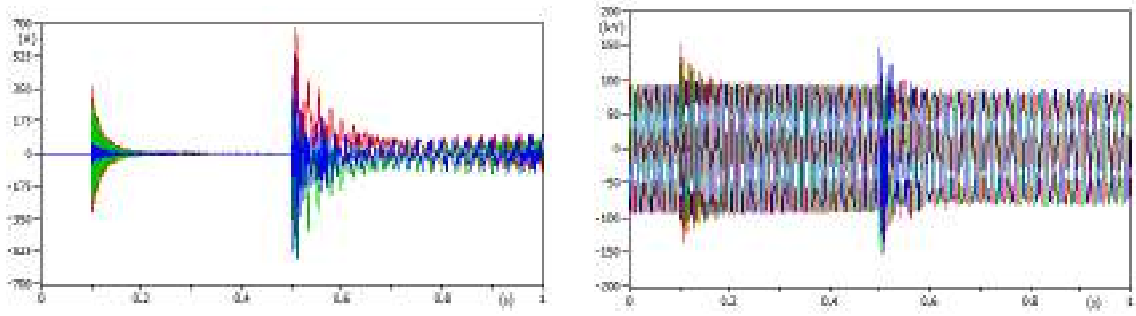

Fig. 5 T101 node current (left) and voltage (right) during distribution lines switching. (nonlinear transformer model)

Substation A Transformer Switching Transients

Generator

Transients (both current and voltage) in with nonlinear transformer model are much more severe when switching the substation transformer. In both cases, the current rises and generator voltage decreases.

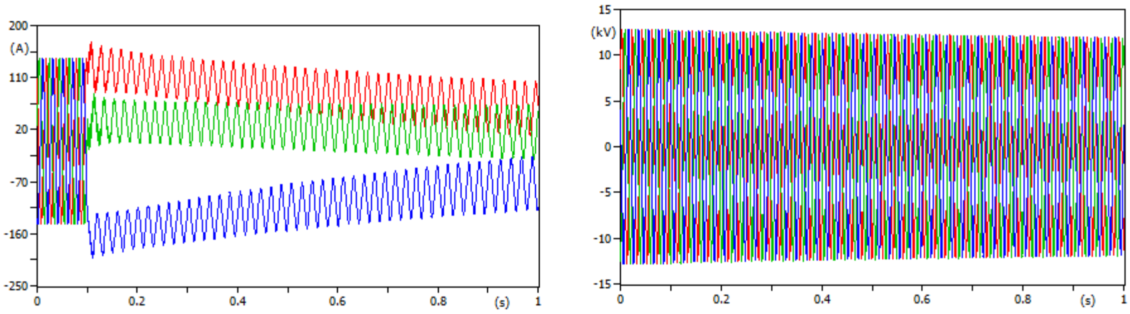

Fig. 6 Generator node current (left) and voltage (right) during Substation A switching. (linear transformer model)

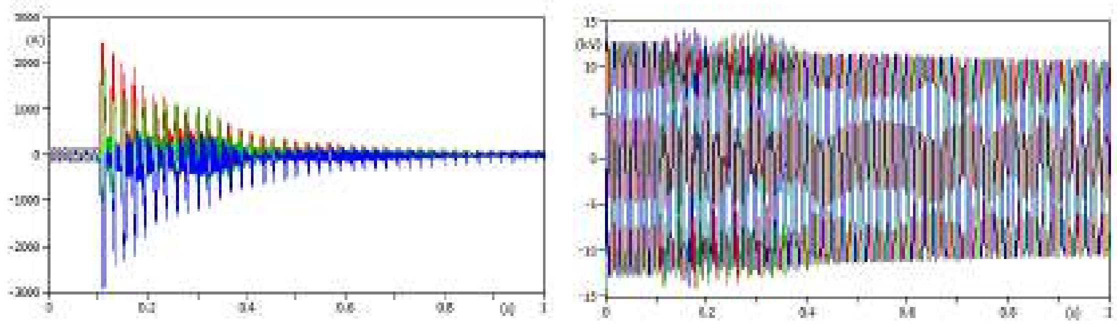

Fig. 7 Generator node current (left) and voltage (right) during Substation A switching. (nonlinear transformer model)

Substation A transformer - secondary winding

In both models, there is notable magnetisation current recognized by distinctive type of asymmetric waveform. For nonlinear model voltage transient is much distinct and current waveforms are further deformed.

