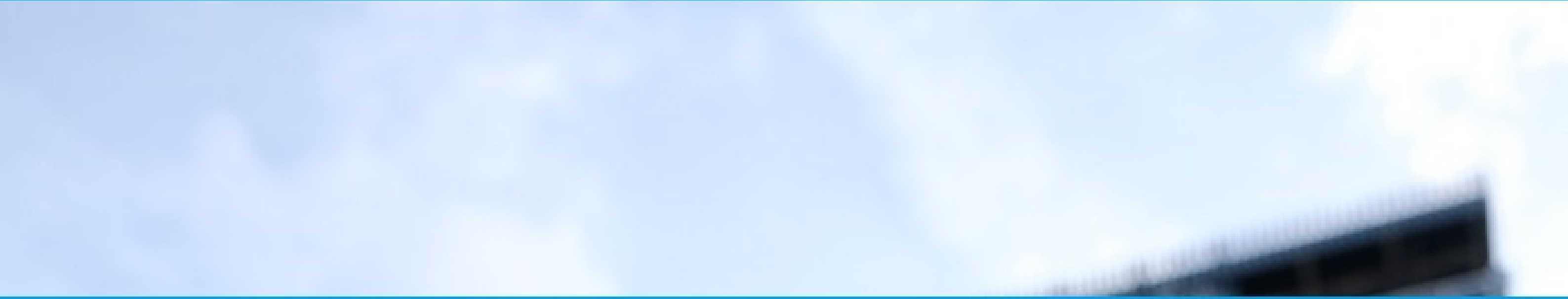

Development of EMT/TS Co-simulation Using PowerFactory and PSS/E

Muhamad Zamroni

Technische Universiteit Delft

TU Delft

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by

Muhamad Zamroni

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Thesis committee:	Prof. dr. Peter Palensky,	Thesis Chair, TU Delft
	Dr. ir. Milos Cvetkovich,	Supervisor, TU Delft
	Dr. D. J. P. Lahaye,	External Member, TU Delft

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Abstract

As the scale and complexity of power systems increase, simulating them in efficient and accurate ways continues to be a challenge in power systems engineering. Electromagnetic Transient (EMT) and Transient Stability (TS) simulation are the two main dynamic power system simulation methods. To simulate large and complex power systems in sufficient detail without sacrificing execution time, one of the idea is to perform a co-simulation that couples EMT and TS simulator. Although several attempts have been made to couple both simulator, only on rare occasions do these hybrid EMT-TS simulators couple two or more industry-adopted simulation tools.

The objective of this thesis is to to develop and study the benefits and limitations of the Electromagnetic Transient – Transient Stability co-simulation based on PowerFactory and PSS/E, both of which are among the most extensively used simulation tools in industry and academia alike. With regards to the objective, the EMT-TS co-simulation using PowerFactory and PSS/E has been developed. Then, several test are performed to evaluate the function of each composing part of the EMT-TS co-simulation, and to test the integration between all its component. Next, The developed co-simulation is applied to study cases and the results are compared to a monolithic EMT simulation to evaluate its accuracy and execution time. Furthermore, the effect of TS and EMT time step to the accuracy and execution time of EMT-TS co-simulation have also been investigated.

The study case results show that the developed EMT-TS co-simulation has not been beneficial yet in terms of accuracy and execution time. Although the active power result shows a similar tendency with the monolithic EMT result, the difference between both are visible. The difference between both are more prominent in the reactive power result. The total execution time of the developed co-simulation in the study cases are in the range of 23-24 minutes, significantly larger than the total execution time obtained from the monolithic EMT simulation which is around of 12s. Also, it is found that reducing the TS time step from 0.02 s to 0.01 s slightly increases the total simulation time from 23 to 26 minutes. However, it does not contribute a significant improvement on the accuracy of the developed EMT-TS co-simulation. The result obtained from reducing the EMT time step to 25μs is the same with the result obtained using 50μs EMT time step. Moreover, the reduction of the EMT time step significantly increases the total simulation time from 23 to 42 minutes. The developed co-simulation still has a lot of room for improvement and further developments in this topic might increase its performance.

