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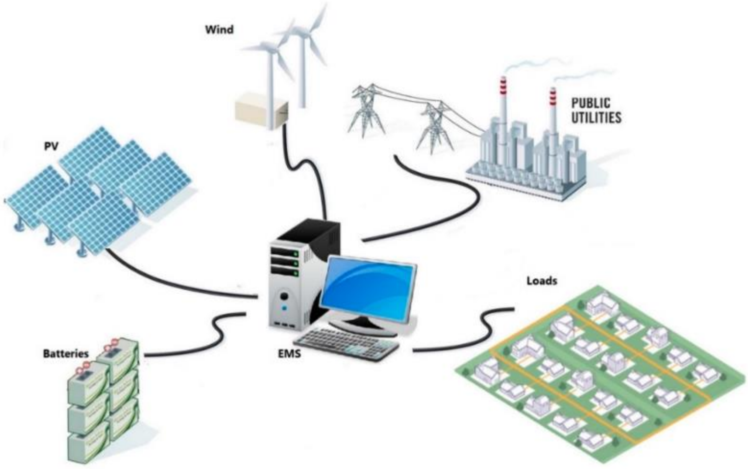
MÁSTER UNIVERSITARIO EN INGENIERIA INDUSTRIAL

TRABAJO FIN DE MASTER

COMPARISON AND TUNING OF SIMULATION TOOLS FOR POWER GRID EMT STUDIES



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Curso: 2023-2024

Fecha: Chicago, USA, 12, Agosto, 2024

Abstract

Electromagnetic transient studies are used to analyse the response of the electrical system to fast transient conditions caused by lightning strikes, resonances, short circuits, etc. These studies are essential for designing reliable power systems, especially with the growing integration of renewable energy sources, such as solar power and wind. In this research project, a comparison between two advanced simulation tools, GridPack-EMT and PSCAD, is being made.

On the one hand, PSCAD is widely used in academia and business because of its user-friendly interface and detailed modelling. On the other hand, GridPack-EMT, an extension of GridPack, offers specialized capabilities for simulating electromagnetic transients in big networks. In this research, an analysis of both these tools is carried out, evaluating their accuracy and applicability in modelling grid stability under fault conditions. Additionally, we have evaluated the influence of different PETSc solver options on GridPack-EMT's performance.

The study highlights the strengths and limitations of each tool, which is important for researches when selecting the appropriate simulation software for EMT studies. Future work emphasizes the need for improved documentation and standardization in GridPack-EMT to enhance its usability and reliability.

Resumen

Los estudios de transitorios electromagnéticos se utilizan para analizar la respuesta del sistema eléctrico a condiciones transitorias rápidas provocadas por rayos, resonancias, cortocircuitos, etc. Estos estudios son esenciales para diseñar sistemas eléctricos fiables, especialmente con la creciente integración de fuentes de energía renovables, como la solar y la eólica. En este proyecto de investigación se realiza una comparación entre dos herramientas avanzadas de simulación, GridPack-EMT y PSCAD.

Por un lado, PSCAD se utiliza ampliamente en el mundo académico y empresarial por su interfaz fácil de usar y su modelización detallada. Por otro lado, GridPack-EMT, una extensión de GridPack, ofrece capacidades especializadas para simular transitorios electromagnéticos en grandes redes. En esta investigación, se lleva a cabo un análisis de estas dos herramientas, evaluando su precisión y aplicabilidad en la modelización de la estabilidad de la red en condiciones de fallo. Además, hemos evaluado la influencia de diferentes opciones del solver PETSc en el rendimiento de GridPack-EMT.

El estudio pone de relieve los puntos fuertes y las limitaciones de cada herramienta, lo cual es importante para los investigadores a la hora de seleccionar el software de simulación adecuado para los estudios de EMT. El trabajo futuro enfatiza la necesidad de mejorar la documentación y la estandarización en GridPack-EMT para mejorar su usabilidad y fiabilidad.

Laburpena

Iragankor elektromagnetikoen azterketak sistema elektrikoak izpiek, erresonantziek, zirkuitulaburrek eta abarrek eragindako baldintza iragankor azkarrei ematen dien erantzuna aztertzeko erabiltzen dira. Azterketa horiek funtsezkoak dira sistema elektriko fidagarriak diseinatzeko, bereziki energia-iturri berriztagarriak, hala nola eguzki-energia eta iturri eolikoa, gero eta gehiago integratzen direnean. Ikerketa-proiektu honetan simulazioko bi tresna aurreraturen arteko alderaketa egiten da: GridPack-EMT eta PSCAD.

Alde batetik, PSCAD asko erabiltzen da akademia- eta enpresa-munduan, erabiltzeko erraza den interfazeagatik eta modelizazio xehatuagatik. Bestalde, GridPack-EMTek, GridPacken hedapen batek, sare handietan iragankor elektromagnetikoak simulatzeko gaitasun espezializatuak eskaintzen ditu. Ikerketa honetan, bi tresna horiek aztertzen dira, eta sarearen egonkortasunaren modelizazioan duten zehaztasuna eta aplikagarritasuna ebaluatzen da, akats-baldintzetan. Gainera, PETSc solverraren aukera desberdinek GridPack-EMT errendimenduan duten eragina ebaluatu dugu.

Azterketak tresna bakoitzaren indarguneak eta mugak nabarmentzen ditu, eta hori garrantzitsua da ikertzaileentzat EMT azterketetarako simulazio-software egokia hautatzeko orduan. Etorkizuneko lanak GridPack-EMTko dokumentazioa eta estandarizazioa hobetzeko beharra nabarmentzen du, haren erabilgarritasuna eta fidagarritasuna hobetzeko.

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1. INTRODUCTION

Transient phenomena (lightning strikes, short circuits, etc.) may occur in the operation of electrical transmission networks. A study of these transient phenomena is needed to obtain a good design of the electrical networks. In order to carry out this study of the EMTs and to be able to make an adequate design of the electrical network, different simulation tools are used. In this project, the simulation tools to be used are PSCAD [1] and GridPACK [2]. These programs will be used to study the stability of the network when a fault occurs and to check its influence on the system.

The integration of renewable energy sources such as solar power and wind into electrical grids is quickly increasing due to their benefits to the environment and economic incentives. However, these energy sources can be unpredictable and intermittent, so they introduce new challenges for grid stability and reliability.

1.1 GridPACK and GridPACK-EMT Overview

The Pacific Northwest National Laboratory (PNNL) [3], a well-known facility of the U.S. Department of Energy, plays an essential role in advancement of energy research and technology. A variety of fields, such as cybersecurity, environmental sustainability, and grid modernization, comprise the PNNL's contributions. The development of the GridPACK and GridPACK-EMT [4] software frameworks is one of their significant contributions to the field of power systems.

GridPACK (Grid Parallel Advanced Computation Kernels) is an open-source high-performance computing (HPC) package designed for the simulation of large-scale electrical grids. Using distributed (parallel) computing and advanced numerical solvers, GridPACK allows fast and efficient simulation of electrical transmission systems. It includes several prebuilt applications, such as AC power flow, dynamics simulation, and contingency analysis, with additional applications like dynamic security assessment and state estimation under development.

GridPACK-EMT (Electromagnetic Transients) extends the capabilities of GridPACK by focusing on the detailed modelling of electromagnetic transients in power systems. It allows researches and engineers to simulate the dynamic response of electrical networks to different faults, providing insights into the behavior of the system under different scenarios, especially in the presence of renewable energy sources. Professor Shrirang Abhyankar (Pacific Northwest National Laboratory) has provided access to a developmental version of GridPACK-EMT for implementation in this project.

Pacific Northwest
NATIONAL LABORATORY

1.2 PSCAD Overview

PSCAD is a highly regarded program for electromagnetic transient modelling in power systems. Renowned for its detailed and precise component representations, PSCAD allows for complex electrical network emulation and investigation of their dynamic responses to various disturbances. It is the tool of choice for many engineers and scientists focusing on profoundly examining power system transients. This software is particularly valuable for assessing the impacts of renewable energy sources on grid stability.

PSCAD

This study concentrates on severalaims relating to the simulation of electromagnetic transients in electricity grids using GridPACK-EMT and PSCAD as the principal instruments. To start, GridPACK-EMT will be documented in an accessible manner, outlining how to execute it, the required files, and the configuration of scenarios and runtime parameters. Following that, comparisons between GridPACK and GridPACK-EMT, as well as between GridPACK-EMT and PSCAD, will be conducted to understand their capabilities with respect to accuracy and computational efficiency. Additionally, the performance of GridPACK-EMT utilizing different PETSc solving selections will be explored.

2. BACKGROUND

Sustainable development is now based on power systems incorporating renewable energy sources (RES). In an effort to reduce their dependence on fossil fuels, more and more countries around the world are adopting RES. Though they present a complicated set of issues that need to be addressed, these renewable energies offer a number of advantages.

2.1 Integration of Renewable Energy Sources (RES) in Power Systems

Due to their lowering costs and environmental advantages, renewable energy sources are becoming increasingly important parts of contemporary electrical grids.

Solar photovoltaic (PV), wind, hydroelectric, biomass, geothermal energy, and wind are important RES. Many benefits are provided by the inclusion of RES in power systems:

- Environmental Sustainability: When compared to conventional fossil fuel-based generation, RES makes a significant contribution to mitigating climate change and lowering greenhouse gas emissions.
- Energy Security: By decreasing dependence on fluctuating global energy markets and imported fuels, diversifying the energy mix with RES improves energy security.
- Economic Viability: The costs of RES are now more competitive and economically viable as a result of advancements in technology, economies of scale, and supportive policies.
- Job Creation: The deployment of RES has led to job creation in manufacturing, installation, and maintenance sectors, supporting local economies.

2.2 Challenges in RES Integration

A number of issues arise when integrating RES into power grids, despite their benefits:

- Intermittency and Variability: As a result of weather conditions, solar and wind generation vary in output; this can cause problems for grid reliability and stability.
- Grid Integration: In order to accommodate variable generation and guarantee a reliable supply of electricity, upgrades to grid infrastructure, including distribution and transmission networks, are necessary in order to integrate large-scale RES deployments.
- Storage and Flexibility: To balance supply and demand fluctuations caused by intermittent RES output, it is necessary to incorporate energy storage systems as well as flexible demand-side management strategies.
- Market Integration: To ensure grid reliability and fair competition, market design and regulatory frameworks must change in order to encourage RES deployment.

2.3 Electromagnetic Transients (EMTs) in Power Systems

- Electromagnetic transients are defined as sudden changes in voltage and current levels in power systems, which are usually caused by:
- Switching Operations: When circuit breakers, switches, or disconnectors are open or closed during normal operation or in fault conditions.
- Faults: Short circuits or ground faults caused by lightning strikes, equipment failures, or other external disturbances.

- Load Changes: Transient disturbances that affect system stability can be caused by rapid switching of large loads, such as capacitors or motors.

2.4 Importance of EMT Studies

For a number of reasons, studying EMTs is essential:

- Equipment Protection: In order to protect equipment and guarantee reliable operation. EMTs can damage power system components; because of that, protective devices such as surge arresters and relays are necessary.

- Power Quality: EMTs can affect voltage and frequency oscillations, which can affect flicker, voltage stability, and harmonics. For maintaining a high-quality power supply, it is essential to understand and reduce these disruptions.

- System Resilience: Examining EMTs helps in the development of resilience strategies, which increase system reliability and reduce downtime during transient events.

2.5 Research Significance

Research in RES integration and EMTs in power systems is significant for:

- Policy Development: Providing information about energy regulations and policies in order to support grid integration while guaranteeing system security and reliability.

- Technology Advancements: In order to improve grid resilience and flexibility advanced grid technologies such as smart grids, energy storage, and grid-interactive devices are being developed and implemented.

- Operational Strategies: To maximize the benefits of RES while maintaining grid stability, optimize operational approaches such as dispatch, demand response, and grid management.

2.6 Simulation Tools

It is practically impossible to conduct tests on real systems due to the complexity of electrical systems and the high cost of installation and operation. Therefore, different tools have been developed to simulate the response of electrical systems to the phenomena affecting them.

Various models have been developed to carry out these simulations:

- Reduced Scale Models: Representation on a smaller scale with real components.

- Analog Models: Represent the electrical system by means of electronic circuits.
- Digital Models: Simulation algorithms on a digital computer.
- Hybrid Models: Combine an analog or reduced scale model with a digital one.

In this research project, the model used is the digital one, whose advantages are as follows:

- Reduced cost
- Large number of algorithms and calculation methods
- Easy data manipulation
- Fast calculation in most cases

3. OBJECTIVES

The project aims to accomplish several objectives focused on the comparison between GridPACK-EMT and PSCAD when simulating electromagnetic transients within electrical power systems.

1. **Documentation of GridPACK-EMT**: Provide comprehensive documentation detailing the setup, execution procedures, required input files, and runtime configurations for GridPACK-EMT simulations. This objective ensures clarity and accessibility for future users and researchers.

2. **Comparison between GridPACK and GridPACK-EMT**: Conduct a thorough comparative analysis to evaluate the strengths and weaknesses of GridPACK and its EMT extension, GridPACK-EMT, in simulating dynamic responses of electrical transmission systems. This comparison will highlight the specific advantages of GridPACK-EMT for modeling electromagnetic transients.

3. **Comparison between GridPACK-EMT and PSCAD**: Perform detailed comparisons between GridPACK-EMT and PSCAD, focusing on their capabilities in accurately modeling transient phenomena in power systems. This objective aims to identify the comparative advantages and limitations of each tool, providing insights into their respective applicability and computational efficiency.

4. **GridPACK-EMT Performance using PETSc Options:** Investigate the performance of GridPACK-EMT by leveraging various PETSc solver options. This objective involves experimenting with different solver configurations and

optimization strategies to assess GridPACK-EMT's computational efficiency and solution accuracy under diverse simulation scenarios.

4. DOCUMENTATION OF GRIDPACK_EMT

For this project, a Linux server equipped with GridPACK-EMT was utilized. The server and necessary software were provided by the Illinois Institute of Technology, along with the required access credentials. A VPN connection is necessary to access this server.

Projects in GridPack-EMT involves several specific file types:

- case.dyr: This file contains data related to the generator, exciter, and governor.
- case.raw: This file includes data pertinent to the modeled system. This file adheres to the PTI Load Flow Data Format for defining these values.
- case.xml: A GridPACK configuration xml file that specifies the configuration for GridPACK and the EMT simulation parameters
- .petscrc: A PETSc [5] configuration file where all PETSc configuration options are specified. This file needs to have the name .petscrc for PETSc to recognize it.

The format definition of the four necessary files is presented below.

4.1 .dyr file

A definition of the format for the .dyr was not available, so taking the parser code, we obtained the necessary fields for our case.

The parser code for every block is available at:

- https://github.com/GridOPTICS/GridPACK/blob/emt-alpha/src/parser/parser_classes/exdc1.hpp
- https://github.com/GridOPTICS/GridPACK/blob/emt-alpha/src/parser/parser_classes/genrou.hpp
- https://github.com/GridOPTICS/GridPACK/blob/emt-alpha/src/parser/parser_classes/wsieg1.hpp

GENERATOR

0	BUS NUMBER	1
1	GENERATOR MODEL	'GENROU'
2	unit ID ??	1
3	GENERATOR_TDOP	7.0
4	GENERATOR_TDOPP	0.03
5	GENERATOR_TQOP	0.75
6	GENERATOR_TQOPP	0.05
7	GENERATOR_INERTIA_CONSTANT_H	30.0
8	GENERATOR_DAMPING_COEFFICIENT_0	10.0
9	GENERATOR_XD	2.1
10	GENERATOR_XQ	2.0
11	GENERATOR_XDP	0.2
12	GENERATOR_XQP	0.5
13	GENERATOR_XDPP	0.18
14	GENERATOR_XL	0.15
15	GENERATOR_S1	0.0
16	GENERATOR_S12	0.0

EXCITER

position 0 = bus number; position 1 = device 'name'; position 2 = unit ID

0	BUS NUMBER	1
1	EXCITER_MODEL	'EXDC1'
2	unit ID	1
3	EXCITER_TR	0.16668E-01
4	EXCITER_KA	68.600
5	EXCITER_TA	0.20000E-01
6	EXCITER_TB	0.0000
7	EXCITER_TC	0.0000
8	EXCITER_VRMAX	7.4500
9	EXCITER_VRMIN	-7.4500
10	EXCITER_KE	1.0000
11	EXCITER_TE	3.8700
12	EXCITER_KF	0.10000
13	EXCITER_TF1	1.0000
14	EXCITER_SWITCH	0.0000
15	EXCITER_E1	3.4000
16	EXCITER_SE1	1.0700

```
17      EXCITER_E2            4.6000
18     EXCITER_SE2            1.2000


              GOVERNOR

0  GOVERNOR_BUSNUMBER        1
1  GOVERNOR_MODEL            'WSIEG1'
2    GENERATOR_ID            1
3  GOVERNOR_JBUS             0
4 GOVERNOR_M                 0
5   GOVERNOR_K               25.0000
6  GOVERNOR_T1               0.00000
7  GOVERNOR_T2               3.30000
8  GOVERNOR_T3               0.300000
9  GOVERNOR_UO               0.250000
10  GOVERNOR_UC              -3.30000
11  GOVERNOR_PMAX            51.01000
12  GOVERNOR_PMIN            0.00000
13  GOVERNOR_T4              0.861200E-01
14  GOVERNOR_K1              1.00000
15  GOVERNOR_K2              0.00000
16  GOVERNOR_T5              0.00000
17  GOVERNOR_K3              0.00000
18  GOVERNOR_K4              0.00000
19 GOVERNOR_T6               0.00000
20  GOVERNOR_K5              0.00000
21  GOVERNOR_K6              0.00000
22  GOVERNOR_T7              0.00000
23  GOVERNOR_K7              0.00000
24  GOVERNOR_K8              0.00000
25  GOVERNOR_DB1             0.00000
26  GOVERNOR_ERR             From now on all zeros
27  GOVERNOR_DB2
28 GOVERNOR_GV1
29  GOVERNOR_PGV1
30  GOVERNOR_GV2
31  GOVERNOR_PGV2
32  GOVERNOR_GV3
33  GOVERNOR_PGV3
34  GOVERNOR_GV4
35 GOVERNOR_PGV4
```