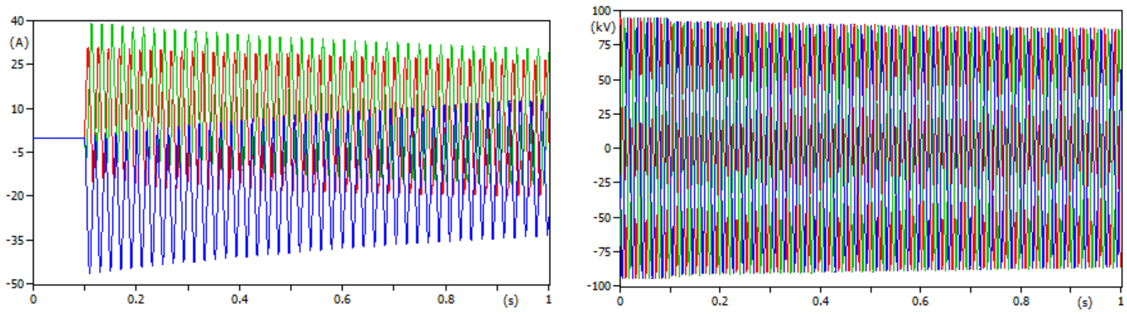

Fig. 8 T101 secondary node current (left) and voltage (right) during Substation A switching. (linear transformer model)

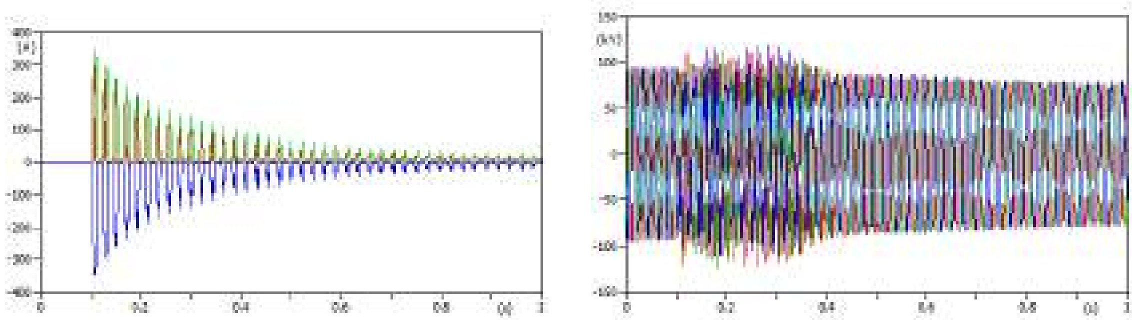

Fig. 9 T101 secondary node current (left) and voltage (right) during Substation A switching. (nonlinear transformer model)

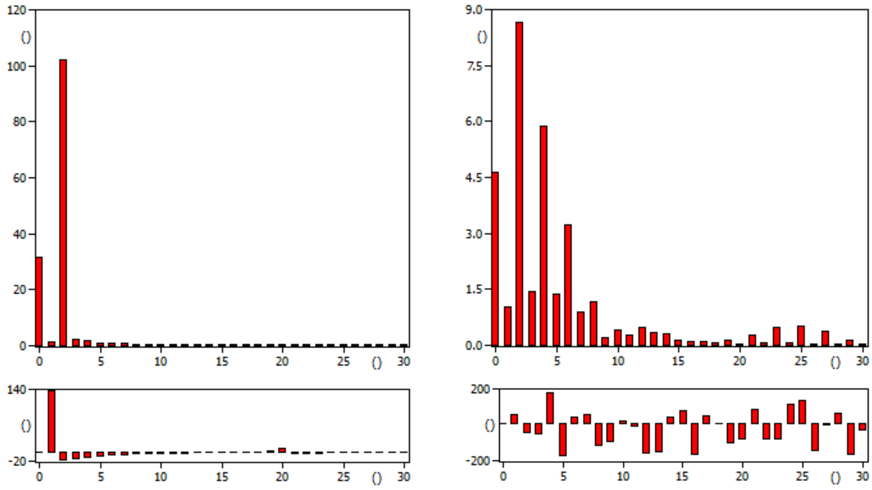

Fig. 10 FFT for no-load Substation A transformer linear model (left) and nonlinear model (right)