Keywords: Co-simulation, Electromagnetic Transient, Transient Stability, PowerFactory, PSS/E

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1
Introduction

1.1. Background To The Problem

Simulation has a major role in power system engineering. It helps the engineer to assess the condition of the power system and to predict situations that may arise in the future. In addition, it also reduces the need to perform expensive, high-risk, and time-consuming experiments. In that way, the advancement in power system simulation technology will have a positive impact both on the power system studies and in practice.

Nowadays, the power system is becoming more complex [9]. The complexity is partially due to the increasing integration of power electronics in the power system such as Photovoltaic (PV) inverters, High Voltage Direct Current (HVDC) converters, and Flexible AC Transmission Systems (FACTS). Consequently, it leads to an increased need to observe and analyze the detail of power system behavior in stability studies.

There are several types of power system simulation. Among those, there are two types which are used in stability studies. They are Electromagnetic Transient Stability (EMT), and Transient Stability (TS) simulation. Each of these has its own advantages and is used in different application. For example, EMT may be used to simulate an HVDC system to better observe the commutation process in its converter, and TS may be used to simulate a generator response to a dynamic event happened in a large power system.

1.1.1. Electromagnetic Transient Simulation

Electromagnetic Transient (EMT) is a type of simulation which performs analysis using a detailed model to represent the power system [9]. It involves differential equations and more complex calculations, resulting in a very accurate representation of the power system. Therefore, using EMT simulation, the power system behavior during dynamic studies can be observed in more detail. Usually, EMT simulation is used to simulate a case in which the fast transient phenomena are of interest. For instance, one might think of a test case for analyzing the behavior of inverter-driven machines, HVDC, and over-voltages phenomena.

The growing number of power electronic components in the power system increases the needs to conduct EMT simulation due to the fact that EMT simulation is able to represent the commutation process of the converter, allowing it to describe an accurate representation of the transient process in the converter. However, the EMT simulation also has a drawback. Due to the detailed modeling of its component and the use of small integration time steps, which are typically in the order of 50 µs, EMT simulation demands high computational effort. If the scale of the system simulated in EMT is large, then the execution time can become too long.

1.1.2. Transient Stability Simulation

On the other hand, Transient Stability (TS) is a type of simulation which is based on simplified phasor representation [9]. In contrast to EMT, TS simulation only uses the fundamental frequency in the calculation process and only involves differential equations on some key devices such as generators, exciters, and governors. The integration step of TS simulation is large compared to EMT, typically in the order of half a cycle of the fundamental frequency. Therefore, it has difficulty simulating power electronics devices such as HVDC equipment since the responses of the controller are too quick. Usually, the implementation of power electronic devices is modeled using pseudo steady state approximation [9].

Due to the limitations, TS simulation is inapplicable to several case studies. For instance, the asymmetric fault and transient analysis [31]. Nevertheless, the lack of accuracy in the computation is traded for advantages in computational effort. Due to the larger integration time and the use of a simpler model, TS simulation could run faster than an EMT simulation of the same system. These advantage could give benefit when the simulation includes a large number of power system devices. Therefore, TS simulation is usually used to simulate a dynamic case of a large power system that does not require great details of simulation result.

1.1.3. EMT - TS Co-simulation

From the description of the previously mentioned simulation, there is a need for a simulation method with a better tradeoff between simulation time and accuracy than the available simulation methods which are unable to provide both of them at the same time. One of the solutions that have been proposed is to combine EMT and TS in a hybrid simulation.

A hybrid simulation is realized by splitting the power system into multiple parts in which each part uses different specialized models (e.g., different component modeling, environments, or languages) and simulated separately from each other. Since the individual part uses a specialized model, each part can place more emphasis on a certain aspect. For instance, one part can be modeled to obtain more detail of dynamic response, and another part can be modeled to reduce the computational effort for simulation purposes. It has to be noted that the terms hybrid simulation is a general term. When the system is divided into multiple parts, each part can be simulated with the same simulator, or it can be simulated using different simulators. A more specific type of hybrid simulation which uses different simulator is referred as hybrid co-simulation.