36	GOVERNOR_GV5	
37	GOVERNOR_PGV5	
38	GOVERNOR_IBLOCK	0

4.2 .raw file

The definition of this format is found in [7].

```
Description of the PTI Load Flow Data Format
============================================

Note that PTI reserves the right to change the format at any time.

For use with the IEEE 300 bus test case in PTI format.

Case Identification Data
========================

First record: IC,SBASE
 IC - 0 for base case, 1 for change data to be added
 SBASE - System MVA base

Records 2 and 3 - two lines of heading, up to 60 characters per line

Bus Data
========

Bus data records, terminated by a record with a bus number of zero.

I,IDE,PL,QL,GL,BL,IA,VM,VA,'NAME',BASKL,ZONE

 I - Bus number (1 to 29997)
 IDE - Bus type
        1 - Load bus (no generation)
        2 - Generator or plant bus
        3 - Swing bus
        4 - Islolated bus
 PL - Load MW
 QL - Load MVAR
 GL - Shunt conductance, MW at 1.0 per unit voltage
 BL - Shunt susceptance, MVAR at 1.0 per unit voltage. (- = reactor)
 IA - Area number, 1-100
 VM - Voltage magnitude, per unit
 VA - Voltage angle, degrees
```

```
 NAME - Bus name, 8 characters, must be enclosed in quotes
 BASKV - Base voltage, KV
 ZONE - Loss zone, 1-999

Generator Data
==============

Generator data records, terminated by a generator with an index of
zero.

I,ID,PG,QG,QT,QB,VS,IREG,MBASE,ZR,ZX,RT,XT,GTAP,STAT,RMPCT,PT,PB

I - Bus number
ID - Machine identifier (0-9, A-Z)
PG - MW output
QG - MVAR output
QT - Max MVAR
QB - Min MVAR
VS - Voltage setpoint
IREG - Remote controlled bus index (must be type 1), zero to control
own
 voltage, and must be zero for gen at swing bus
MBASE - Total MVA base of this machine (or machines), defaults to
system
 MVA base.
ZR,ZX - Machine impedance, pu on MBASE
RT,XT - Step up transformer impedance, p.u. on MBASE
GTAP - Step up transformer off nominal turns ratio
STAT - Machine status, 1 in service, 0 out of service
RMPCT - Percent of total VARS required to hold voltage at bus IREG
 to come from bus I - for remote buses controlled by several
generators
PT - Max MW
PB - Min MW

Branch Data
===========

Branch records, ending with a record with from bus of zero

I,J,CKT,R,X,B,RATEA,RATEB,RATEC,RATIO,ANGLE,GI,BI,GJ,BJ,ST

I - From bus number
J - To bus number
```

```
CKT - Circuit identifier (two character) not clear if integer or alpha
R - Resistance, per unit
X - Reactance, per unit
B - Total line charging, per unit
RATEA - MVA rating A
RATEB, RATEC - Higher MVA ratings
RATIO - Transformer off nominal turns ratio
ANGLE - Transformer phase shift angle
GI,BI - Line shunt complex admittance for shunt at from end (I) bus,
pu.
GJ,BJ - Line shunt complex admittance for shunt at to end (J) bus, pu.
ST - Initial branch status, 1 - in service, 0 - out of service

Transformer Adjustment Data
===========================

Ends with record with from bus of zero

I,J,CKT,ICONT,RMA,RMI,VMA,VMI,STEP,TABLE

I - From bus number
J - To bus number
CKT - Circuit number
ICONT - Number of bus to control. If different from I or J, sign of
ICONT
 determines control. Positive sign, close to impedance (untapped) bus
 of transformer. Negative sign, opposite.
RMA - Upper limit of turns ratio or phase shift
RMI - Lower limit of turns ratio or phase shift
VMA - Upper limit of controlled volts, MW or MVAR
VMI - Lower limit of controlled volts, MW or MVAR
STEP - Turns ratio step increment
TABLE - Zero, or number of a transformer impedance correction table 1-
5

Area Interchange Data
=====================

Ends with I of zero

I,ISW,PDES,PTOL,'ARNAM'

I - Area number (1-100)
ISW - Area interchange slack bus number
```

```
PDES - Desired net interchange, MW + = out.
PTOL - Area interchange tolerance, MW
ARNAM - Area name, 8 characters, enclosed in single quotes.

DC Line Data
============

Ends with I of zero

Each DC line has three consecutive records

I,MDC,RDC,SETVL,VSCHD,VCMOD,RCOMP,DELTI,METER
IPR,NBR,ALFMAX,ALFMN,RCR,XCR,EBASR,TRR,TAPR,TPMXR,TPMNR,TSTPR
IPI,NBI,GAMMX,GAMMN,RCI,XCI,EBASI,TRI,TAPI,TPMXI,TPMNI,TSTPI

I - DC Line number
MDC - Control mode 0 - blocked 1 - power 2 - current
RDC - Resistance, ohms
SETVL - Current or power demand
VSCHD - Scheduled compunded DC voltage, KV
VCMOD - Mode switch DC voltage, KV, switch to current control mode below this
RCOMP - Compounding resistance, ohms
DELTI - Current margin, per unit of desired current
METER - Metered end code, R - rectifier I - Inverter
IPR - Rectifier converter bus number
NBR - Number of birdges is series rectifier
ALFMAX - Maximum rectifier firing angle, degrees
ALFMN - Minimum rectifier firing angle, degrees
RCR - Rectifier commutating transformer resistance, per bridge, ohms
XCR - Rectifier commutating transformer reactance, per bridge, ohms
EBASR - Rectifier primary base AC volts, KV
TRR - Rectifier transformer ratio
TAPR - Rectifier tap setting
TPMXR - Maximum rectifier tap setting
TPMNR - Minimum rectifier tap setting
TSTPR - Rectifier tap step

Third record contains inverter quantities corresponding to rectifier quantities above.

Switch Shunt Data
=================
```

```
Ends with I = 0.

I,MODSW,VSWHI,VSWLO,SWREM,BINIT,N1,B1,N2,B2...N8,B8

I - Bus number
MODSW - Mode 0 - fixed 1 - discrete 2 - continuous
VSWHI - Desired voltage upper limit, per unit
VSWLO - Desired voltage lower limit, per unit
SWREM - Number of remote bus to control. 0 to control own bus.
VDES - Desired voltage setpoint, per unit
BINIT - Initial switched shunt admittance, MVAR at 1.0 per unit volts
N1 - Number of steps for block 1, first 0 is end of blocks
B1 - Admittance increment of block 1 in MVAR at 1.0 per unit volts.
N2, B2, etc, as N1, B1
```

4.3 .xml file

The.xml is the GridPACK configuration that controls the input for the EMT simulation. The main elements of this xml file are detailed below. Note, the file has some other elements for controlling other features but we will only focus on those that are needed for EMT.

- Setting the raw file: The network raw file is set with the tag <networkConfiguration>. In the input_2bus.xml file the network file is set to <networkConfiguration> case2mod.raw </networkConfiguration>. Recall case2mod.raw is the file we copied. GridPACK supports various version of PTI raw data files including v23, v33, v34, v35. <networkConfiguration> tag assumes the file format is v23. If you have files in other versions then add an _vXX to the tag where XX is the version number. For e.g., to read a v34 file use <networkConfiguration_v34> tag.

- Setting the dyr file: The dyr file is set with the tag <generatorParameters>. In the input_2bus.xml file the dyr file is set to <generatorParameters> case2.dyr </generatorParameters>

- Setting the simulation time and timestep: The simulation time and time-step is set with the tags <simulationTime> and timeStep, respectively.

- Scenarios/Disturbances/Events: GridPACK currently supports two different types of disturbances. These events need to be within the <Events> tag.

- Output monitoring: The output from EMT simulation can be saved to output csv file. GridPACK currently supports saving a subset of generator output (generator terminal voltage, generator real power, angle,and per unit speed)

4.4 .petscrc file

The only parameter that was used in this case is:

-emt_ts_type: it describes the type of numerical method used for the calculation (bdf, beuler…)

To execute GridPack-EMT you type: emt.x case.xml

Emt.x is the executable name and case.xml is the configuration file for the case to be calculated.

5. GRIDPACK_EMT VS GRIDPACK

- **GridPACK**

GridPACK (Grid Parallel Advanced Computational Kernels) is an open-source framework specifically designed to facilitate the development of high-performance computing applications for simulating power grids. This tool provides a set of modules aimed to simplify the complex task of modeling power grid systems and executing simulations of parallel computing platforms.

Key Features:

- Parallel Computing: The framework is designed for high-performance computing environments It handles many of the challenges of parallel processing, such as data distribution and communication between processors.
- Modular Design: It is made up of different modules, each of them are designed to handle specific tasks needed for power grid simulations. These modules can be used together as a library to develop applications, making sure that various parts of the simulation process are well-structured and simple to manage.
- Comprehensive Functionalities: GridPack includes comprehensive functionalities for power grid simulations, including tools for setting up and distributing power grid networks across multiple processors, modeling the behavior of network components such as buses and branches, and converting these models into algebraic equations for solving. This system includes libraries for parallel matrix and vector operations, linear and non-linear solvers, and preconditioners.

- Focus on Physics: GridPack allows developers to concentrate on the physical modeling of the power grid without needing to manage the low-level details of parallel data handling and communication.

- Ease of maintenance: The modular design of the system facilitates easier maintenance and updates. Developers can adjust or improve individual components without affecting the whole system.

- Integration with existing tools: It can interface with other software tools and libraries commonly used in power grid analysis, which increases its versatility.

- Community and Support: Being an open-source project, GridPack benefits from community contributions and support, providing a collaborative environment, which allows continuous improvements and innovations.

Use Cases:

- Power flow studies: GridPACK analyzes a variety of operational scenarios, such as peak load conditions and system contingencies, through its high-performance parallel computing capabilities, which makes it exceptional in conducting comprehensive power flow studies. Precise predictions of power flows and system behavior are guaranteed by its capacity to model large and complex grids with high resolution. GridPACK is a useful tool for optimizing and managing grid performance, as integration with SCADA systems enhances real-time analysis and operational decision-making.

- Reliability assessment: GridPACK assists in-depth reliability assessments by calculating critical reliability metrics like SAIDI and SAIFI, as well as by modeling the risks associated with system outages and component failures. Through its scenario-based analysis capabilities, users are able to assess system reliability in a variety of circumstances, such as high demand periods or extreme weather. Effective plans to increase system resilience and to guarantee a reliable, continuous power supply are aided by this comprehensive approach.

- Large-scale grid simulations: GridPACK is designed for high-efficiency large-scale grid simulations; thanks to its strong parallel processing capabilities, it is capable of handling extensive networks with thousands of buses and branches. Enabling thorough testing of various grid configurations, operational strategies, and emergency responses, it optimizes simulation performance through sophisticated algorithms and effective data management. For conducting extensive simulations that support decision-making and strategic planning, this scalability and performance is ideal.

Overall, GridPack is a powerful tool that simplifies the development of high-performance power grid simulation applications, making it easier for researchers and engineers to focus on solving complex power grid problems while leveraging advanced parallel computing resources.

- **GridPACK-EMT**

GridPACK-EMT (Electromagnetic Transient) is an extension of GridPACK designed for electromagnetic transient simulations, focusing on short-term dynamic events. It provides accurate analyses essential for understanding and reducing the impact of transient phenomena in power systems.

Key Features:

- Transient Analysis: Simulates electromagnetic transients for faults and switching operations that produce rapid changes in voltage and currents. It uses time-domain methods to capture the detailed behavior of electrical components over very short time intervals.
- Detailed Modeling: High-fidelity modeling of power system components. Furthermore, it accurately represents nonlinear elements such as power electronics, protection relays etc.
- Integration with GridPACK: It takes advantage of GridPack's parallel computing infrastructure, which ensures efficient data distribution and high-performance simulations. It also maintains GridPack's modular architecture, allowing an ideal integration of EMT-specific modules with other power grid simulation tools.
- Simulation Accuracy: It offers high temporal resolution, allowing it to accurately capture the fast dynamics of electromagnetic transients. It accurately models events such as faults, clearing, and reclosing, as well as switching operations of breakers and switches, ensuring a detailed and reliable analysis.

Use Cases:

- Fault analysis: It simulates fault conditions, allowing an analysis of the impact on the power system, which helps in the design and coordination of protection systems. Moreover, it can assist in determining the location and severity of faults within the power network.
- Protection system testing: It tests and validates the performance of protection relays under different fault conditions. With this, it evaluates the effectiveness and response times of the protection in a system, ensuring the system reliability.

- Switching Transient Studies: It examines the impacts of breaker switching activities, such as closing and opening, to reduce switching spikes.

- Power electronics: It models the transient behavior of power electronic devices, such as converters and inverters. These simulations are crucial for understanding their behavior within the grid during switching operations and faults.

- Grid Integration: It analyzes how renewable energy sources, such as wind and solar inverters, respond to grid disturbances. It also models the transient behavior of high voltage direct current (HVDC) links and their control systems.

In summary, GridPACK is a broader framework for large-scale simulations, while GridPack-EMT specializes in capturing electromagnetic transients. It is a powerful tool for fault analysis, protection system testing, and studying switching transients, crucial for maintaining the reliability and stability of modern power systems. The choice of which one to use depends on the specific purpose of each simulation.

6. PSCAD VS GRIDPACK-EMT

PSCAD is a comprehensive simulation software used widely in the field of power systems. It allows engineers and researchers to build, simulate and analyze a wide range of power system models efficiently. This tool is notorious for its accuracy and versatility, making it a good choice in both academic and industrial settings. Its features and capabilities are as follows:

- Intuitive Interface: PSCAD offers user-friendly graphical interface that simplifies the process of creating and managing complex power system models. It has an intuitive design that allows the user to drag and drop components, and easily configure parameters.

- Comprehensive Library: The software includes an extensive library of pre-built system models. These models go from simple passive elements like resistors and capacitors to advanced components such as electric machines, transformers, and control systems. This library is continually updated and expanded based on user feedback and technological advancements.

- Accurate Simulation: PSCAD uses advanced numerical methods to ensure precise modeling of transient phenomena, making it ideal for studying dynamic behaviors and interactions in power systems.

- Versatility: The software supports a wide range of applications like power generation, transmission, distributions, etc. This makes it useful for a variety of projects, from small studies, to larger, complex power networks.
- Continous Development: PSCAD benefits from over 40 years of continuous research and development.
- Global User Base: PSCAD has an extensive global user base whose feedback helps in its development. This collaborative approach helps ensure that the software meets the evolving needs of its users and incorporates the latest industry trends and best practices.

Some of PSCAD applications are:

- Power System Design and Analysis: Engineers use PSCAD to design and analyze power systems, ensuring that they are efficient, reliable and capable of meeting demand.
- Research and Development: Research use PSCAD to explore new technologies, study system behaviors, and develop innovative solutions for power system challenges.
- Education and Training: PSCAD is used in an academic environment to teach students about power system dynamics, modeling and simulation techniques.

Both PSCAD and GridPack-EMT are tools for power system simulation. On the one hand, PSCAD is good in providing a user-friendly platform for a variety of power system simulations. It presents an intuitive graphical interface and a library of components, making it accessible and practical for users with different levels of expertise.

On the other hand, GridPack-EMT specializes in the detailed modeling of electromagnetic transients, making it ideal for high-frequency event analysis. This includes fast transients such as lightning strikes and switching events. However, GridPack-EMT requires a more technical interface compared to PSCAD, which can be challenging for new users. This needs a deeper understanding of electromagnetic transient phenomena and modeling, making it more suitable for advanced users and specific research applications.

In summary, PSCAD offers accessibility but may sacrifice performance for convenience, while GridPACK prioritizes parallel computing efficiency. The choice of which one to use depends on your specific requirements and expertise.

7. GRIDPACK_EMT VS PSCAD (EXAMPLE)

The simulation of the electrical circuit performed in GridPack EMT and PSCAD is presented below. The data necessary to perform the simulation in each program will be detailed. The simulated case is a 2-bus system with one generator and two branches, one of which is out of service.

7.1 GRIDPACK-EMT

The data of the electrical circuit to be simulated in GridPack-EMT as well as the information of the fault to be studied are detailed as follows. All the data was taken from GridPack files and are included at the end of this document in the Appendix B.

7.1.1 Electrical network

Table 1. Bus data

Bus Number	1	5
Type	3	1
Load MW	0	90
Load MVAR	0	0
Shunt Conductance	0	0
Shunt Susceptance	0	0
Area Number	1	1
Voltage Magnitude	1	0.97547
Voltage Angle	0	-4.01726
Name	bus-1	bus-5
Base Voltage	100	100
Zone	2	2

Table 2. Generator data

Bus Num	1
Machine Identifier	1
MW Output	71.9547
MVAR Output	24.0689
Max MVAR	53.4

Min MVAR	-20.4
Voltage Setpoint	1
MVA Base	100
Machine Impedance (ZR)	0.1
Machine Impedance (ZX)	1
Step-up Transformer Turns Ratio	1
Machine Status	1
Percent VARS	100

Table 3. Branch data

From Bus	1	1
To Bus	-5	-5
Circuit Identifier	A	B
Resistance (R)	1.00E-02	1.00E-02
Reactance (X)	0.0576	0.0576
Line Charging (B)	0.176	0.176
MVA Rating A	0	0
MVA Rating B	0	0
MVA Rating C	0	0
Transformer Turns Ratio	0	0
Transformer Phase Shift Angle	0	0
Line Shunt Admittance (From End)	0	0
Line Shunt Admittance (To End)	0	0
Branch Status	0	1

7.1.2 Fault Information

In the simulation, we introduce a fault scenario to analyze the system's response. The fault is a Three-Phase fault applied at bus 5 with the following specifications:

Table 4. Fault info

Fault Type	Fault Inception (s)	Fault Clearance (s)	Fault Bus	Fault Impedance (Ohms)	Ground Impedance (Ohms)
Three-Phase	0.5	0.51	5	0.001	0.01

These parameters replicate the conditions and scenarios as described in the XML file used by GridPACK-EMT. The objective is to observe the system's behavior during the fault and compare the simulation results with expected outcomes.

7.2 PSCAD

Thanks to the information from the GridPACK-EMT simulation and all the provided data, we were able to replicate the circuit in PSCAD and simulate the same fault. The following image shows the simulated circuit.