From FFT analysis, while in the linear model only 0th and 2nd harmonic are of notice, in nonlinear pair multiples are highly noticeable up to 8th harmonic.

NPP Substation Transformer Switching Transients

Generator

In the linear model, the generator voltage and current decrease, whereas in the nonlinear model both quantities initially increase before exhibiting a slight decline. This behaviour is most likely caused by a shift in the reactive power balance, as reactive power is absorbed to magnetize the transformer core.

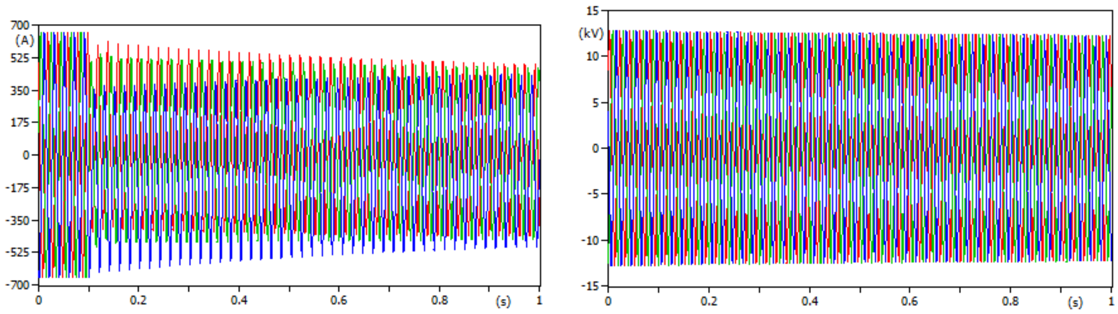

Fig. 11 Generator node current (left) and voltage (right) during NPP Substation transformer switching. (linear transformer model)

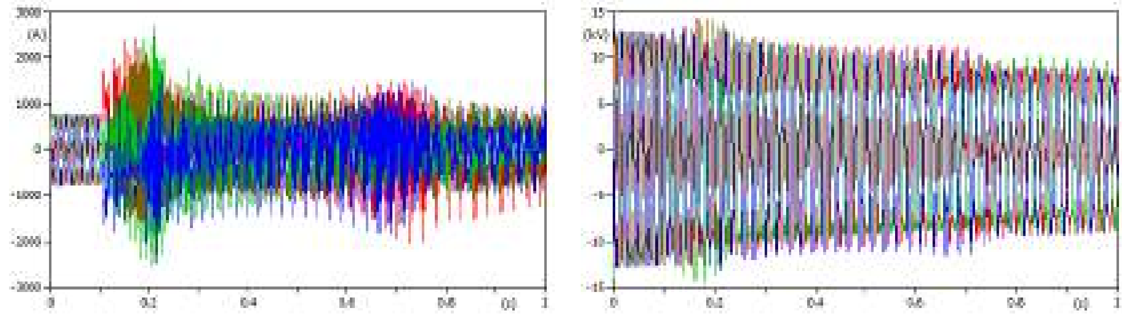

Fig. 12 Generator node current (left) and voltage (right) during NPP Substation transformer switching. (nonlinear transformer model)