In EMT-TS hybrid simulation, the system is divided into two parts. One part is simulated using EMT simulation, and the other part by TS simulation. Figure 1.1 shows the example of network partition in hybrid co-simulation. One smaller part which contains a subsystem that is of interest is simulated using EMT simulation to obtain the detailed result. Meanwhile, the other part wich contains the rest of the power system is simulated using TS simulation. In this part, the detailed result is not required. However, as it contains the bigger part of the system, a fast computation featured by TS simulation is crucial to obtain a shorter overall computation time.

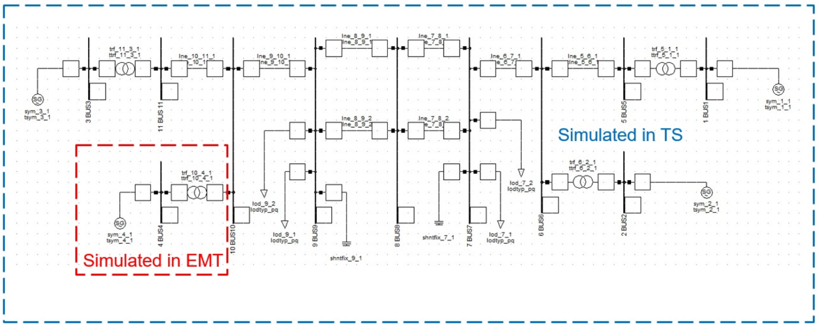

Figure 1.1: The example of network separation in hybrid co-simulation

EMT-TS hybrid simulation has the potential to realize a detailed simulation result in a part of power system without sacrificing the overall simulation time. Thus, its realization could increase the simulation capability. For instance, it could bring advantages in the situation where the computational resources are limited.

1.1.4. Brief Summary of Co-simulation Development History

The attempts to couple EMT and TS simulation have been started as early as 1981 from the papers published by Heffernan et. al [7] [28] [27]. In their papers, the study regarding the development of a tool which combines the features of EMT and TS is presented. The papers proposed the model of an HVDC system in EMT domain which interacts with an AC system in TS domain. Since then, there have been several types of publications which discuss in detail about the implementation of hybrid simulation and its interfacing techniques. For example, [30] [2] [26] [25] [5]

Apart from the hybrid simulation and the interfacing techniques, there are also another research in this topic. For example, In 2011, Wen-Zhuo et al. published a paper regarding EMT-TS simulation method that considers asymmetrical faults [31]. Later on, in 2012, Irwin proposed parallel processing to increase the computation power in solving the simulation in EMT domain [9]. Next, in 2014 Plumier proposed an improvement in interaction protocol called relaxation scheme [17]. Van der Meer in 2015 also proposed an improvement in interaction protocol and interfacing techniques related to equivalent impedance refactorization after faults, Thevenin equivalent source updating method, and phasor determination during a fault [29]. Lastly, in 2016 Huang et al. proposed an interesting scheme in interaction protocol by combining serial and parallel scheme [8].

1.1.5. Co-simulation Between PowerFactory and PSS/E

Several attempts have been made to couple EMT -TS simulation. However, none of them are purely based on widely-adopted software tools. Among the available power system simulation tools, PSS/E and DIgSILENT PowerFactory are commonly used worldwide. In regards to stability studies, PSS/E has the capability to simulate in TS, and DIgSILENT PowerFactory has the capability to simulate in both EMT and TS. In the writer's knowledge, there has not been any platform yet which enables hybrid co-simulation between them. The realization of an EMT-TS hybrid co-simulation platform using DIgSILENT PowerFactory and PSS/E could make the EMT-TS hybrid simulation easier to be adopted in industrial application.

Based on the issues mentioned above, there is a need to develop the hybrid co-simulation platform which couples only popular commercial EMT-TS simulators. This thesis tries to fill the gap by developing hybrid co-simulation platform using PowerFactory as EMT simulator and PSS/E as TS simulator, both widely adopted commercial software in power system engineering.