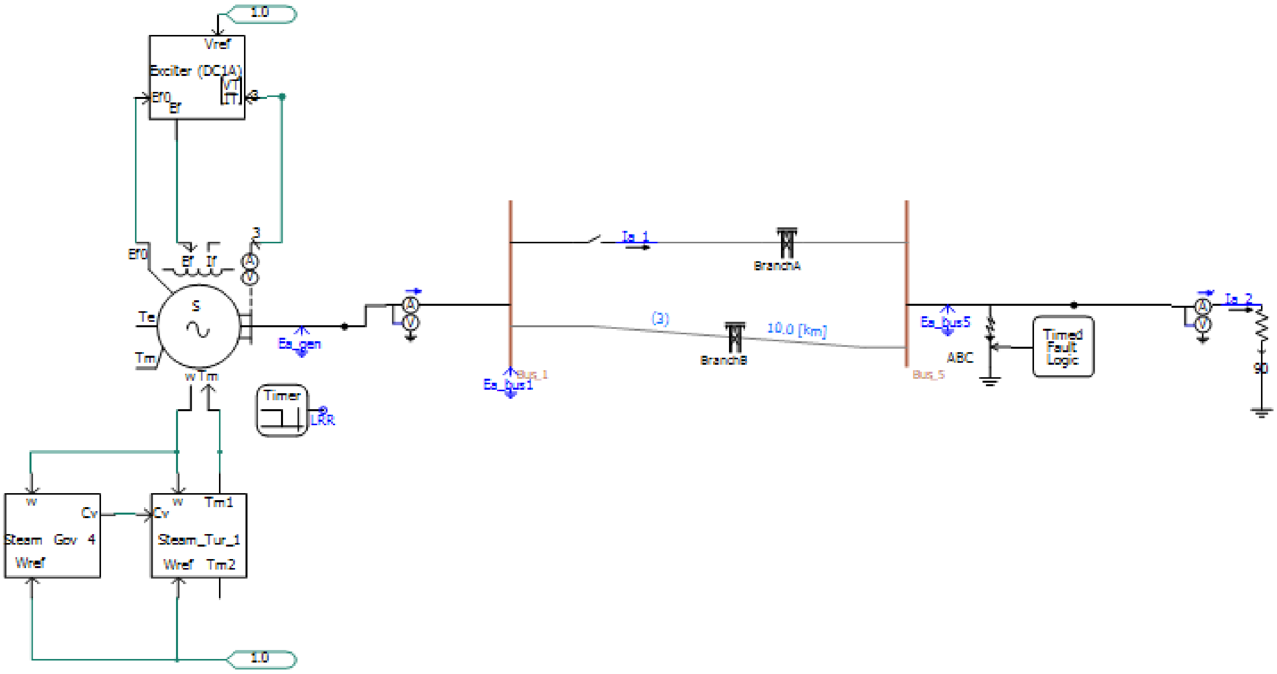
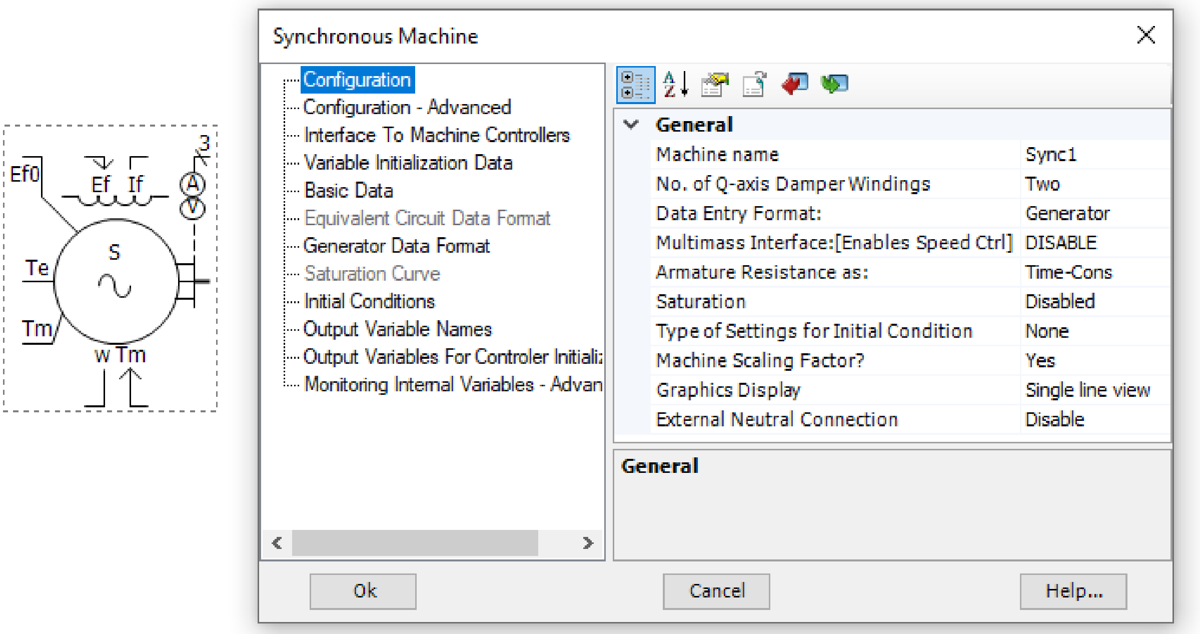


Figure 1. Electrical Network

The parameters used in the definition of the case are presented below.

7.2.1 Synchronous Machine

This component includes an option to model two damper windings in the Q-axis, making it suitable for use as either a round rotor machine or a salient pole machine. The speed of the machine can be controlled directly by inputting a positive value into the ω\omega (speed) input, or by applying a mechanical torque to the Tm (torque) input.



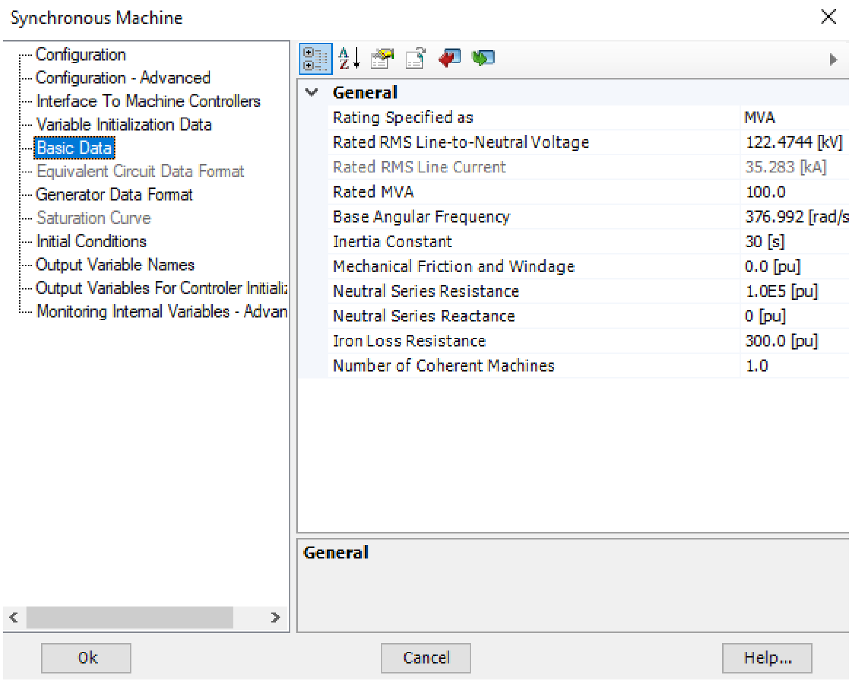
Configuration
Configuration - Advanced
Interface To Machine Controllers
Variable Initialization Data
Basic Data
Equivalent Circuit Data Format
Generator Data Format
Saturation Curve
Initial Conditions
Output Variable Names
Output Variables For Controler Initiali:
Monitoring Internal Variables - Advan

General

Machine name	Sync1
No. of Q-axis Damper Windings	Two
Data Entry Format:	Generator
Multimass Interface:[Enables Speed Ctrl]	DISABLE
Armature Resistance as:	Time-Cons
Saturation	Disabled
Type of Settings for Initial Condition	None
Machine Scaling Factor?	Yes
Graphics Display	Single line view
External Neutral Connection	Disable

General

Figure 2. Synchronous machine

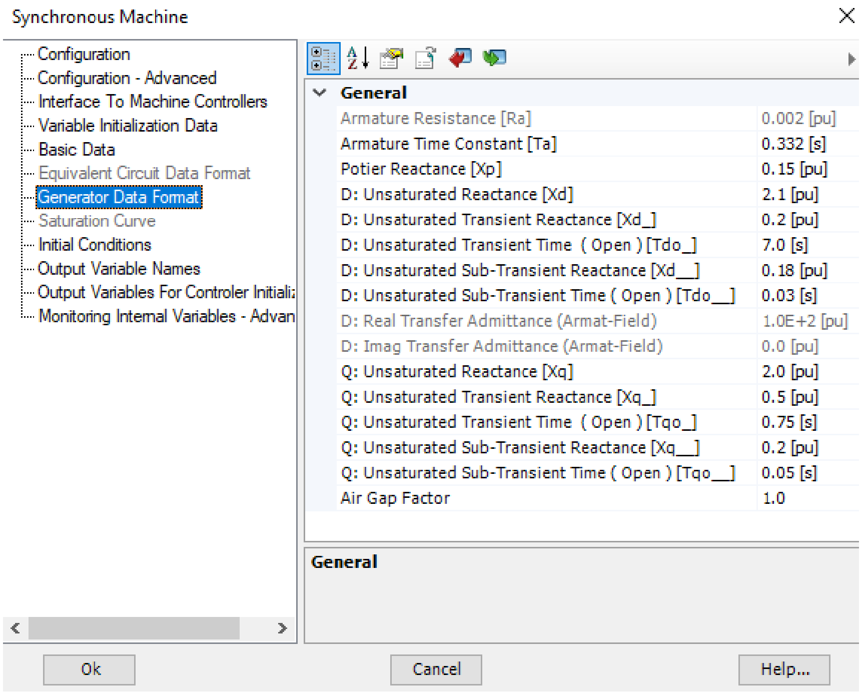


Configuration
Configuration - Advanced
Interface To Machine Controllers
Variable Initialization Data
Basic Data
Equivalent Circuit Data Format
Generator Data Format
Saturation Curve
Initial Conditions
Output Variable Names
Output Variables For Controler Initiali:
Monitoring Internal Variables - Advan

General

Rating Specified as	MVA
Rated RMS Line-to-Neutral Voltage	122.4744 [kV]
Rated RMS Line Current	35.283 [kA]
Rated MVA	100.0
Base Angular Frequency	376.992 [rad/s
Inertia Constant	30 [s]
Mechanical Friction and Windage	0.0 [pu]
Neutral Series Resistance	1.0E5 [pu]
Neutral Series Reactance	0 [pu]
Iron Loss Resistance	300.0 [pu]
Number of Coherent Machines	1.0

General



General

Armature Resistance [Ra]	0.002 [pu]
Armature Time Constant [Ta]	0.332 [s]
Potier Reactance [Xp]	0.15 [pu]
D: Unsaturated Reactance [Xd]	2.1 [pu]
D: Unsaturated Transient Reactance [Xd_]	0.2 [pu]
D: Unsaturated Transient Time (Open) [Tdo_]	7.0 [s]
D: Unsaturated Sub-Transient Reactance [Xd__]	0.18 [pu]
D: Unsaturated Sub-Transient Time (Open) [Tdo__]	0.03 [s]
D: Real Transfer Admittance (Armat-Field)	1.0E+2 [pu]
D: Imag Transfer Admittance (Armat-Field)	0.0 [pu]
Q: Unsaturated Reactance [Xq]	2.0 [pu]
Q: Unsaturated Transient Reactance [Xq_]	0.5 [pu]
Q: Unsaturated Transient Time (Open) [Tqo_]	0.75 [s]
Q: Unsaturated Sub-Transient Reactance [Xq__]	0.2 [pu]
Q: Unsaturated Sub-Transient Time (Open) [Tqo__]	0.05 [s]
Air Gap Factor	1.0

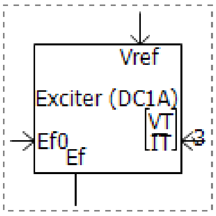
General

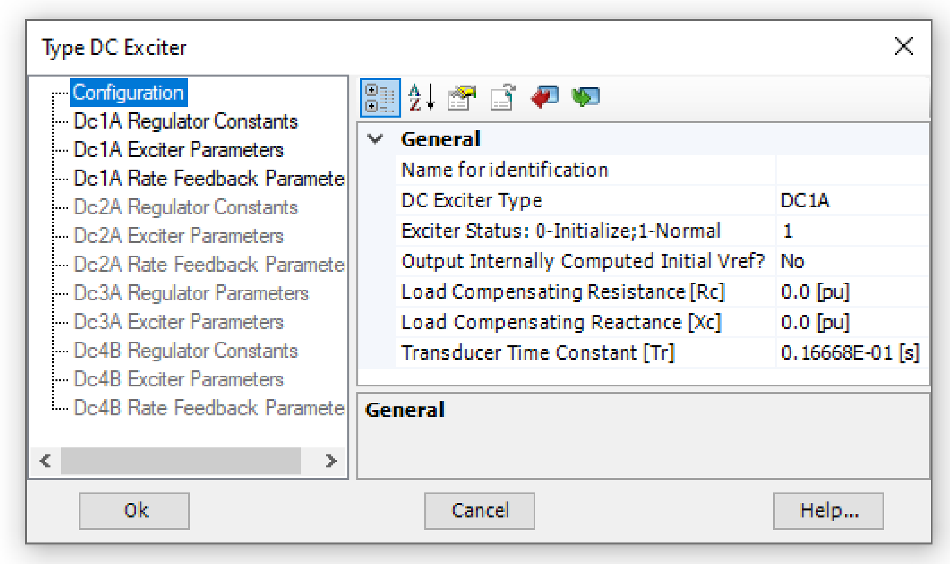
7.2.2 Exciter

This component models a standard IEEE type exciter with inputs in seconds (time constants) or per-unit (other inputs).

- **Inputs:**
    - **Ef0**: Initial field voltage, user-defined or from the synchronous machine.
    - **[VT/IT]**: Terminal voltage (VT) and complex current (IT) from the synchronous machine.
    - **VS**: For power system stabilizer (not for DC3A).
    - **Vref**: Voltage reference for the machine.
- **Outputs:**
    - **Ef:** Field voltage to the synchronous machine.

- **Vref0:** Initialized reference voltage.



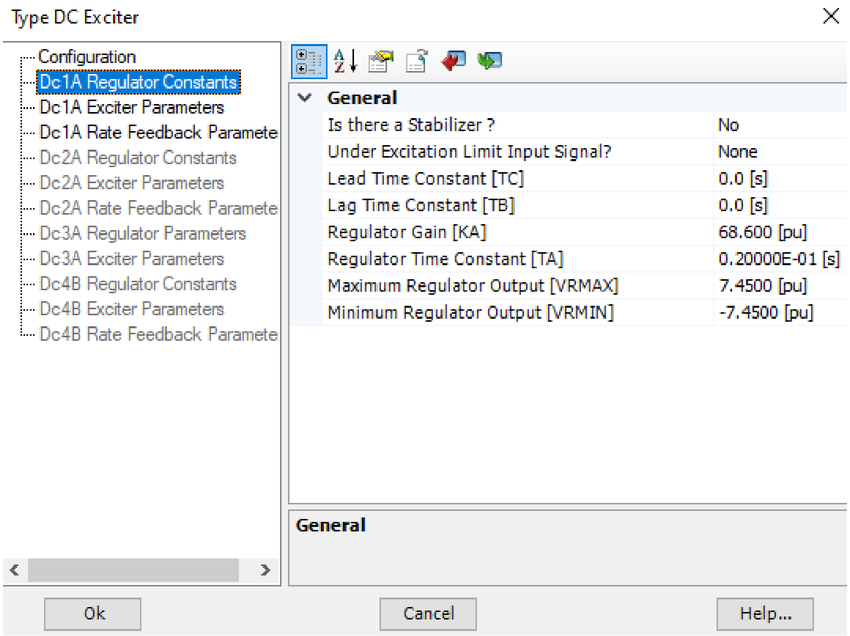


General

Name for identification	
DC Exciter Type	DC1A
Exciter Status: 0-Initialize;1-Normal	1
Output Internally Computed Initial Vref?	No
Load Compensating Resistance [Rc]	0.0 [pu]
Load Compensating Reactance [Xc]	0.0 [pu]
Transducer Time Constant [Tr]	0.16668E-01 [s]

General

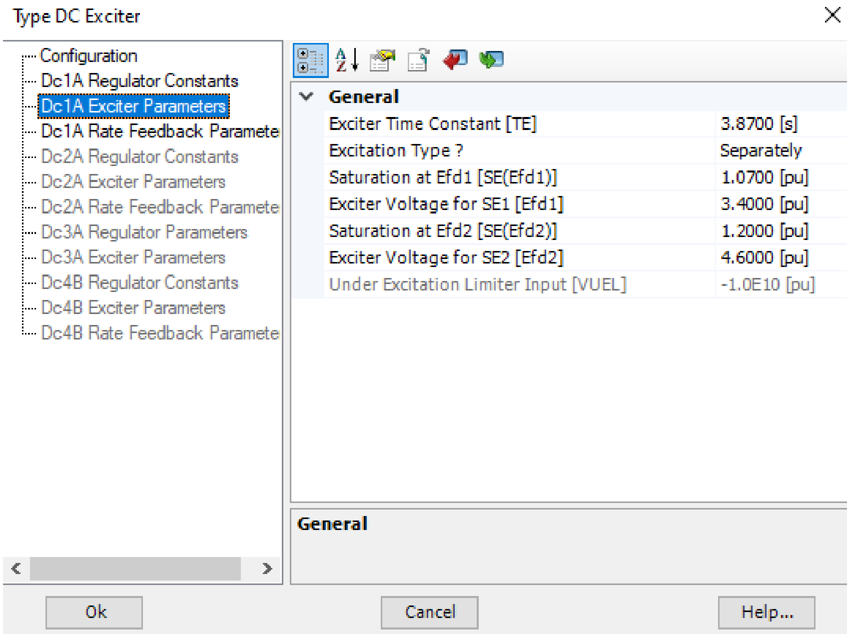
Figure 3. Exciter DC



General

Is there a Stabilizer ?	No
Under Excitation Limit Input Signal?	None
Lead Time Constant [TC]	0.0 [s]
Lag Time Constant [TB]	0.0 [s]
Regulator Gain [KA]	68.600 [pu]
Regulator Time Constant [TA]	0.20000E-01 [s]
Maximum Regulator Output [VRMAX]	7.4500 [pu]
Minimum Regulator Output [VRMIN]	-7.4500 [pu]

General



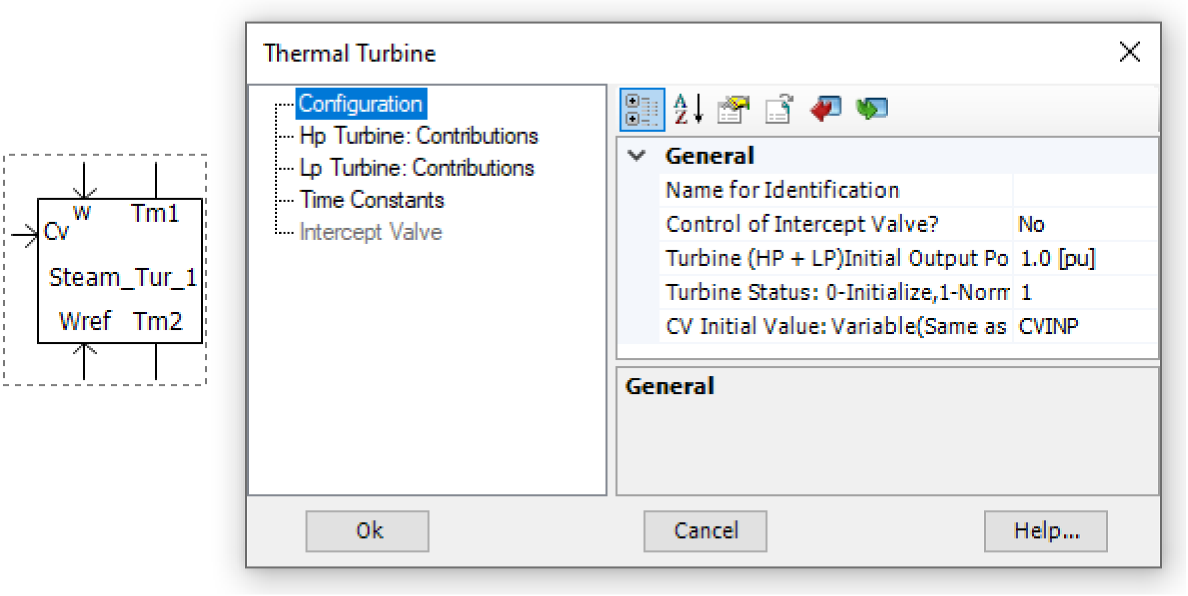
General	
Exciter Time Constant [TE]	3.8700 [s]
Excitation Type ?	Separately
Saturation at Efd1 [SE(Efd1)]	1.0700 [pu]
Exciter Voltage for SE1 [Efd1]	3.4000 [pu]
Saturation at Efd2 [SE(Efd2)]	1.2000 [pu]
Exciter Voltage for SE2 [Efd2]	4.6000 [pu]
Under Excitation Limiter Input [VUEL]	-1.0E10 [pu]

7.2.3 Turbine

This component models an IEEE type thermal turbine.

- **Inputs:**
  - **w**: Per-unit speed.
  - **Wref**: Per-unit speed reference.
  - **Cv**: Per-unit control valve position.
  - **Iv**: Per-unit intercept valve position from the thermal (steam) governor.
- **Outputs:**
  - **Tm1**: Mechanical torque from the HP turbine.

- **Tm2**: Mechanical torque from the LP turbine.