2) NPP Substation Transformer – primary winding

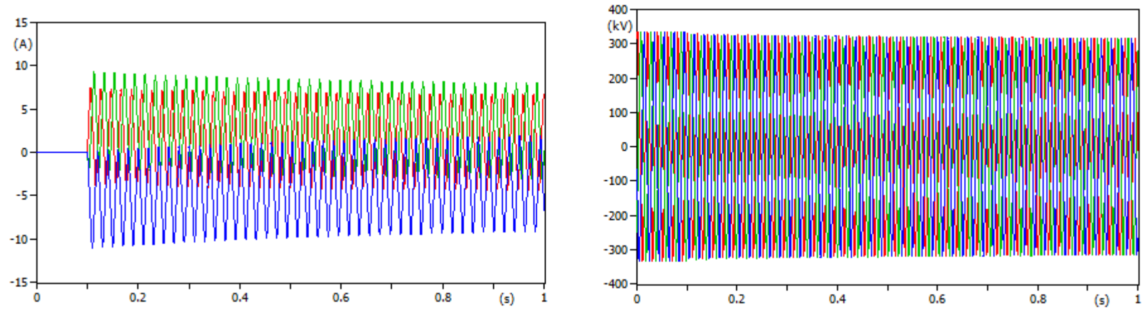

Fig. 13 T201 secondary node current (left) and voltage (right) during NPP Substation switching. (linear transformer model)

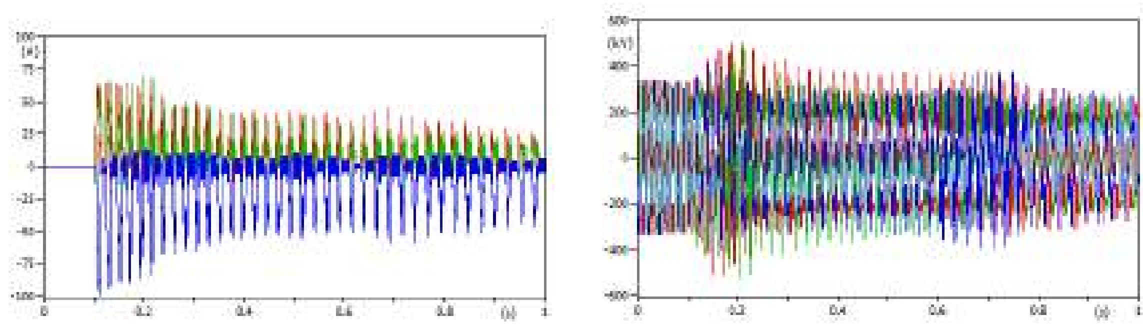

Fig. 14 T201 secondary node current (left) and voltage (right) during NPP Substation switching. (nonlinear transformer model)

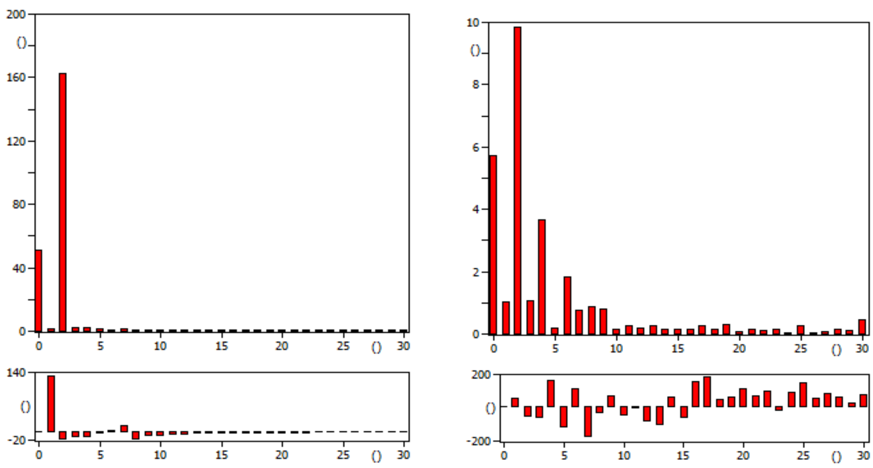

Fig. 15 FFT for no-load NPP Substation transformer linear model (left) and nonlinear model (right)