However, it should be noted that the development to reach a complete-fledged solution needs a considerable amount of effort. This thesis tries to give contribution as the first step of the EMT-TS hybrid co-simulation development using PowerFactory and PSS/E. As this is the first attempt to couple PowerFactory and PSSE to perform hybrid co-simulation platform; the benefits, limitations, and applicability of such platform are still unclear. Therefore, from the results obtained by this thesis, the mentioned aspects are evaluated. The result of the evaluation can be used as a suggestion to develop an improved version of a hybrid co-simulator.

1.2. Research Question

Based on the motivation described in the previous section, the main research question in this thesis can be defined as follows:

Can an Electromagnetic Transient -Transient Stability hybrid co-simulation platform based on PowerFactory and PSS/E be beneficial in terms of accuracy and execution time?

1.3. Objectives

The main objective of this thesis is to develop and study the benefits and limitations of the Electromagnetic Transient – Transient Stability co-simulation based on PowerFactory and PSS/E. The objective can be further expanded into these following specific objectives:

Specific Objectives:

- O1. To do a literature review on the existing implementations of EMT-TS co-simulation.

  To develop a co-simulation for this thesis, a sufficient knowledge is required. The first objective aims to provide the theory regarding the available design approach, the explanations of technical aspects, as well as the state of the art for the recent development of EMT-TS hybrid co-simulation to give more insight for the design process in this thesis

- O2. To develop EMT-TS co-simulation between PowerFactory and PSS/E.

  This objective aims to fill the EMT-TS co-simulation tool gap between PowerFactory and PSS/E which has been described in the previous section

- O3. To test the implementation of the developed EMT-TS co-simulation.

  After the EMT-TS co-simulation is developed, it needs to be examined to ensure that the design is correctly implemented. This objective aims to test whether the designed co-simulation and its components are able to function properly before the co-simulation is applied into study case

- O4. To compare the accuracy and execution time between the EMT-TS co-simulation result and the benchmark result from monolithic EMT simulation.

To study the benefit and limitations of the developed co-simulation, the results obtained from the developed co-simulation need to compared with a benchmark result to evaluate its performance. Based on the comparation, the conclusion regarding to which extend the developed co-simulation is beneficial in terms of accuracy and execution time can be drawn

- O5. To investigate the effect of different simulator time step on the accuracy and the execution time of the developed EMT-TS co-simulation.

  The selection of parameter may affects the accuracy and execution time of the developed co-simulation. By this objective, the effect of simulator time step as one of the parameter in the developed co-simulation is examined to provide better insight on how does the developed co-simulation performs differently when its time step is varied

- O6. To provide recommendation for the further development of EMT-TS co-simulation.

  As this thesis is the first attempt to couple PowerFactory and PSS/E to perform hybrid co-simulation, a recommendation needs to be provided to support the continuity of the research in this topic

1.4. Methods

In correspond to the defined specific objectives, the methods for each of them are described as follows:

- Related to O1: The activity is carried out through a study of literatures which covers the knowledge of hybrid simulation, co-simulation, the recent development of hybrid co-simulation, and the interfacing techniques. Furthermore, the results of the literature review are applied to determine the appropriate design for the developed hybrid co-simulation.
- Related to O2: The activity is executed by firstly defining the architecture of co-simulation tool. Then, the interface on the PowerFactory side and the PSS/E side are developed. Finally, the master algorithm is designed in order to integrate the interface between EMT and TS. All the development are implemented using the python programming language.
- Related to O3: A simple test case consisting of a generator, transmission line, and a load is simulated using the developed hybrid co-simulation platform. The result from co-simulation is compared with the benchmark result obtained using monolithic EMT simulation in order to evaluate the accuracy of the developed tool.
- Related to O4: A co-simulation network based on Kundur's two area four generator system is created. The co-simulation network is applied to several case studies. For each case study, the results are compared with the benchmark results and evaluated in terms of accuracy and execution time.
- Related to O5: one of the study case related to O4 is re-simulated by using a different EMT and TS time step. Then, the results obtained from different time step are compared to each other. Based on the result comparison, the discussion regarding the effect of different time step are presented.
- Related to O6: Based on the comparison and evaluation of the previous the test cases, the result of implementation, the applicability of the co-simulation tool, and the possible further improvement for next development are discussed.