General

Name for Identification	
Control of Intercept Valve?	No
Turbine (HP + LP)Initial Output Po	1.0 [pu]
Turbine Status: 0-Initialize,1-Norm	1
CV Initial Value: Variable(Same as	CVINP

General

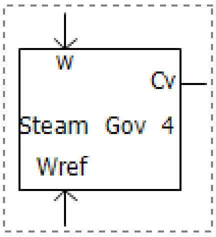
Figure 4. Steam turbine

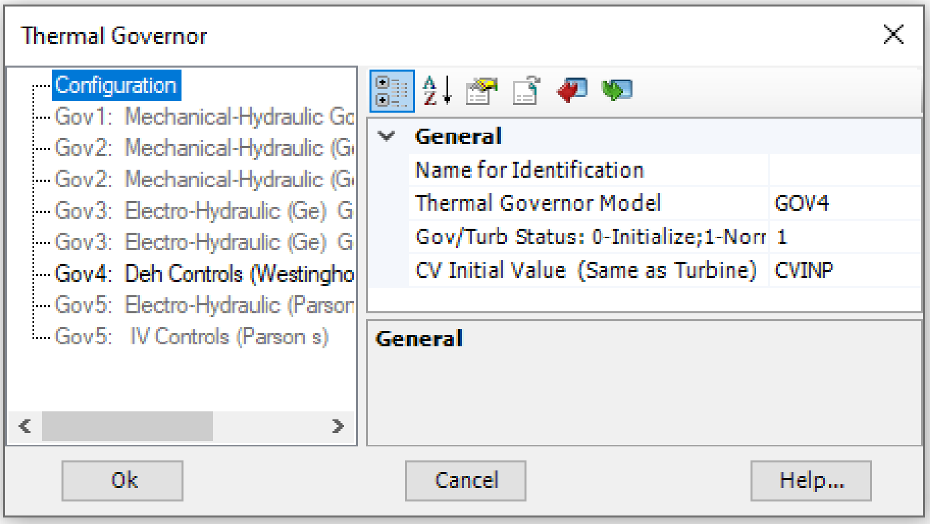
7.2.4 Governor

This model includes the following parameters:

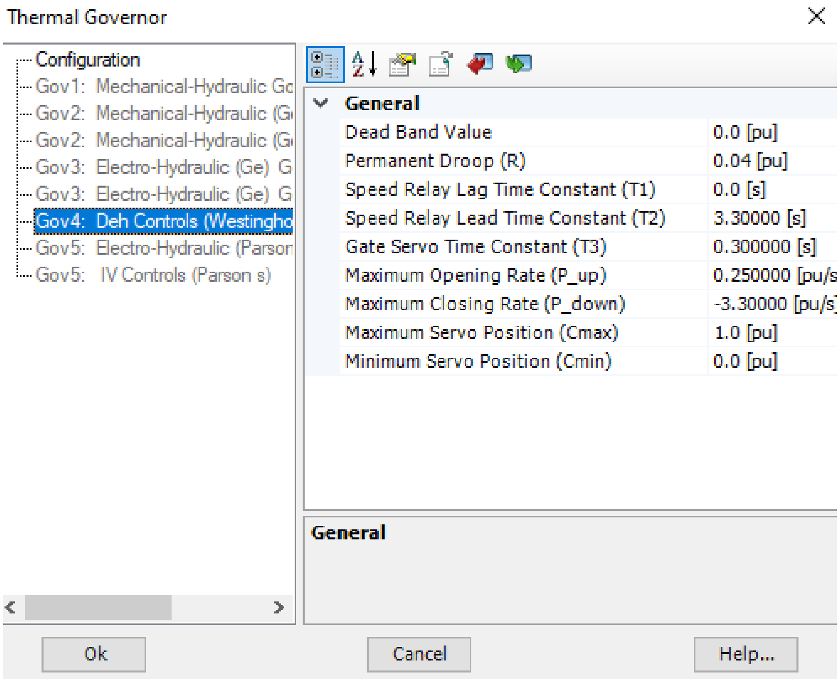
- Control Valve Flow Area [pu]
- Initial Control Valve Flow Area [pu]
- Permanent Droop [pu]
- Speed Relay Lag Time Constant [s]
- Speed Relay Lead Time Constant [s]
- Gate Servo Time Constant [s]

Note: Only normal speed controls are modeled; over-speed controls are not included.





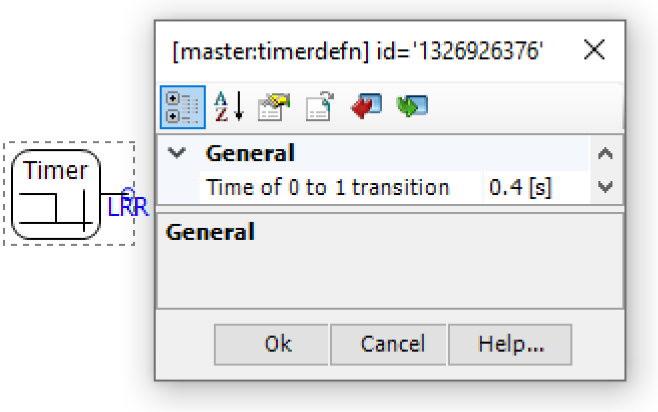
General	
Name for Identification	
Thermal Governor Model	GOV4
Gov/Turb Status: 0-Initialize;1-Norr	1
CV Initial Value (Same as Turbine)	CVINP



General	
Dead Band Value	0.0 [pu]
Permanent Droop (R)	0.04 [pu]
Speed Relay Lag Time Constant (T1)	0.0 [s]
Speed Relay Lead Time Constant (T2)	3.30000 [s]
Gate Servo Time Constant (T3)	0.300000 [s]
Maximum Opening Rate (P_up)	0.250000 [pu/s
Maximum Closing Rate (P_down)	-3.30000 [pu/s]
Maximum Servo Position (Cmax)	1.0 [pu]
Minimum Servo Position (Cmin)	0.0 [pu]

7.2.5 Timer

We used a timer that changes its output from 0 to 1 after 0.4 seconds. This transition switches the synchronous machine from speed control to torque control.



[master:timerdefn] id='1326926376'

General

Time of 0 to 1 transition 0.4 [s]

General

Figure 5. Timer

7.2.6 Branches

There are two branches in the model, but Branch A is out of service or has an open switch. The model has been implemented according to the data provided by Gridpack EMT.

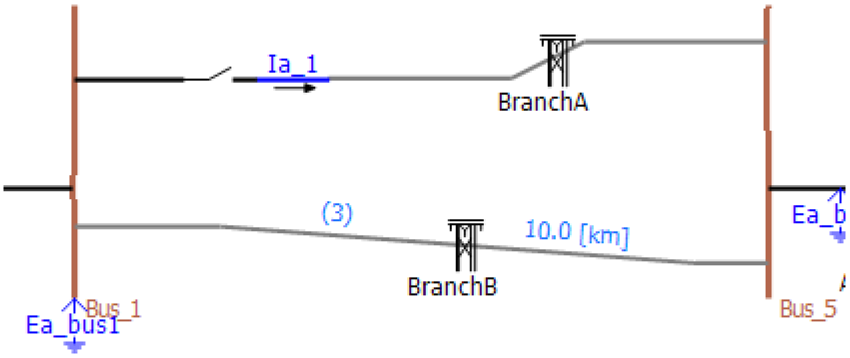
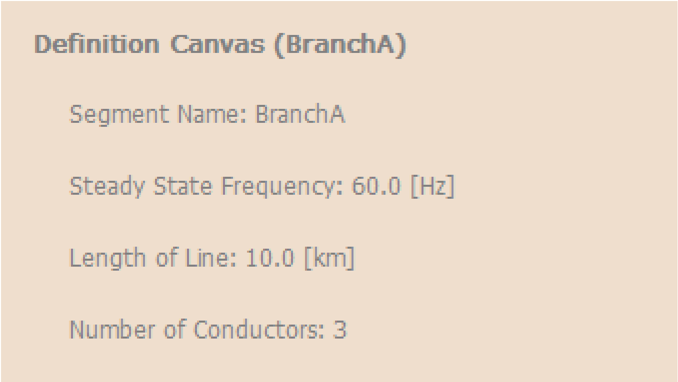


Figure 6. Branches



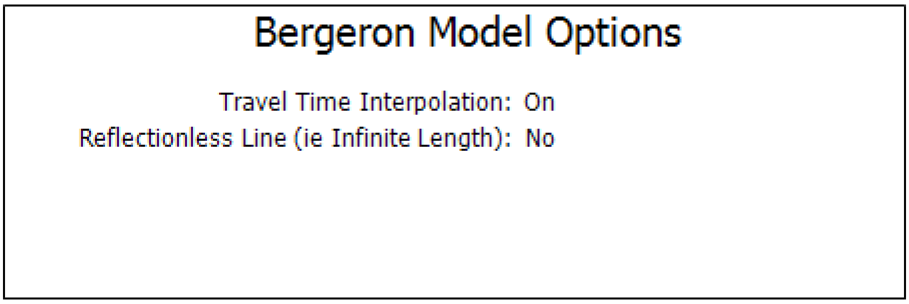
Definition Canvas (BranchA)

Segment Name: BranchA

Steady State Frequency: 60.0 [Hz]

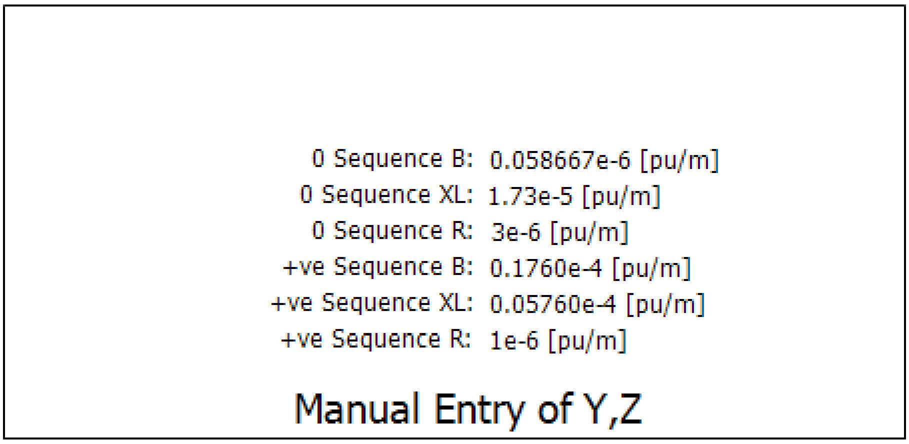
Length of Line: 10.0 [km]

Number of Conductors: 3



Bergeron Model Options

Travel Time Interpolation: On
Reflectionless Line (ie Infinite Length): No

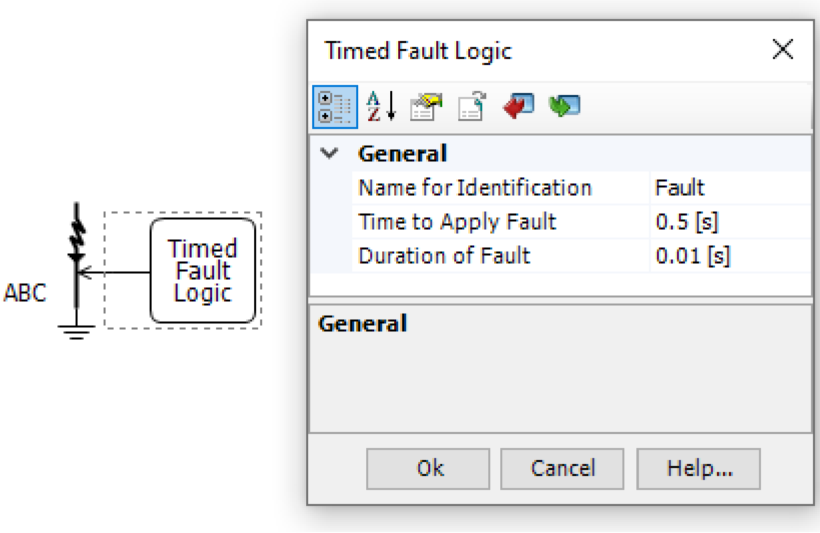


0 Sequence B: 0.058667e-6 [pu/m]
0 Sequence XL: 1.73e-5 [pu/m]
0 Sequence R: 3e-6 [pu/m]
+ve Sequence B: 0.1760e-4 [pu/m]
+ve Sequence XL: 0.05760e-4 [pu/m]
+ve Sequence R: 1e-6 [pu/m]

Manual Entry of Y,Z

7.2.7 Fault

A three-phase fault has been introduced at 0.5 seconds with a duration of 0.01 seconds.



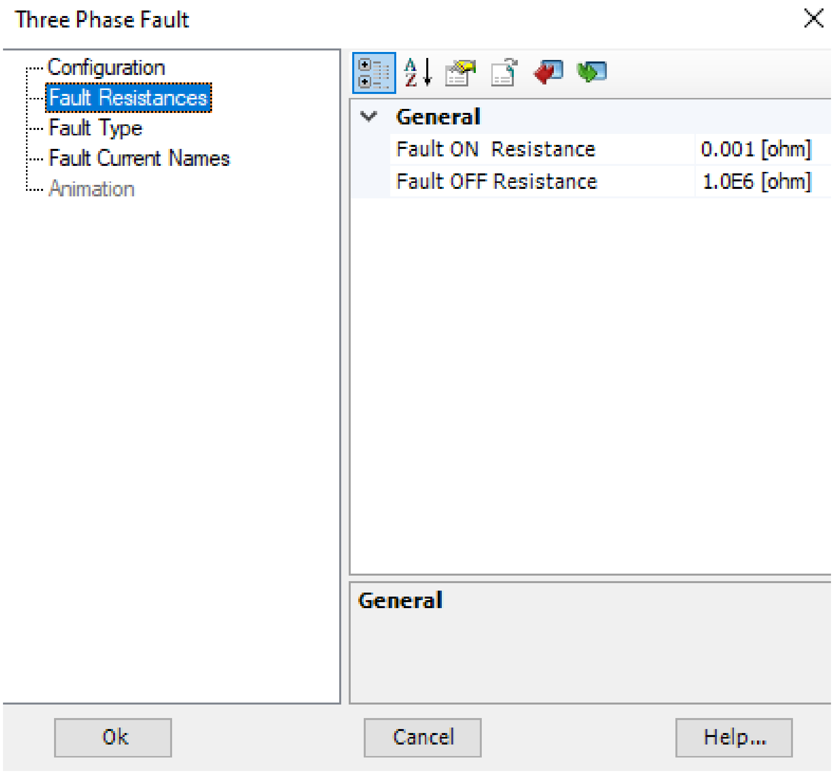
Timed Fault Logic

General

Name for Identification	Fault
Time to Apply Fault	0.5 [s]
Duration of Fault	0.01 [s]

General

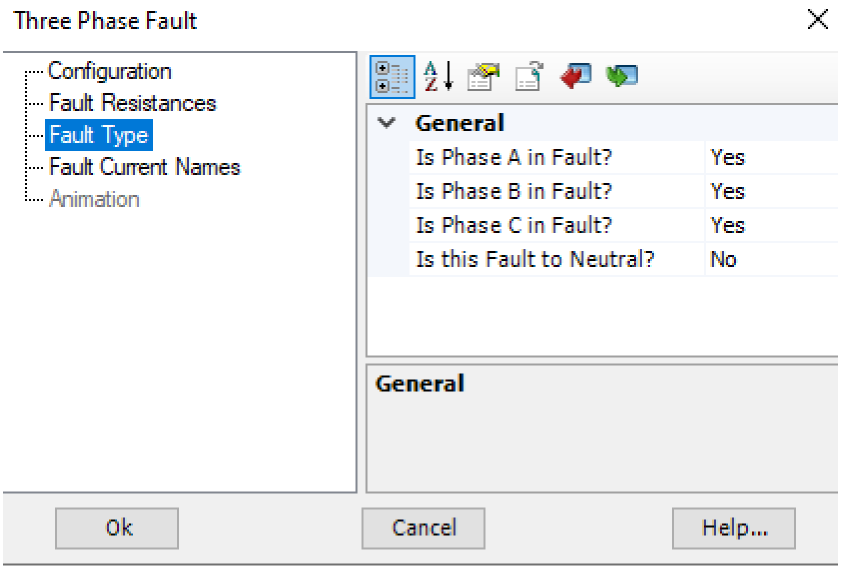
Figure 7. Timed Fault Logic


Three Phase Fault

General

Fault ON Resistance	0.001 [ohm]
Fault OFF Resistance	1.0E6 [ohm]

General



General

Is Phase A in Fault?	Yes
Is Phase B in Fault?	Yes
Is Phase C in Fault?	Yes
Is this Fault to Neutral?	No

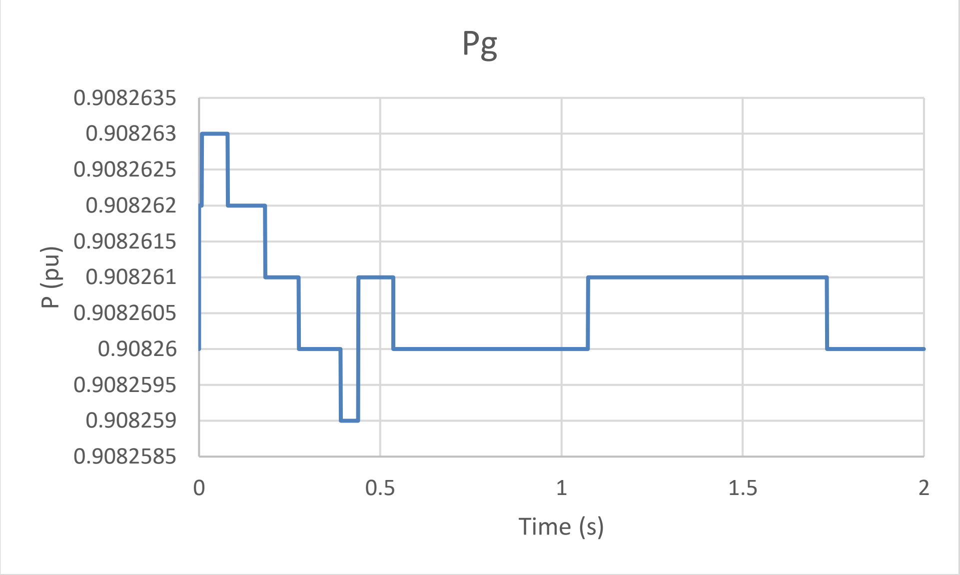
General

Figure 8. Three Phase Fault

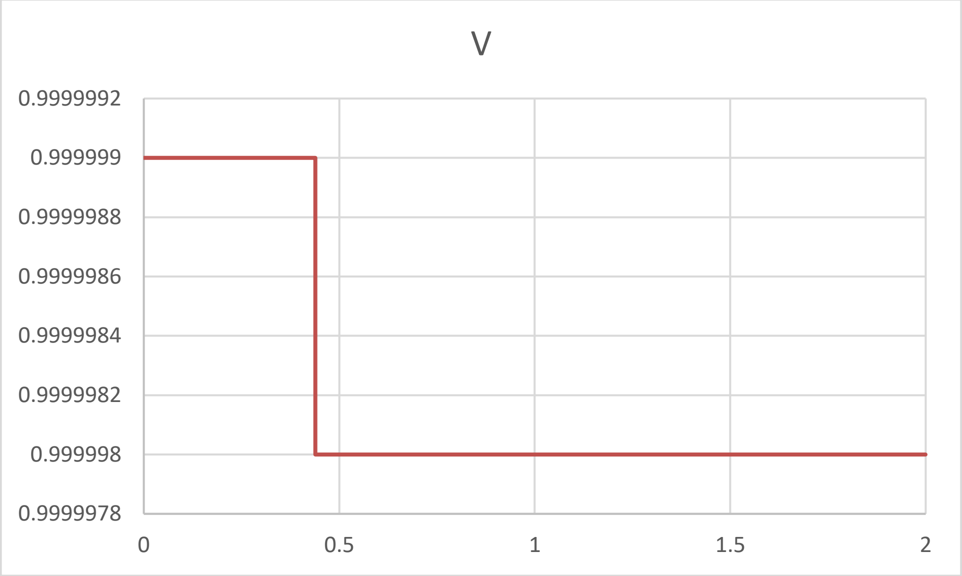
8. RESULTS

8.1 GridPack

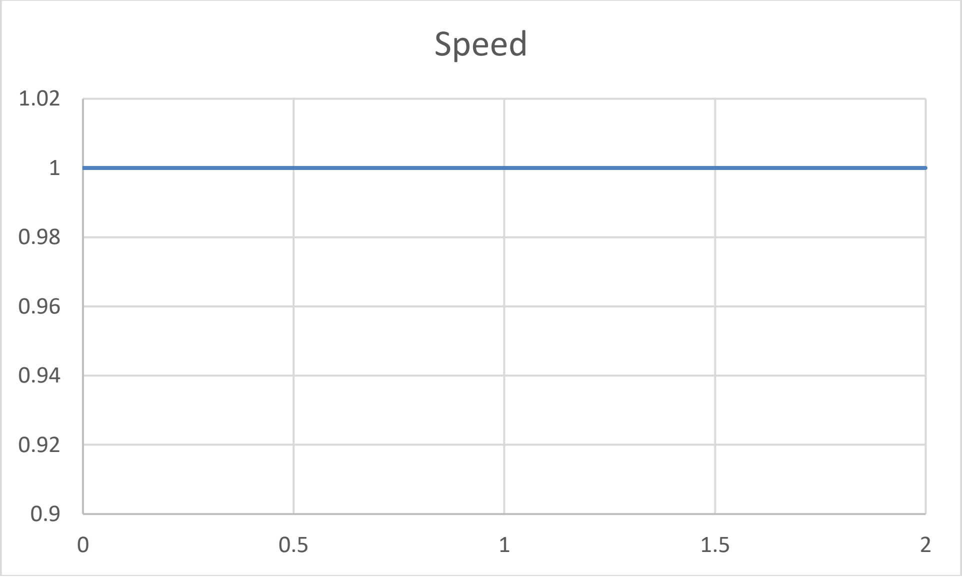
The following graphs were obtained using GridPack and simulating the case obtained from the GridPack files.