Auxiliary Transformer Switching Transients

Generator

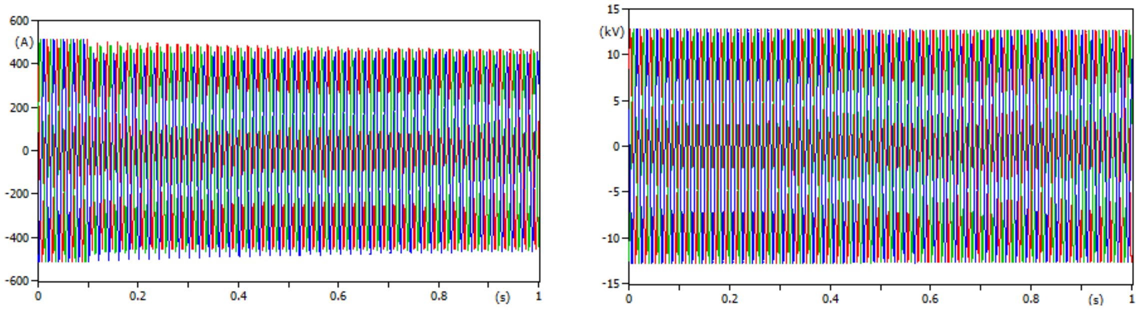

Fig. 16 Generator node current (left) and voltage (right) during auxiliary transformer switching. (linear transformer model)

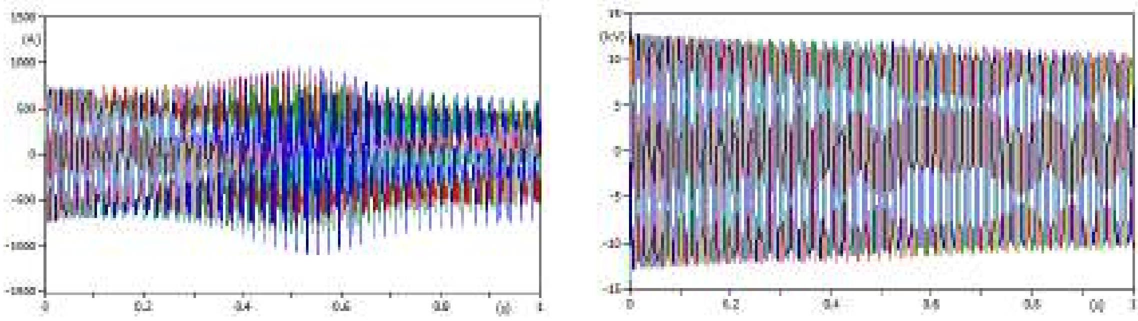

Fig. 17 Generator node current (left) and voltage (right) during auxiliary transformer switching. (nonlinear transformer model)

NPP Substation Transformer – secondary winding

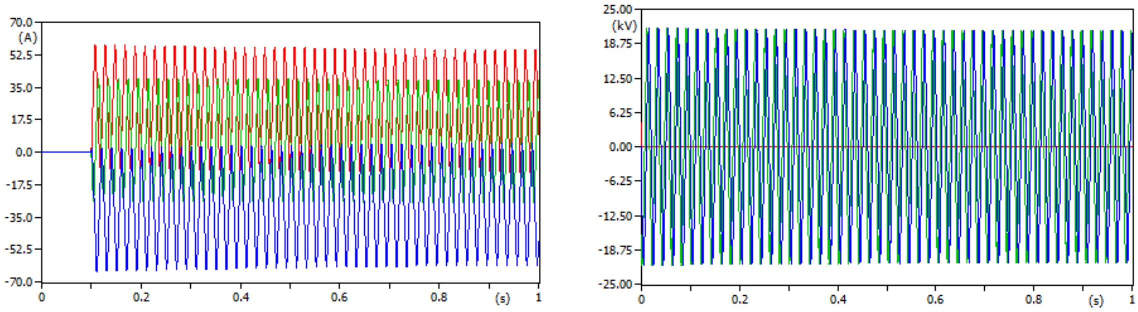

Fig. 18 T201 secondary node current (left) and voltage (right) during auxiliary transformer switching. (linear transformer model)