Graph 1. Power in the Generator



Graph 2. Voltage in the Generator



Graph 3. Speed

The results obtained lead us to believe that there are some problems with the numerical method used. My tutor advised me to modify the XML configuraton file.

The steps I followed were the following:

1. Copying the example XML file

When logging into the Linux server, I navigated to the working directory where GridPack was installed using the command:

```
cp /opt/GridPACK/src/install/share/gridpack/example/dynamic_simulation_full_y/input_9b3g.xml .
```

I copied the example XML file into my working directory to allow me to work directly woth the required input format.

2. Editing the XML file

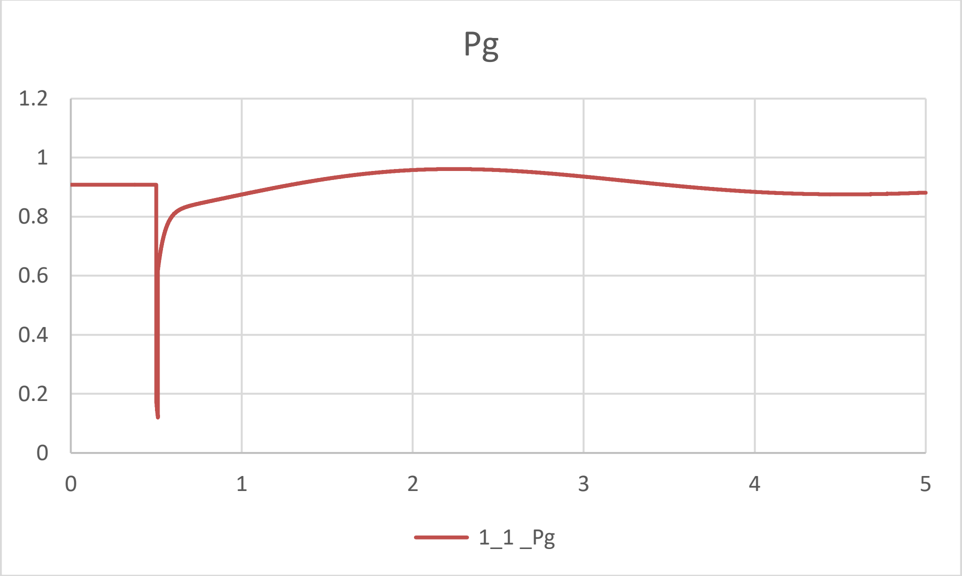
The next step was to modify the fault branch. Initially the branch was set to

```
<faultBranch>6 7</faultBranch>
```

However, for it to be consistent with the GridPack-EMT simulation we want to compare it to, the fault needed to be placed at bus 5.

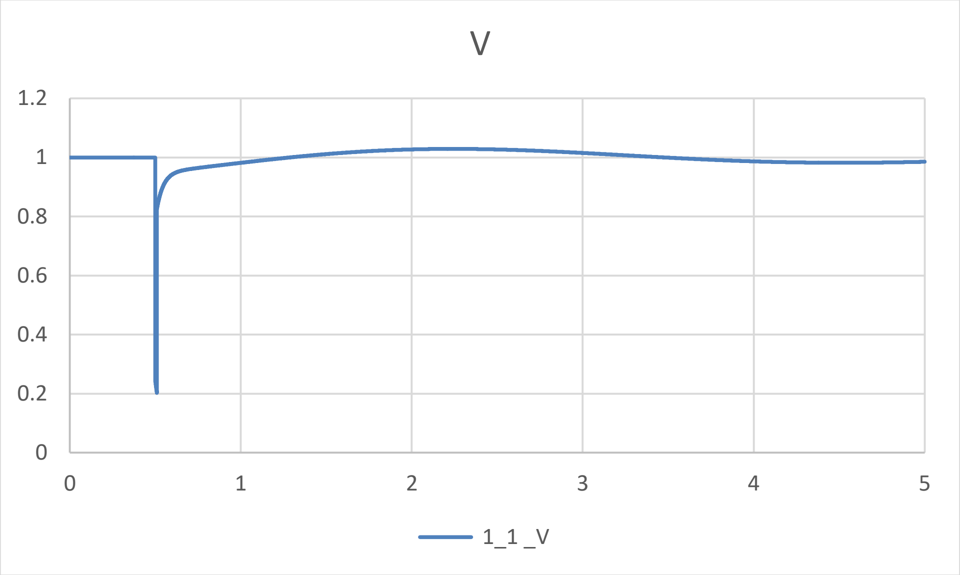
```
<faultBranch>5 1</faultBranch>
```

3. After making the correction the simulation was rerun. The results obtained were significantly improved.

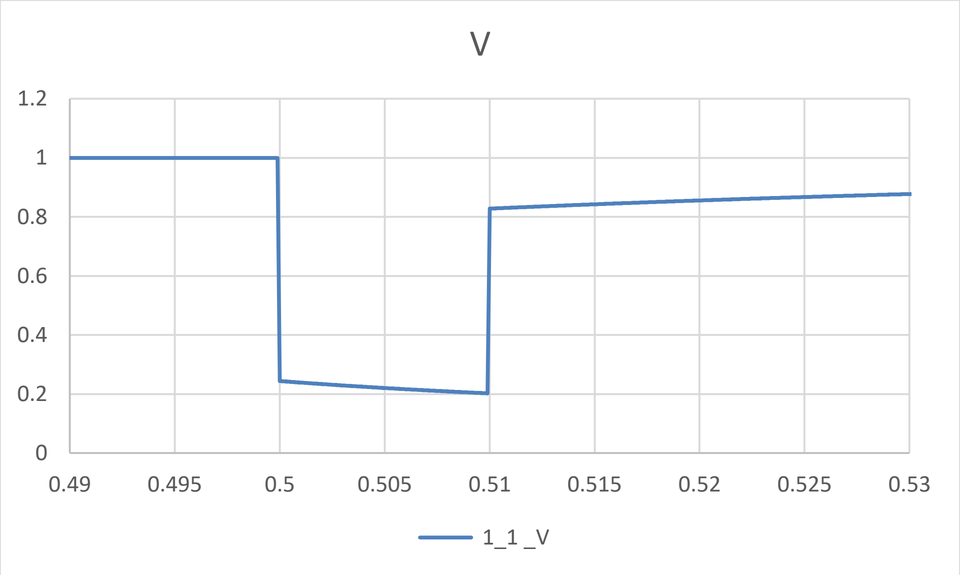


Graph 4. Power in Generator

In this graph the active power generated (Pg) is represented. It starts bellow 1 pu and drops significantly during the fault. After the disturbance, Pg gradually increases and stabilizes. This is typical behaviour of a generator responding to a disturbance where the power generations temporarily drops and then recovers and stabilizes meeting the system load.

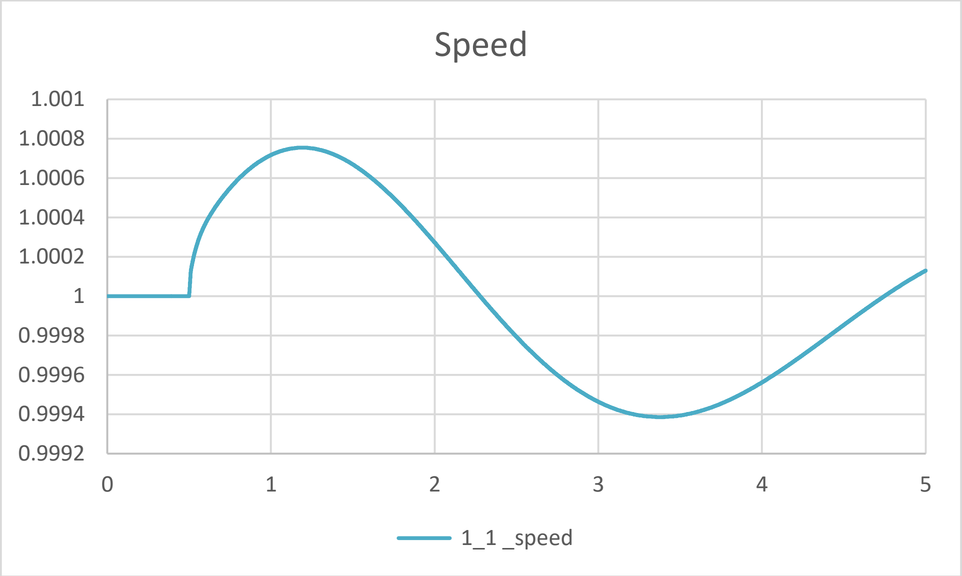


Graph 5. Voltage in Generator



Graph 6. Voltage in the Generator

In this graph the voltage in the generator is represented (in pu). The system starts with a stable voltage of 1 pu and drops drastically when the fault occurs at 0.5 s. Then it rapidly stabilizes at 1 pu again.



Graph 7. Speed

This third curve represents the speed of the generator. We can observe a change when the fault occurs. However the oscillations are minimal and the system recovers quickly.

8.2 GridPack-EMT

In the 4 cases that have been analyzed, the input files that have been used were taken from the GridPack documentation [6]. In each of them a modification has been made, the type of calculation, or the time step, in order to be able to compare them and analyze the impact of each one. The three different calculation methods used in the GridPack.EMT simulations are: Backward Difference Formula (BDF), Crank-Nicolson (CN) and Backward Euler (BEULER). After the simulation GridPack generates a .csv file than is later processed with excel to obtain the graphs.

Table 5. Calculation Methods

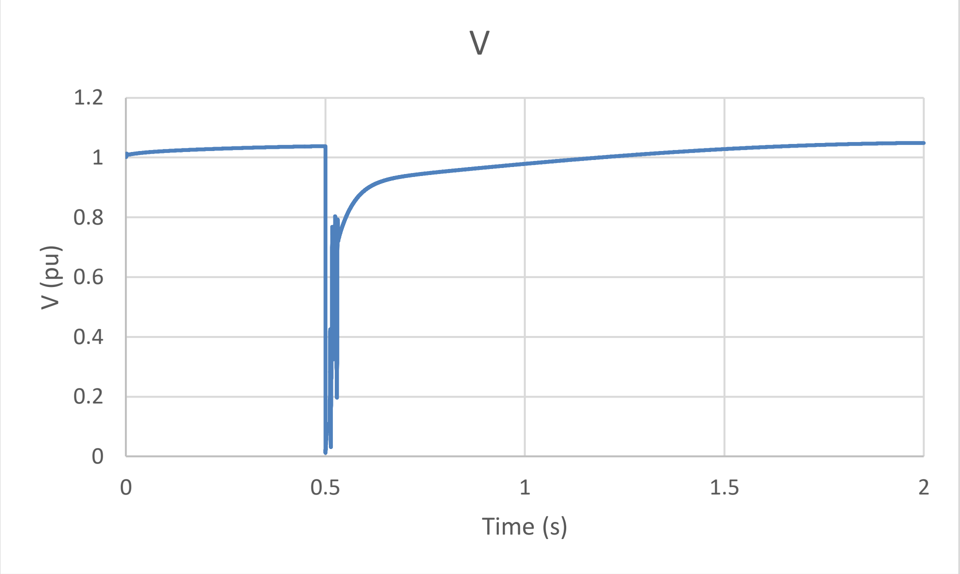
Method	Description	Order	Stability	Usage
BDF	Implicit, linear multistep method for stiff ODEs. Uses several previous time steps.	Varies (can be high)	Strong stability, suitable for large time steps.	Best for stiff systems with fast and slow dynamics

Method	Description	Order	Stability	Usage
CN	Second-order implicit method, averages solution between current and next time step.	Second-order	Unconditionally stable for linear problems, may introduce oscillations in non-linear cases.	Used for problems needing both accuracy and stability (e.g., wave propagation, heat conduction).
BEULER	Simplest implicit method, uses only the current time step for the derivative.	First-order	Unconditionally stable, may introduce numerical damping.	Used when stability is more critical than accuracy, especially in stiff systems.

8.2.1 Case 1: Backward Differences Formula (BDF)

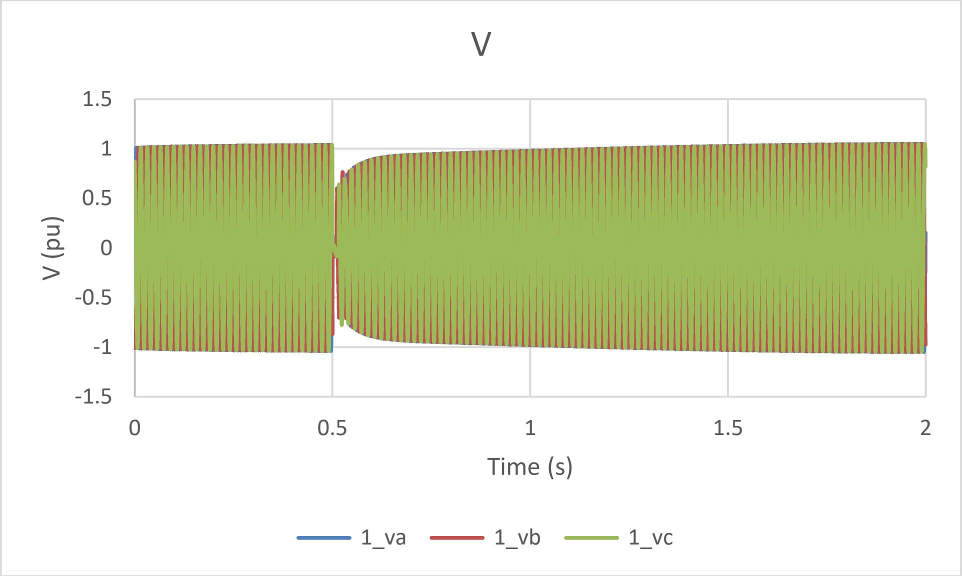
In case 1 of the simulations, the input_2bus.xml base file, is used. The Backward Difference Formula (BDF) as the calculation method is selected by default for this configuration. The time used in this calculation was 1min and 3.95 seconds.

The generator's voltage is shown on this initial graph. The impact of the fault is evident at 0.5 seconds and continues until 0.51 seconds. The voltage stabilizes once again following the fault.



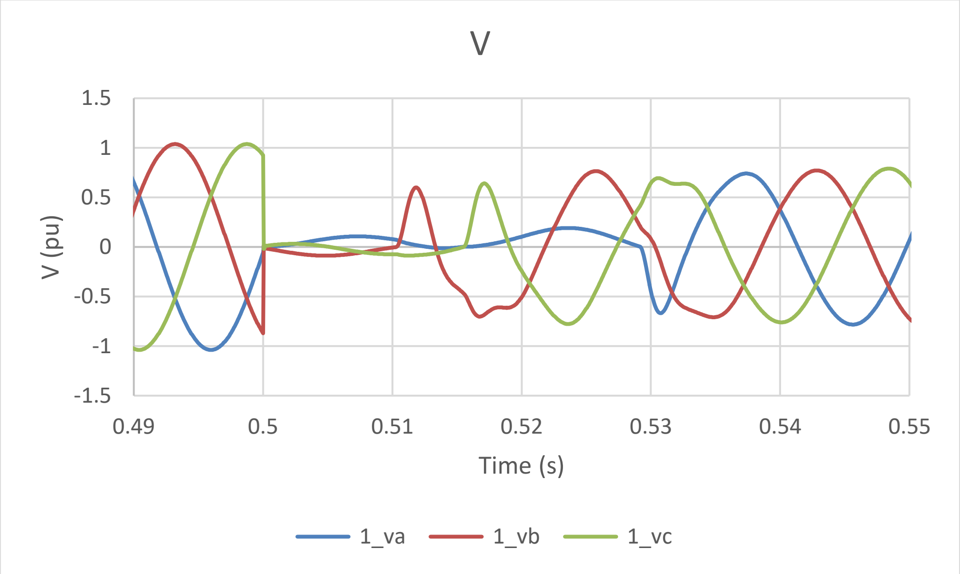
Graph 8. Voltage in the Generator (EMT bdf)

The voltages at the bus's three phases (1_va, 1_vb, 1_vc) are shown in the second graph. A significant disturbance in all three phases and a sharp drop in voltage during the fault interval are signs that the fault has occurred.



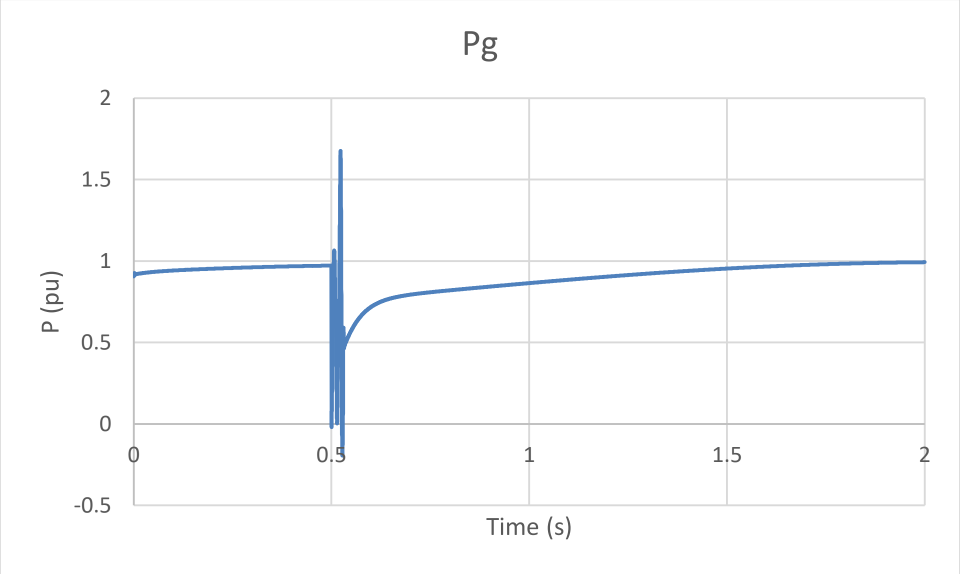
Graph 9. Voltage in 3 phases (EMT bdf)

The bus voltage during the fault is shown in detail on the third graph. During the fault's initiation at 0.5 seconds and its resolution by 0.51 seconds, it emphasizes the transient behavior of each phase. Each phase's oscillatory response is apparent, indicating how the system tries to stabilize following the disruption.



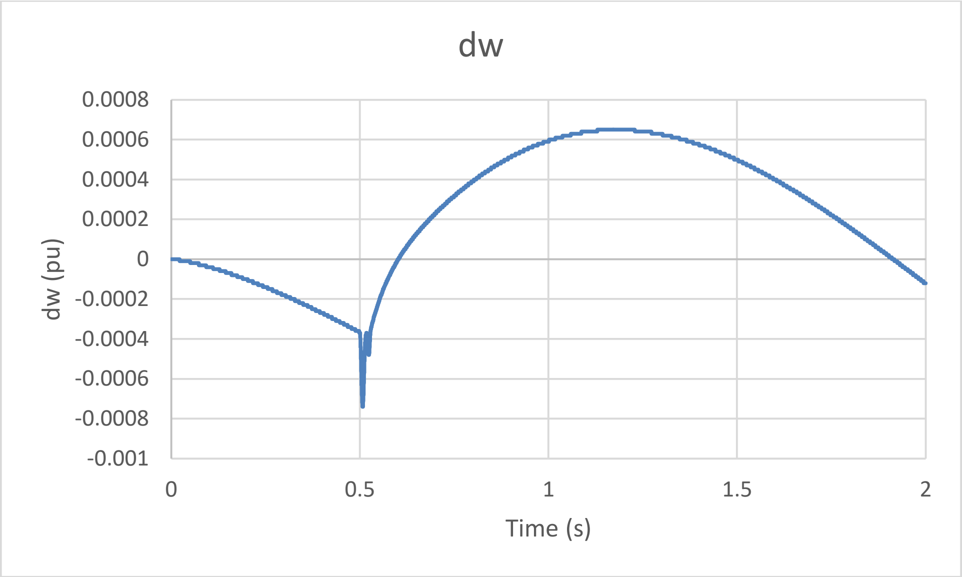
Graph 10. Voltage in 3 phases (EMT bdf)

In the following graph, we observe the active power (P) in the generator, represented in per unit (pu) values. Initially, the graph shows that the power remains approximately at a value of 1 pu. However, at the moment of the fault, which is clearly marked on the timeline, we see a noticeable disruption. This fault introduces significant perturbations in the power output, causing deviations from the steady-state value. Following this transient period, the power gradually returns to its nominal level, stabilizing once again around 1 pu. This behavior underscores the generator's response to the fault and its ability to quickly regain stability post-disturbance.



Graph 11. Power in the Generator (EMT bdf)

The plot shows the angular velocity delta (Δω) of a generator over time, highlighting its response to a fault occurring at second 0.5. Initially, Δω decreases slightly, indicating a small drop in angular velocity just after the fault. Subsequently, the angular velocity recovers, reaching a peak before gradually returning toward zero. This behavior suggests that the initial drop is not significant and demonstrates the ability of the generator control system to quickly stabilize the angular velocity after the disturbance caused by the fault.

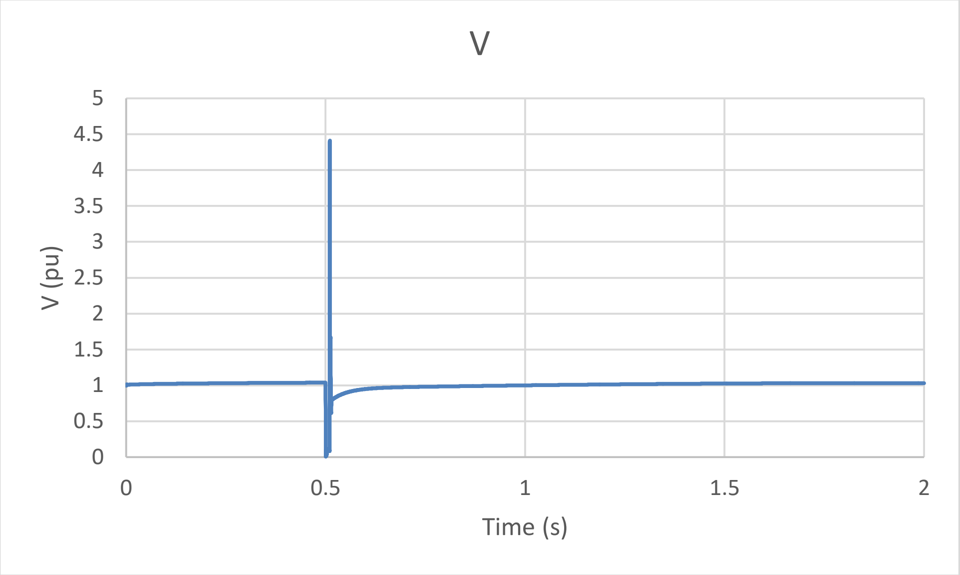


Graph 12. Delta w (EMT bdf)

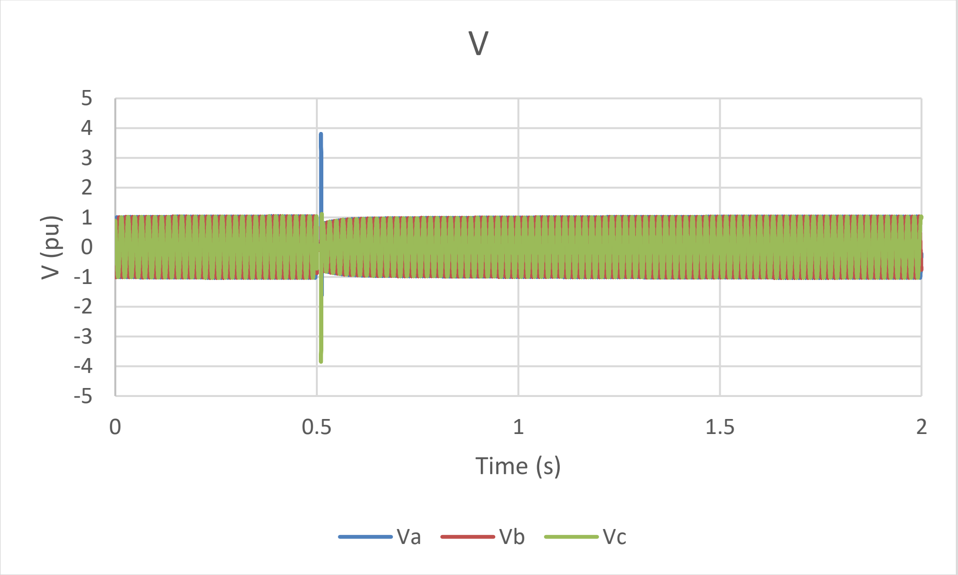
8.2.2 Case 2: Crank-Nicolson (CN)

In simulation case 2, the calculation method is changed to Crank-Nicolson. All other input data remains unchanged. In this second case, the same graphs are generated, but due to the use of a different calculation method, noticeable differences can be observed in each of them. The time used in this calculation was 1 min and 3.24 seconds.

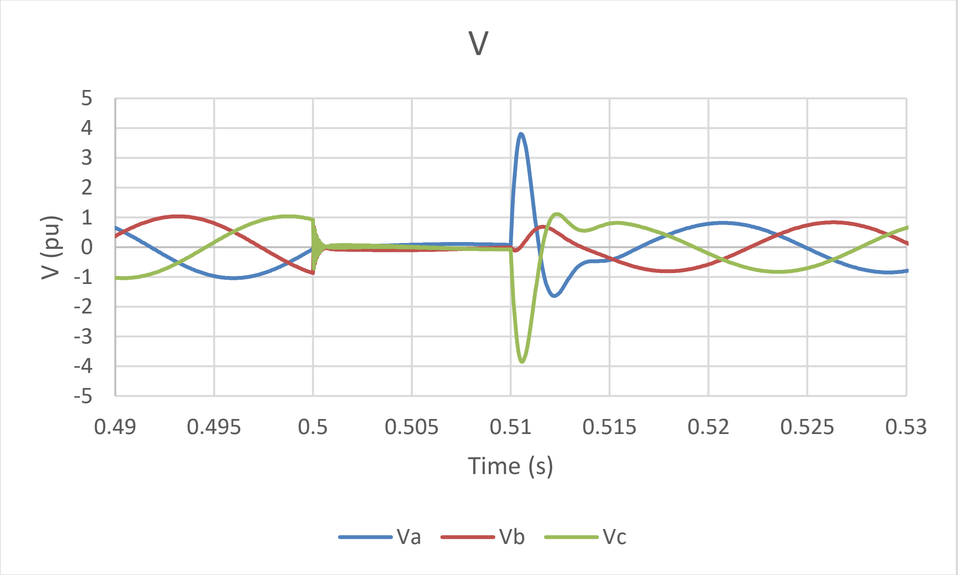
The main difference observed in all the graphs is that, during the fault, the voltage, power, and speed exhibit more pronounced and exaggerated peaks compared to the previous case. This indicates a stronger and more intense response of the system when the fault occurs under the different calculation method.



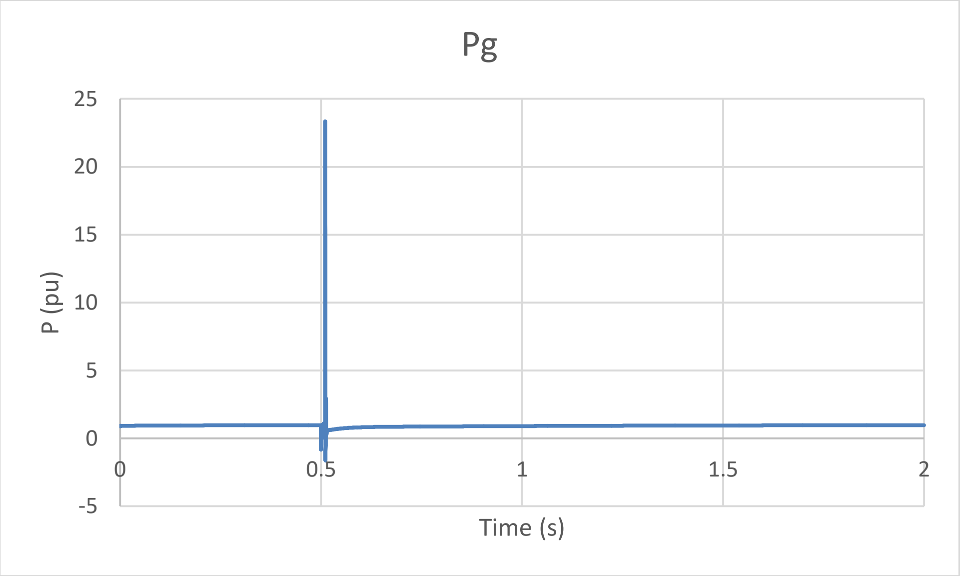
Graph 13. V in the Generator (EMT Crank-Nicolson)



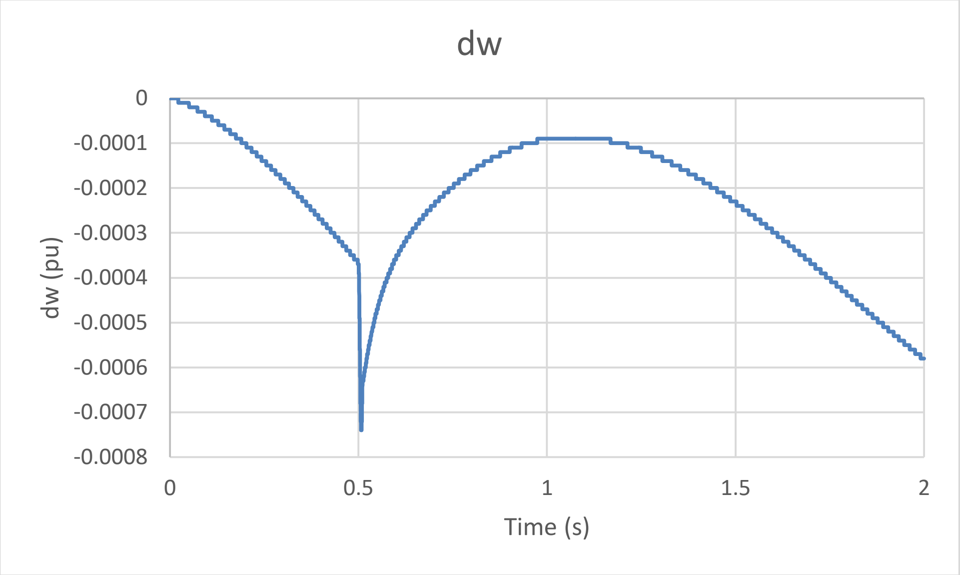
Graph 14. Voltage in the 3 phases (EMT Crank-Nicolson)



Graph 15. Voltage in the 3 phases (EMT Crank-Nicolson)



Graph 16. Power in the Generator (EMT Crank-Nicolson)

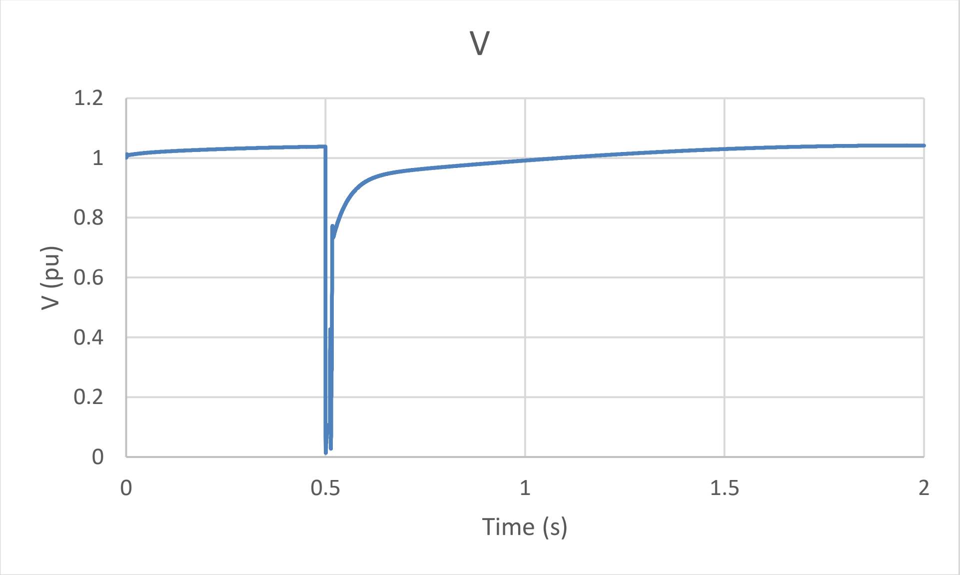


Graph 17. Variation in the Generator's Speed (EMT Crank-Nicolson)

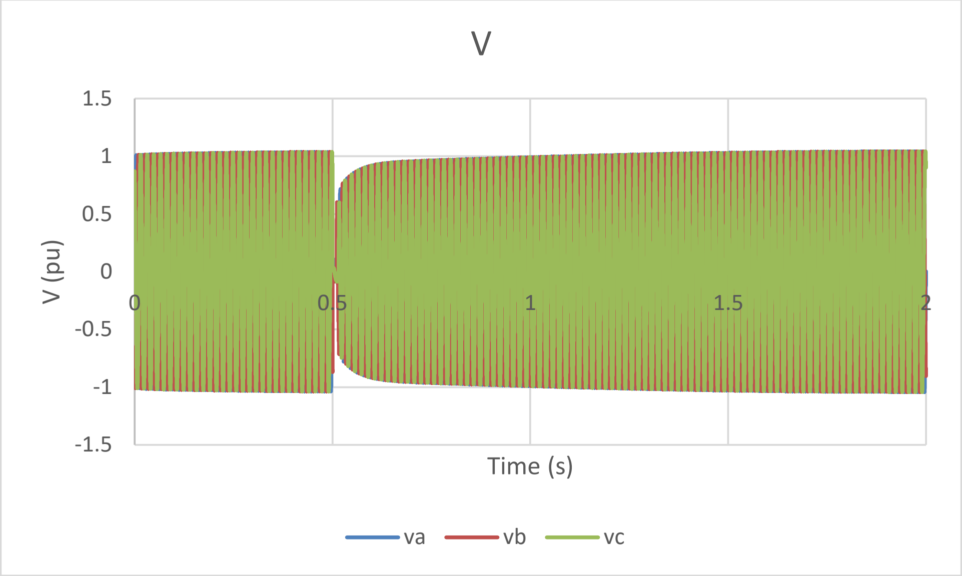
8.2.3 Case 3: Backward Euler (BEULER)

In simulation case 3, the calculation method is changed to Backward Euler. All other input data remains unchanged. The time used in this simulation was 1 min and 52.07 seconds.

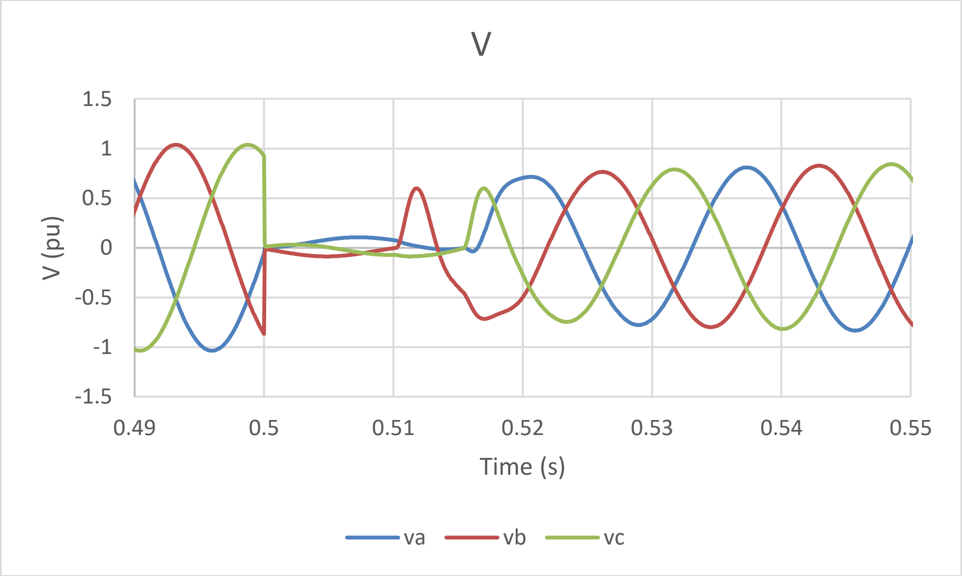
As before, the same graphs are shown. As observed, these graphs are more similar to Case 1 than to Case 2. Although the graphs were very similar, some differences prompted the question of whether reducing the time step could yield even more similar and possibly more accurate results. This consideration leads us to explore Case 4.