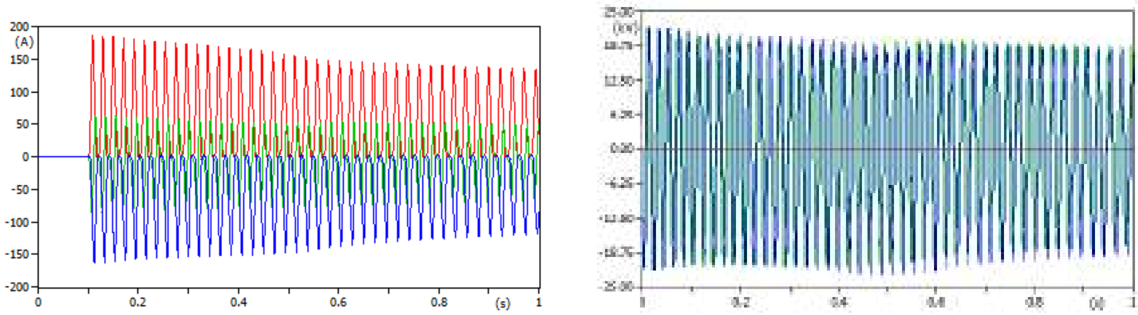

Fig. 19 T201 secondary node current (left) and voltage (right) during auxiliary transformer switching. (nonlinear transformer model)

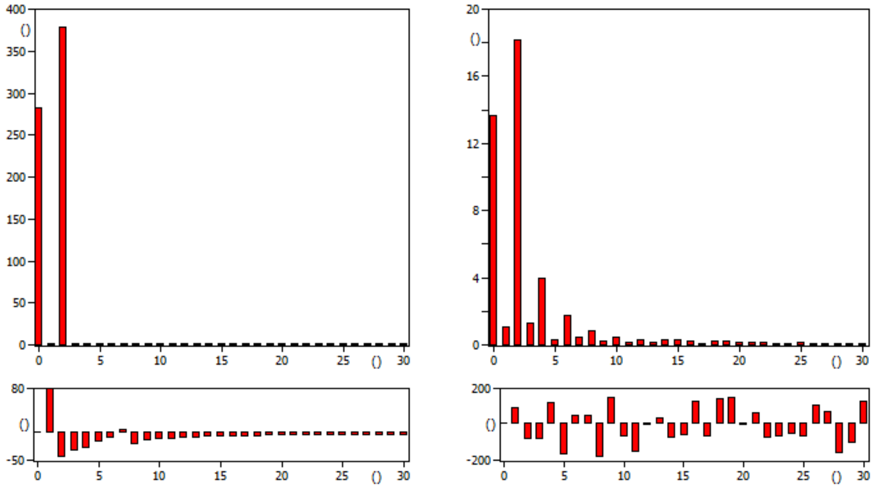
Fig. 20 FFT for no-load NPP auxiliary transformer linear model (left) and nonlinear model (right)

Simultaneous Energisation Transients

Generator

Both current and voltage exhibit similar behaviour, after the first peak, there is a steady decline. In nonlinear model the decline voltage is more pronounced.

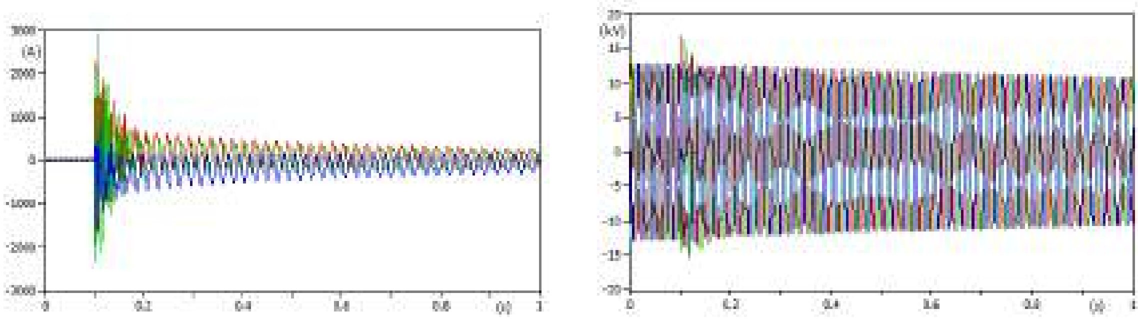
Fig. 21 Generator node current (left) and voltage (right) during simultaneous switching. (linear transformer model)