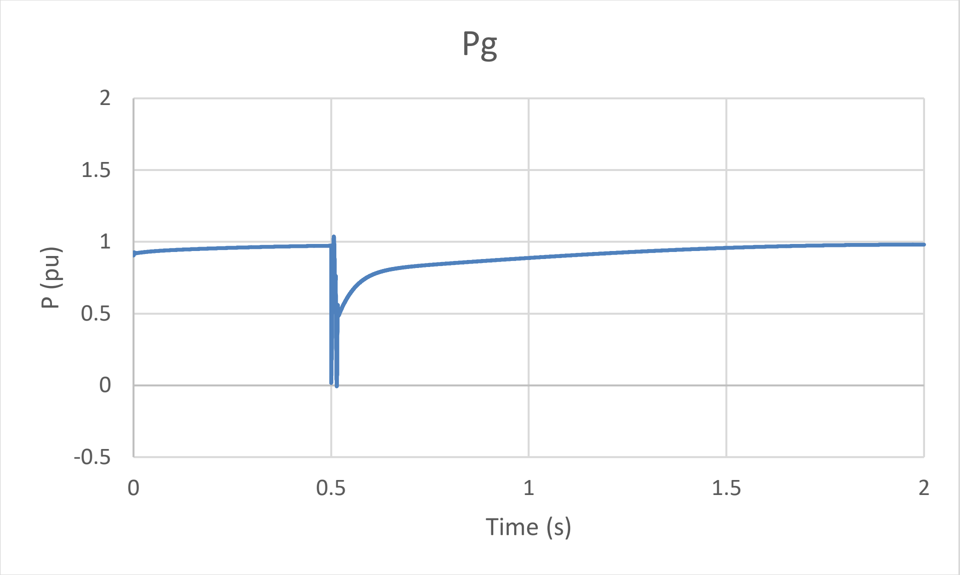
Graph 18, Voltage in the Genreator (EMT beuler)



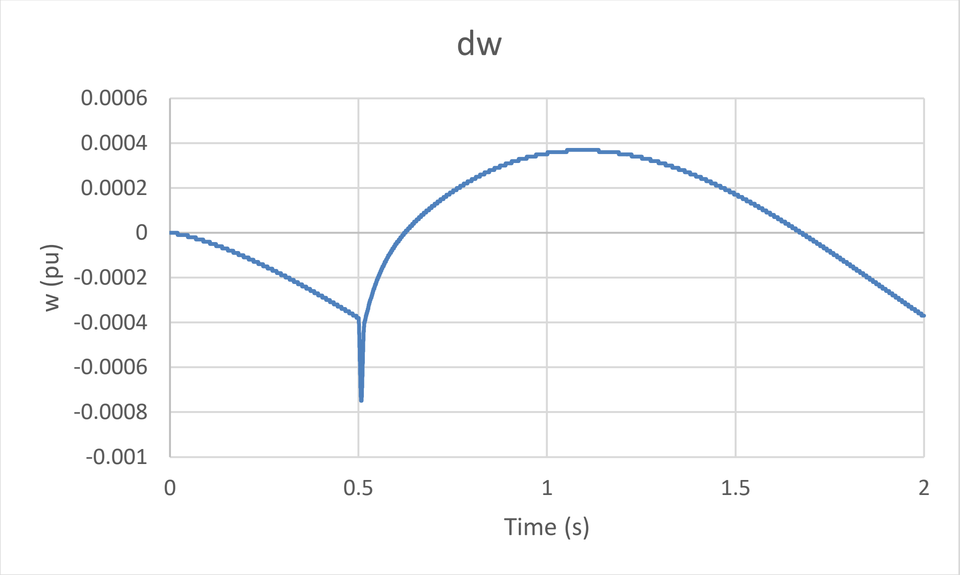
Graph 19. Voltage in the 3 phases (EMT beuler)



Graph 20. Voltage in the 3 phases (EMT beuler)



Graph 21. Power in the Generator (EMT beuler)

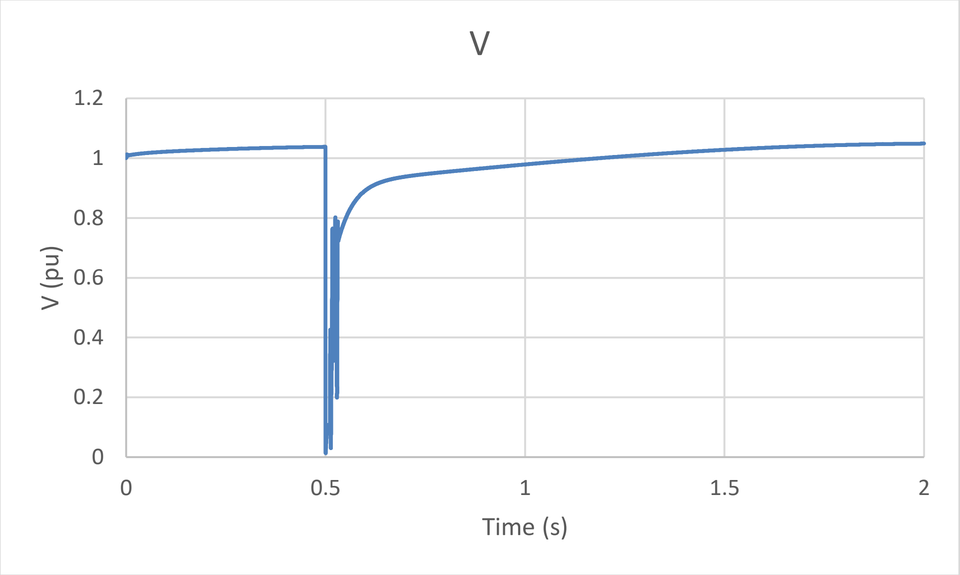


Graph 22. Variation in the Generator's Speed (EMT beuler)

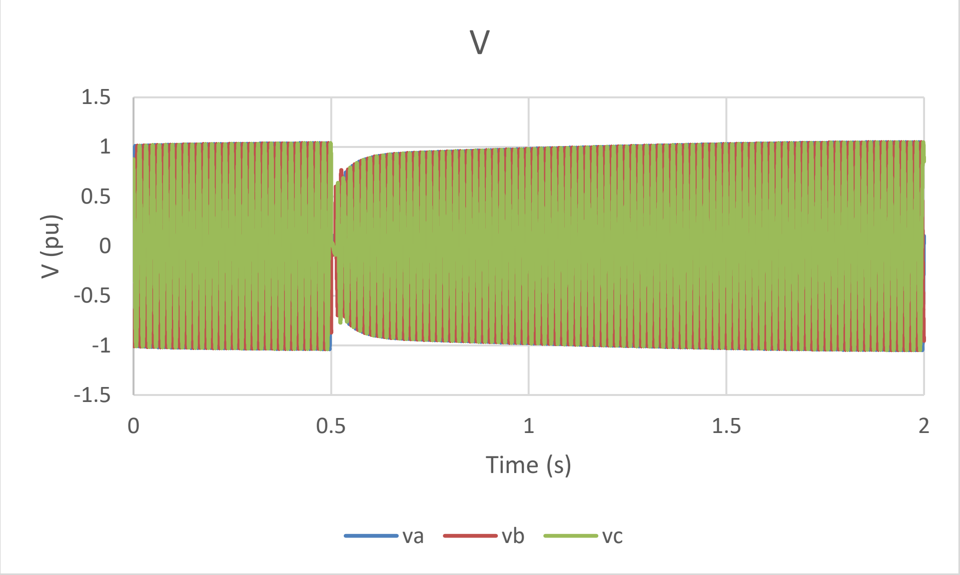
8.2.4 Case 4: Backward Euler 2 (BEULER 2)

In this final case, the same calculation method as in the previous section, Backward Euler, is used, but the time step is reduced to improve accuracy. The time used in this simulation was 2 min and 40.7 seconds

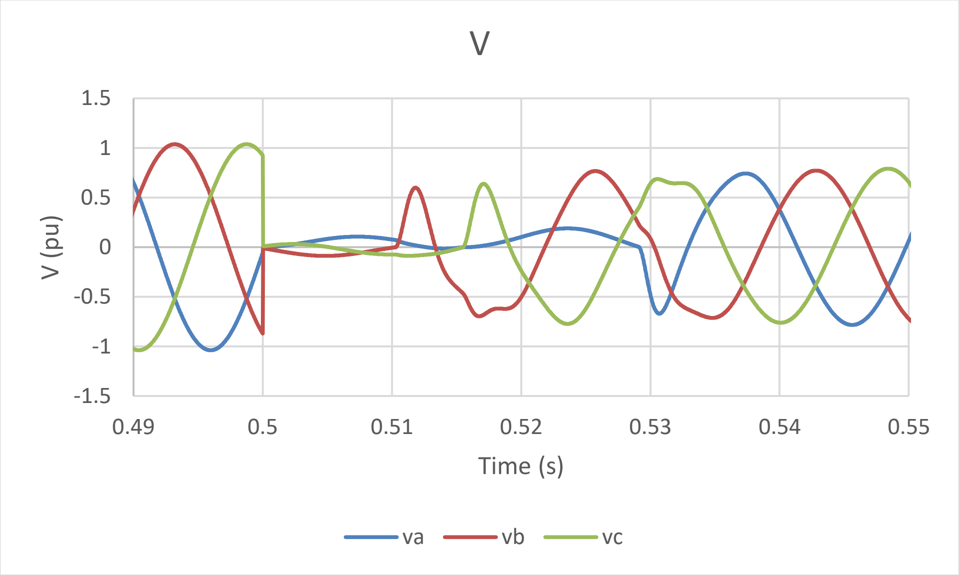
The results obtained are almost identical to those in the base case, Case 1.



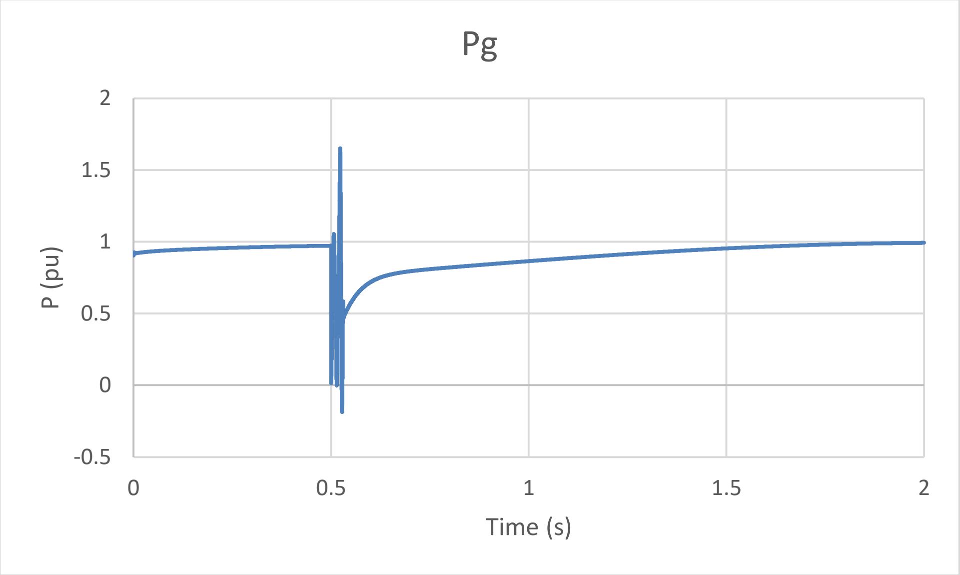
Graph 23. Voltage in the Generator (EMT beuler 2)



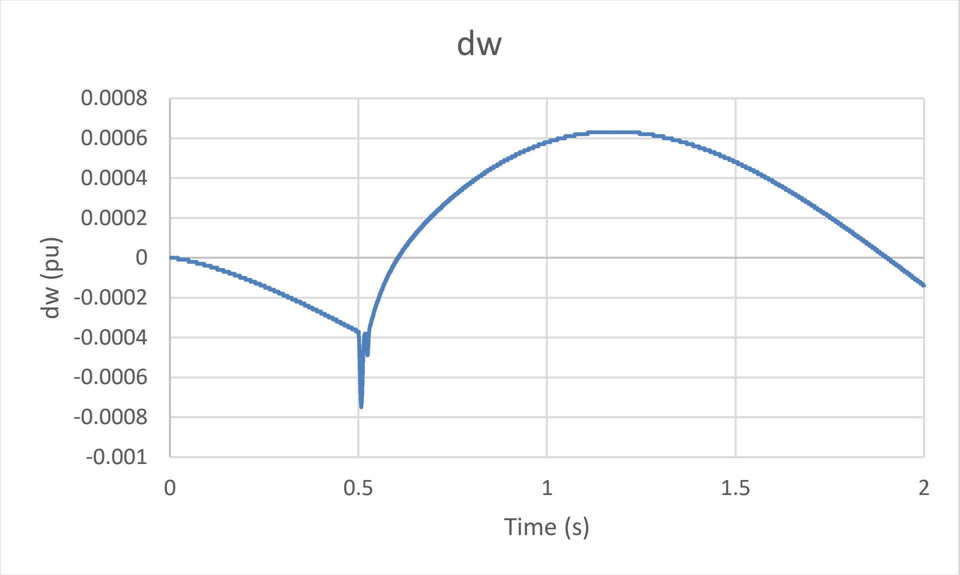
Graph 24. Voltage in the 3 phases (EMT beuler 2)



Graph 25. Voltage in the 3 phases (EMT beuler 2)



Graph 26. Power in the Generator (EMT beuler 2)



Graph 27. Variation of the Generator's Speed (EMT beuler 2)

8.2.5 Comparison

Comparing Case 1 and Case 2 we can observe how in the second simulation, the peak values of voltage, power and speed during the fault are more pronounced than on Case 1. However, the general shape of the graphs are very similar.

When it comes to Case 3, we can observe a strong similarity with Case 1. Nevertheless, it was observed in Graph 16, how it took less time to stabilize the voltages than on Case 1. For that reason, time step was reduced in Case 4 to try to improve the accuracy. The results obtained in Case 4 were nearly identical to the ones obtained in Case 1.

In Table 6 the simulation times are presented. We can observe how Case 1 and Case 2 have very similar execution times. However, cases 3 and 4 have a much larger execution time. Particularly case 4 as it has a smaller time step. In this small electrical network, the difference is not very important as all of them have low execution times. Nevertheless, if we had a larger electrical network, we would have to analyze our needs and priorities to choose between the numerical methods.

Table 6. Simulation Times

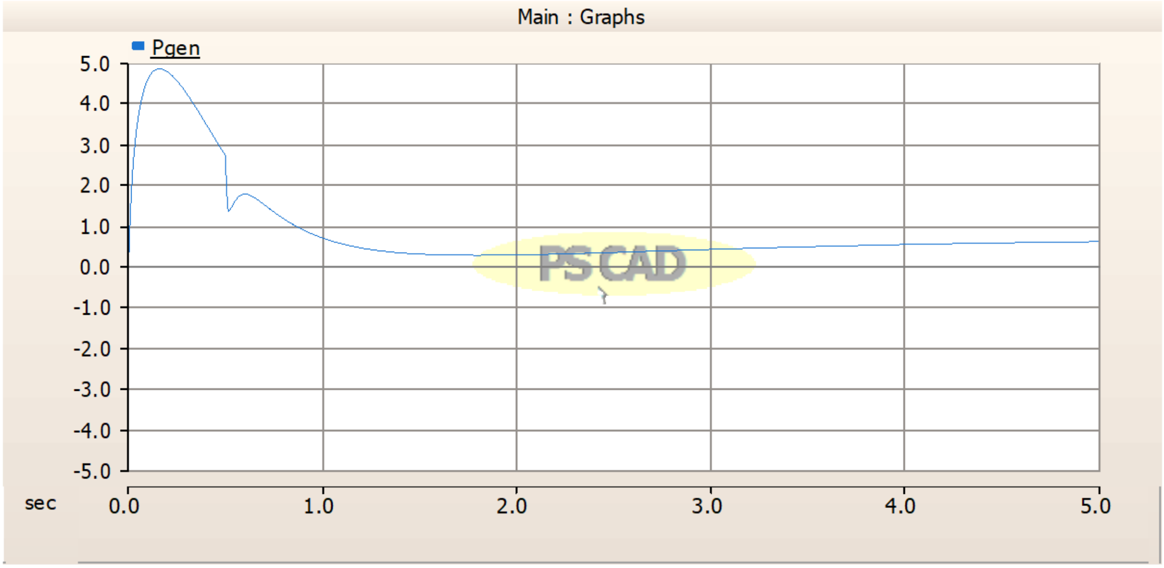
Simulation Case	Calculation Method	Simulation Time	Time Step (s)
Case 1	Backward Difference Formula (BDF)	1 min and 3.95 seconds	0.00005

Simulation Case	Calculation Method	Simulation Time	Time Step (s)
Case 2	Crank-Nicolson	1 min and 3.24 seconds	0.00005
Case 3	Backward Euler	1 min and 52.07 seconds	0.00005
Case 4	Backward Euler (reduced time step)	2 min and 40.7 seconds	0.00002

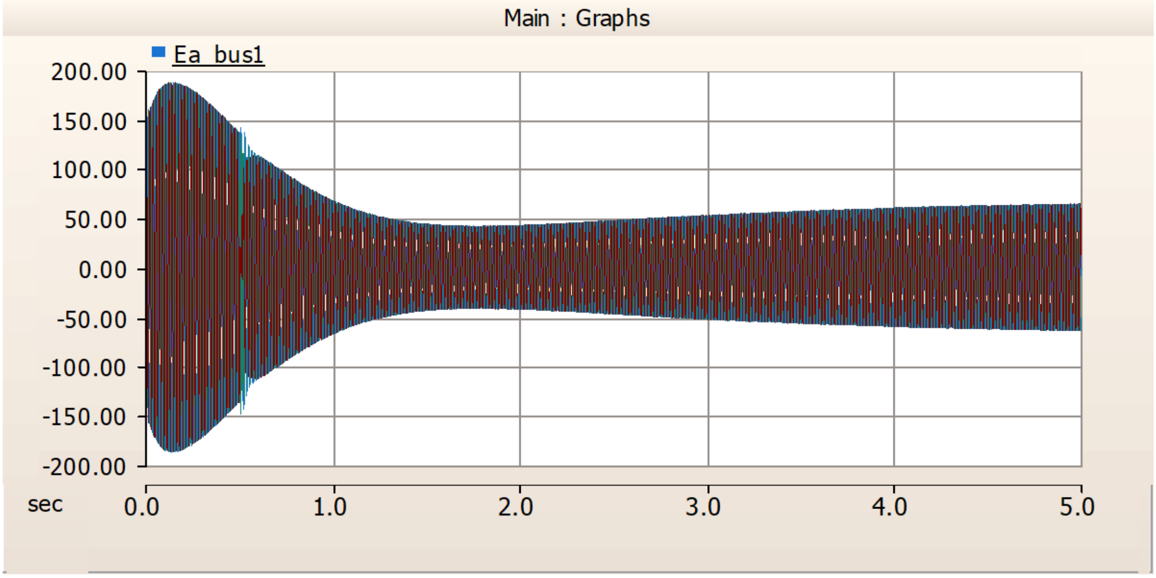
8.3 PSCAD

The following graphs were obtained by PSCAD.

In this first graph, we observe the active power (P) of the generator, measured in per unit (pu) values. Initially, as the generator starts, the power output increases, reflecting its ramp-up phase. At exactly 0.5 seconds, a fault occurs, causing a noticeable drop in the power output. This drop is followed by a brief period of instability, during which the power level fluctuates. After this short disturbance, the power output stabilizes and levels out at approximately one pu. This graph illustrates both the initial increase in power as the generator ramps up and its response to the fault, highlighting its recovery and stabilization post-disturbance.



Graph 28. Power Generator

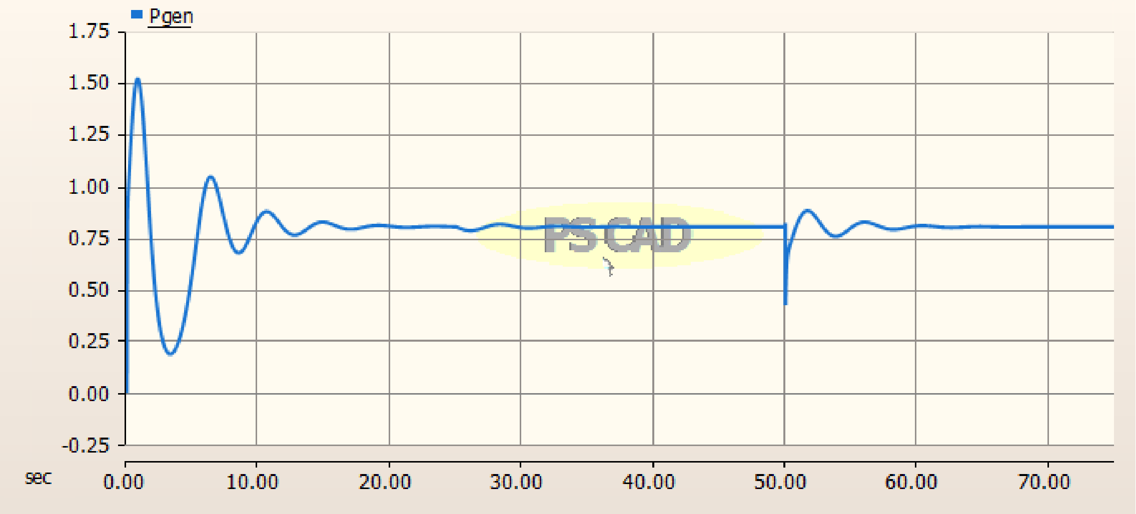


Graph 29. Ea Bus1

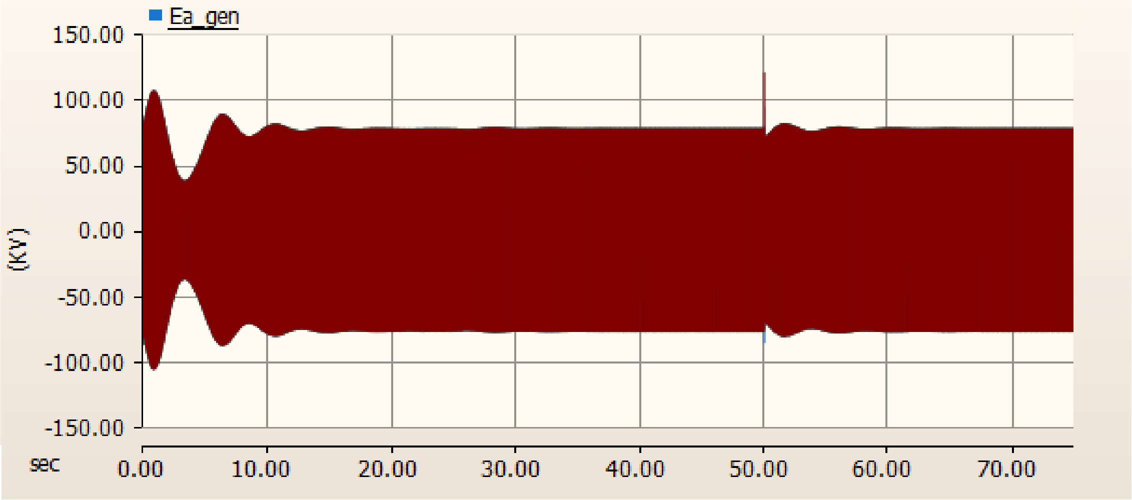
We can observe in the generator power plots that there are notable discrepancies between the simulations performed with PSCAD and Gridpack-EMT. These differences are mainly explained by the starting point of each simulation. In Gridpack-EMT, the simulation starts with the generator already operating in a steady state. However, in PSCAD, the simulation includes the entire process of starting the generator until it reaches its steady state.

In order to avoid this problem, a different simulation was run with the fault applied once the generator is in a steady state. The results obtained are the following:

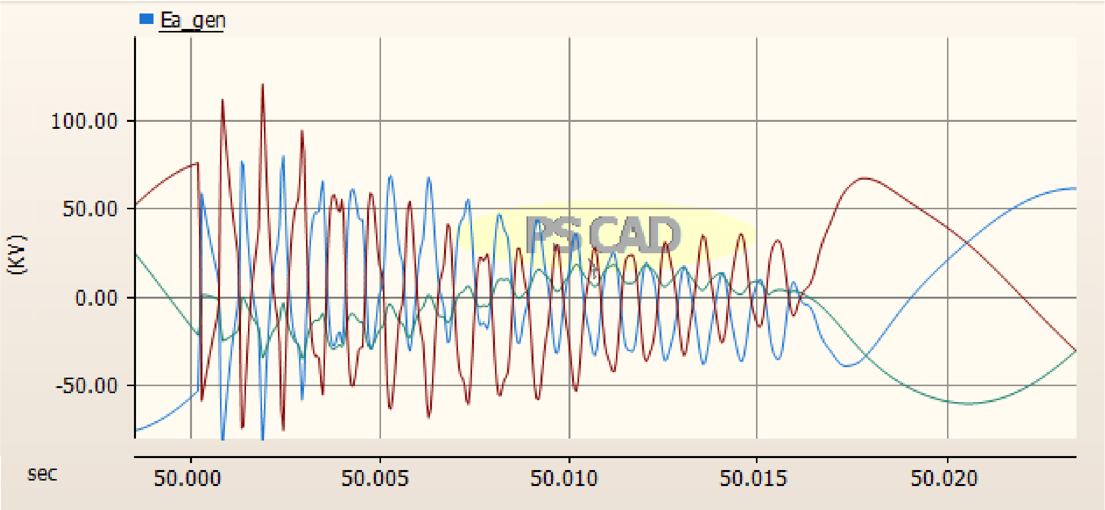
After the generator stabilizes, a fault occurs at time 50.00sec and we can see how the control system of the generator stabilizes it quickly.



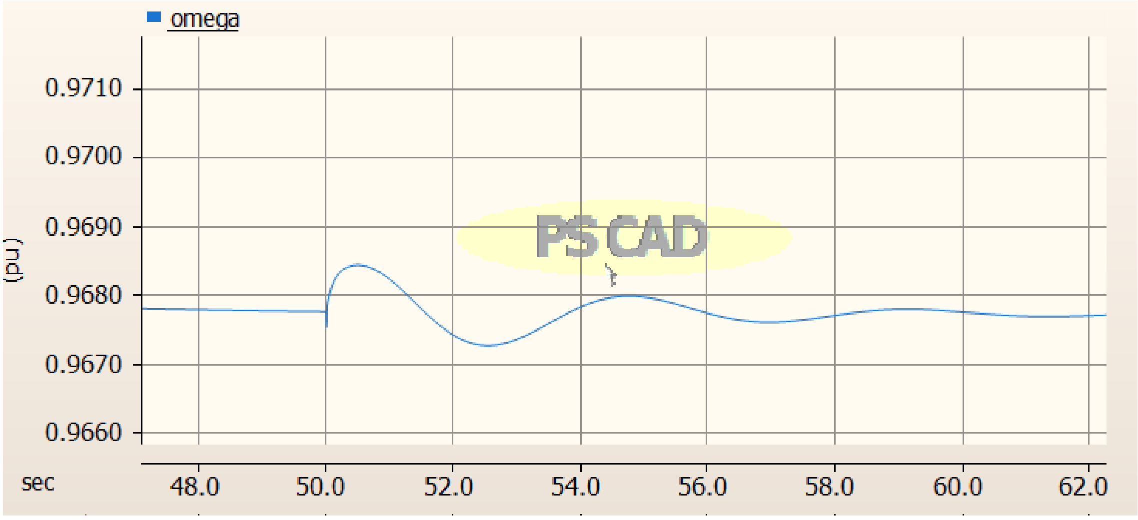
Graph 30. Power in the Generator



Graph 31. Voltage in the Generator



Graph 32. Voltage in the Generator



Graph 33. Speed of the Generator

In general, all of the graphs follow a similar pattern as the ones obtained with GidPack-EMT. There are some discrepancies, which are expected, as it is very difficult to replicate the same generator in both simulation tools.

9. CONCLUSIONS

When it comes to the simulation time, in the implemented case, the differences found are not very relevant, because the total time is small. However, if the case that is being simulated is bigger and more complex, different programs and different calculation methods could lead to very different times. Anyway, for complex cases, GridPack and

PSCAD both have the possibility of parallel computing, executing the simulation distributed in various machines.

After simulating the system with GridPack as well as with GridPack-EMT we can observe some differences between the results obtained with each one. When it comes to GridPack-EMT, the results obtained seem to be more detailed, which is more apparent when the fault occurs. In GridPack details in the oscillations are lost. This was expected, because GridPack is not specifically developed for EMT case studies. Because of this, we can confirm that GridPack-EMT should be used when precision is needed when doing EMT studies.

Both PSCAD and GridPack-EMT execute the EMT calculations with enough accuracy for the studies that are being carried out. Accuracy is crucial when it comes to these EMT studies, so the decisions made with either one of them are reliable, which is very important for the design of electrical networks.

PSCAD is more user friendly than GridPack-EMT, because it presents an intuitive graphical interface and a library of components, making it accessible and practical for users with different levels of expertise. GridPack-EMT requires a more technical interface compared to PSCAD, which can be challenging for new users. This needs a deeper understanding of electromagnetic transient phenomena and modeling, making it more suitable for advanced users and specific research applications.

PSCAD is a commercial product and GridPack-EMT is an open source research project. Which means that PSCAD has a more up to date documentation and support.

Furthermore, one recurrent issue when simulating the system in all 3 different simulation tools, was the mismatch of between the parameters introduced to correctly simulate the system. In some cases, the translation is easy while in others there is no information available in the documentation of the tools about the meaning of each parameter. Because of that, assumptions needed to be done, but the exact impact of them was not known. Some of the differences between results could be explained by these assumptions.

In summary, for those who are researching and want to compare different calculation methods, GridPack-EMT is a good tool. However, for new users without a deep understanding of electromagnetic modeling, GridPack-EMT can be challenging. In this regard, PSCAD is a good option for people doing standard EMT analysis.

10. FUTURE WORK

After finishing this research project, we conclude that there is still room for a lot of improvements.

When doing the comparison between GridPack and GridPack-EMT, we observed a big improvement in the calculation methods, which allowed for more detailed results, as has been mentioned before. However, GridPack-EMT still lacks a lot of documentation to facilitate the understanding and use of the program for new users. To help with the accessibility of GridPack-EMT it is fundamental to develop clear guides, examples and manuals to guide users on how to use the software.

Furthermore, when using tools like GridPack-EMT and PSCAD, it is usually an issue to implement the same case in two different tools, because of the difference in the parameters used. It would be beneficial to standardize and document the parameters that are used for each of the components. By doing this, it would be easier to switch between tools and improve the reliability of comparative analysis, making it easier to validate results and ensure consistency across different simulation platforms.

In summary, while GridPack-EMT has proven to be a powerful tool, it is essential to resolve the documentation and standardization challenges in order to maximize its potential and expand its user base. By making these improvements, GridPack-EMT can become more accessible, and user-friendly, eventually contributing to more efficient and reliable research and development in the field of EMTs.

11. REFERENCES

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12. APPENDIX B – GRIDPACK-EMT FILES

These are the real files that were executed for the simulations.

12.1 Case2.dyr

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     1, 'EXDC1',1 ,   0.16668E-01,   68.600,     0.20000E-01,   0.0000,

     0.0000,       7.4500,      -7.4500,       1.0000,       3.8700,

     0.10000,       1.0000,       0.0000,       3.4000,       1.0700,

     4.6000,       1.2000    /

     1, 'WSIEG1',1 ,      0, 0 ,  25.0000 ,     0.00000 ,     3.30000 ,
0.300000 ,    0.250000 ,    -3.30000   ,    51.01000 ,     0.00000 ,
0.861200E-01 , 1.00000,

     0.00000 ,     0.00000   ,    0.00000    ,   0.00000   ,    0.00000 ,
0.00000   ,    0.00000   ,    0.00000    ,   0.00000   ,    0.00000   ,

     0.00000 ,     0.00000   ,    0.00000    ,   0.00000   ,    0.00000 ,
0.00000   ,   0.00000   ,    0.00000    ,   0.00000   ,    0.00000   ,

     0.00000 ,     0.00000   ,    0.00000   ,   0 /
```

12.2 Case2mod.raw

```
     0  100.000

      0,    100.00, 23, 0, 0, 60.00       / February 17, 2014 16:14:23

      0,    100.00, 23, 0, 0, 60.00       / February 17, 2014 16:14:23

          1, 3,     0.000,     0.000,     0.000,     0.000,   1,1.00000,
0.00000,'bus-1       ',100.0000,   2

          5, 1,    90.000,     0.000,     0.000,     0.000,   1,0.97547,
-4.01726,'bus-5       ',100.0000,   2

     0
```

```
         1,'1 ',   71.9547,     24.0689,    53.400,    -20.400, 1.0000,
0,   100.000,   0.10000,   1.00000,   0.00000,   0.00000,   1.00000,1,
100.0,     0.000,     0.000

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           1,       -5,'A ',   1.0000E-2,   0.05760,   0.17600,    0.00,
0.00,   0.00,0.00000,000.000, 0.00000, 0.00000, 0.00000, 0.00000, 0

           1,       -5,'B ',   1.0000E-2,   0.05760,   0.17600,    0.00,
0.00,   0.00,0.00000,000.000, 0.00000, 0.00000, 0.00000, 0.00000, 1

     0 / END OF BRANCH DATA, BEGIN TRANSFORMER ADJUSTMENT DATA

     0 / END OF TRANSFORMER ADJUSTMENT DATA, BEGIN AREA DATA

        1,      0,     0.0,  3.000,'            '

     0 / END OF AREA DATA, BEGIN TWO-TERMINAL DC DATA

     0 / END OF TWO-TERMINAL DC DATA, BEGIN SWITCHED SHUNT DATA

     0 / END OF SWITCHED SHUNT DATA, BEGIN IMPEDANCE CORRECTION DATA

     0 / END OF IMPEDANCE CORRECTION DATA, BEGIN MULTI-TERMINAL DC DATA

     0 / END OF MULTI-TERMINAL DC DATA, BEGIN MULTI-SECTION LINE DATA

     0 / END OF MULTI-SECTION LINE DATA, BEGIN ZONE DATA

         1,'ZONE_0      '

     0 / END OF ZONE DATA, BEGIN INTER-AREA TRANSFER DATA

     0 / END OF INTER-AREA TRANSFER DATA, BEGIN OWNER DATA

     0 / END OF OWNER DATA, BEGIN FACTS DEVICE DATA
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12.3 Input_2bus.xml

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  <PETScOptions>
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    -ksp_type richardson
    -pc_type lu
    -pc_factor_mat_solver_package superlu_dist
    -ksp_max_it 1
  </PETScOptions>
</LinearSolver>
<UseNonLinear>false</UseNonLinear>
<UseNewton>false</UseNewton>
<NewtonRaphsonSolver>
  <SolutionTolerance>1.0E-05</SolutionTolerance>
  <FunctionTolerance>1.0E-05</FunctionTolerance>
  <MaxIterations>50</MaxIterations>
  <LinearSolver>
    <SolutionTolerance>1.0E-08</SolutionTolerance>
    <MaxIterations>50</MaxIterations>
    <PETScOptions>
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      -pc_type bjacobi
      -sub_pc_type ilu -sub_pc_factor_levels 5 -sub_ksp_type preonly
      <!-ksp_monitor
```

```
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             </PETScOptions>
           </LinearSolver>
         </NewtonRaphsonSolver>
         <NonlinearSolver>
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           <FunctionTolerance>1.0E-05</FunctionTolerance>
           <MaxIterations>50</MaxIterations>
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             -pc_type bjacobi
             -sub_pc_type  ilu  -sub_pc_factor_levels  5  -sub_ksp_type
preonly
             <!-snes_view
             -snes_monitor
             -ksp_monitor
             -ksp_view>
           </PETScOptions>
         </NonlinearSolver>
       </Powerflow>
       <EMT>
         <generatorParameters> case2.dyr </generatorParameters>
         <machineIntegrationType> IMPLICIT </machineIntegrationType>
         <simulationTime>5.0</simulationTime>
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<end>0.51</end>

<bus>5</bus>

<type>SLG</type>

<Ron>1e-3</Ron>

<Rgnd>1e-2</Rgnd>

     </BusFault>

   </Events>

   <Monitors>

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<bus> 1 </bus>

<id> 1 </id>

     </Generator>

   </Monitors>

   <DAESolver>

     <PETScPrefix>emt_</PETScPrefix>

   </DAESolver>

 </EMT>

</Configuration>
```

12.4 .petscrc

```
# These are the options to tune the solver for the EMT application

# To see the full range of options available with PETSc, run the application with -h
```

```
# ./emt.x -h

# All the options prefixed with "-emt_" are used for time-stepping and the nonlinear solver

# associated with the time-stepper.

# Any options that do not have the prefix are either general options OR those for the nonlinear

# solver used for handling disturbances.

# For disabling any options use a preceding #, i.e., comment them out.



# Numerical integration scheme

-emt_ts_type bdf # 2nd order backward BDF method



# Time-step adaptivity

-emt_ts_adapt_type none # turn off step adaptivity

#-emt_ts_adapt_type basic # basic (Use -emt_ts_adapt_type basic to turn on adaptivity)



# Tolerances for step adaptivity (only used when step adaptivity is on)

-emt_ts_atol 1e-2

-emt_ts_rtol 1e-2



# Tolerance for event location

-emt_ts_event_tol 1e-5



# Minimum step size for event
```

```
-emt_ts_event_dt_min 1e-6


# Step size after event

-emt_ts_event_post_eventinterval_step 50e-6


# Min. and max. steps (only used when step adaptivity is on)

-emt_ts_adapt_dt_max 500e-6

-emt_ts_adapt_dt_min 50e-6


# End last time at the given final time

-emt_ts_exact_final_time MATCHSTEP


# Show progress of time-stepper

-emt_ts_monitor


# Show progress of nonlinear solver during each step

#-emt_snes_monitor


# Use full Newton step

-emt_snes_linesearch_type basic


# Use LU factorization as the linear solver

-emt_pc_type lu

-emt_pc_factor_mat_ordering_type qmd

-emt_pc_factor_shift_type NONZERO
```

```
#-emt_pc_type asm

#-emt_pc_asm_overlap 2

#-emt_sub_pc_type lu

#-emt_sub_pc_factor_mat_ordering_type qmd


# Use SuperLU_Dist package for doing the linear solve (Note: PETSc must be configured with --download-superlu_dist --download-metis --download-parmetis)

#-emt_pc_type lu

#-emt_pc_factor_mat_solver_package superlu_dist


# Use finite-difference Jacobian

#-emt_snes_fd


# Save the output at each time-step

#-emt_ts_save_trajectory

#-ts_trajectory_keep_files
```