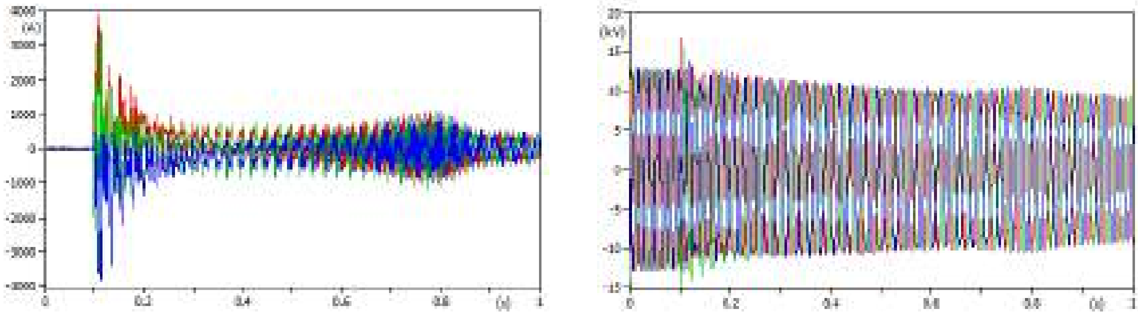
Fig. 22 Generator node current (left) and voltage (right) during simultaneous switching. (nonlinear transformer model)

Substation A Transformer – secondary winding

Difference between linear and nonlinear models' voltage is almost negligible, both reaching peak value of 250 kV. The difference in currents is more significant, 400 A and 600A for linear/nonlinear model respectively.

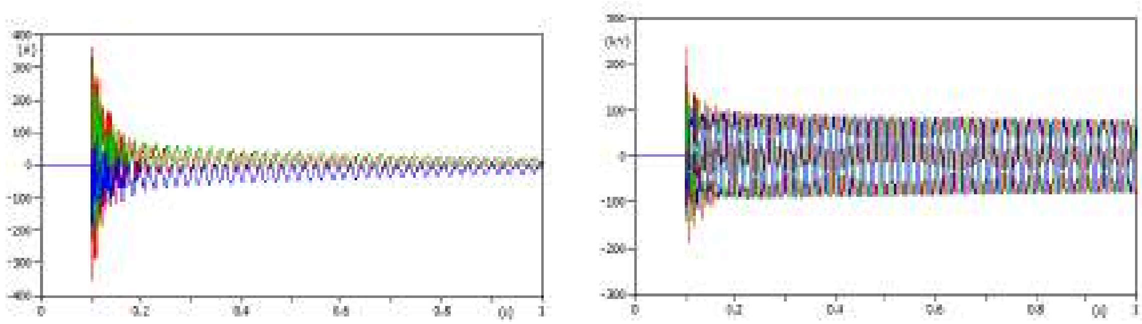

Fig. 23 T401 secondary node current (left) and voltage (right) during simultaneous switching. (linear transformer model)

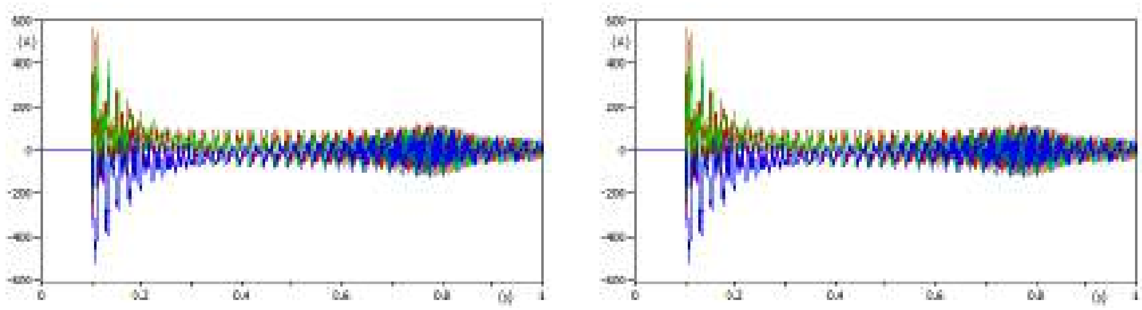

Fig. 24 T401 secondary node current (left) and voltage (right) during simultaneous switching. (nonlinear transformer model)

NPP Substation Transformer – secondary winding

There is not a substantial difference in models in transient voltage amplitude. As in Substation A node, the difference is in current - 60 A of inrush current for the linear model and almost 120 A for the nonlinear model.

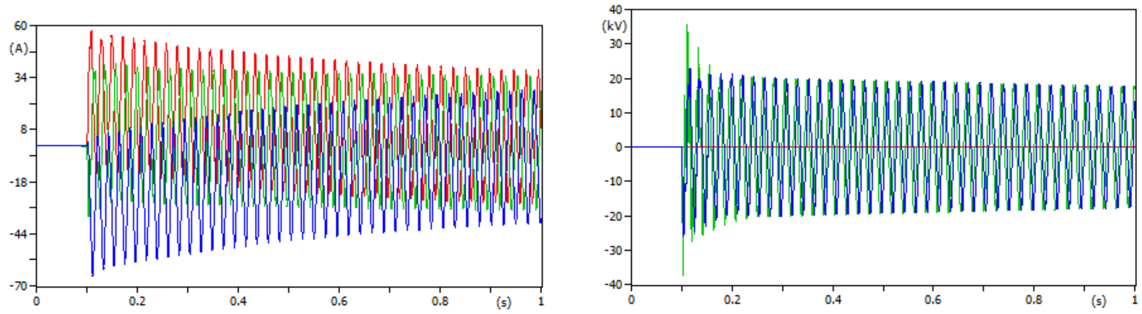

Fig. 25 T201 secondary node current (left) and voltage (right) during simultaneous switching. (linear transformer model)

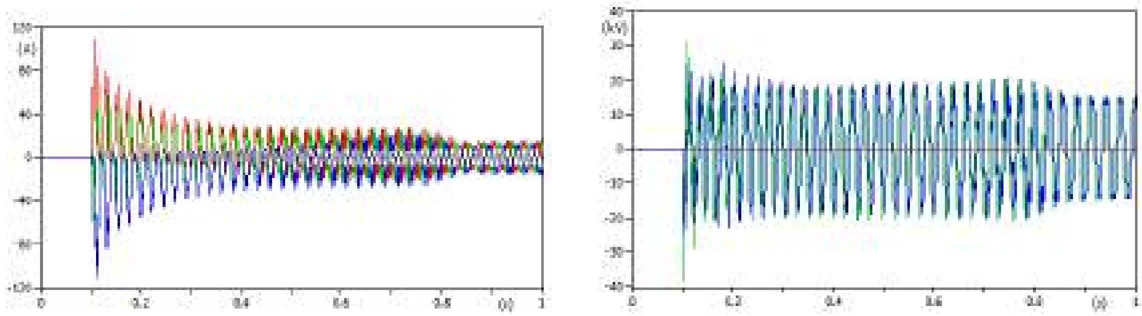

Fig. 26 T201 secondary node current (left) and voltage (right) during simultaneous switching. (nonlinear transformer model)

Conclusions

Commission Regulation (EU) 2017/2196 mandates that TSOs include restoration paths, black-start units, and high-priority users in their restoration plans. This study highlights the importance of this obligation when considering the accuracy of modelled elements in the restoration route. Two approaches were considered, sequential and simultaneous energisation. For the chosen models, no significant differences have been discovered. This is unlike the difference between models used – linear and nonlinear magnetic core of a transformer. Significant transients are apparent in both models, generally more pronounced in the nonlinear model with higher inrush currents, overvoltages and content of harmonics.
It is important to note that those models are to demonstrate difference between transformer core models. For deeper analysis, it is crucial to consider factors such as:

- Generator excitation regulator
- Other stray elements of the real path such as insulators and bushings
- Influence of the precise moment of switching

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