Figure 1.2 describes the flow of the methods and the relation with the corresponding thesis chapter.

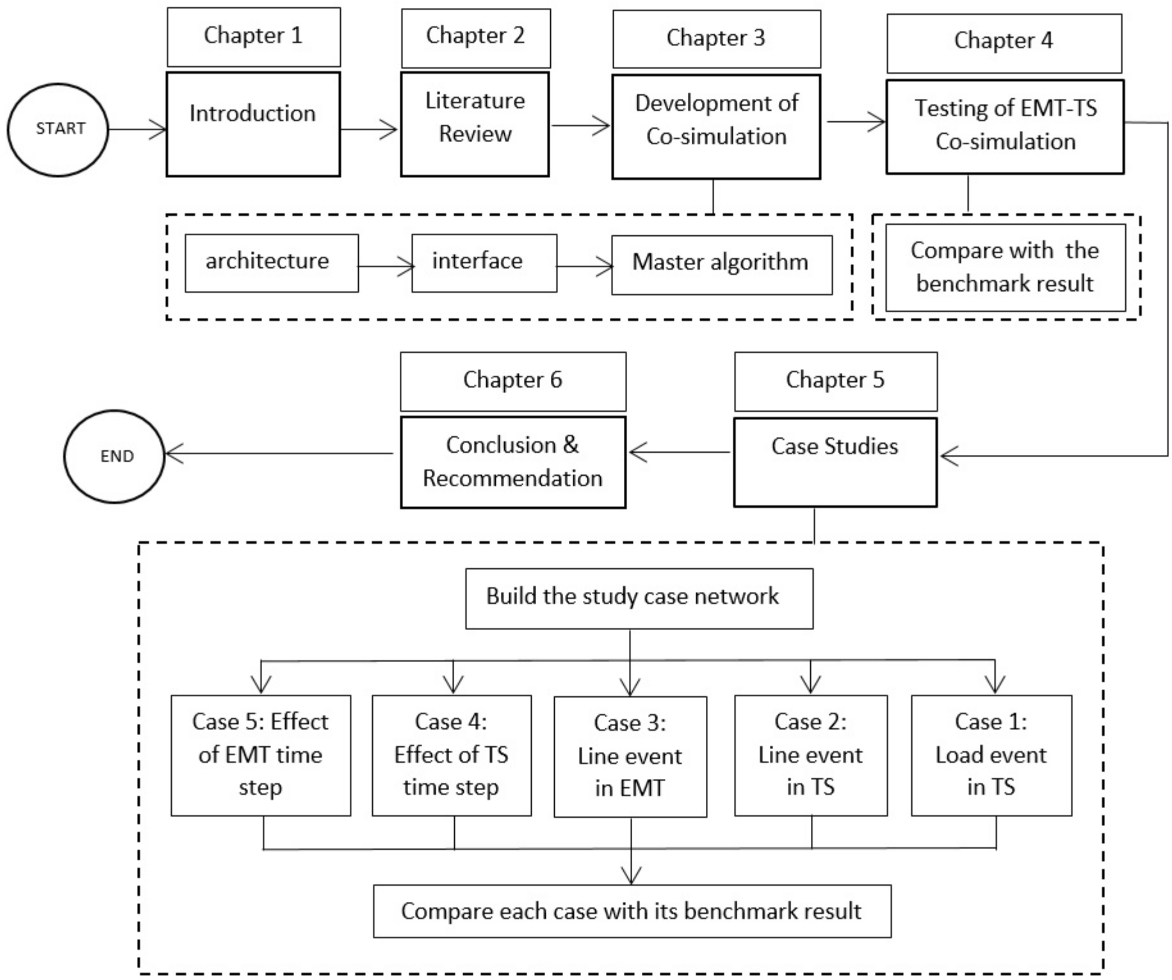

Figure 1.2: The flowchart of methods

1.5. Scope of the Research

The scope of the work that has been done in this thesis are as follows:

- The research is conducted using DIgSILENT PowerFactory as EMT simulator and PSS/E as Transient Stability simulator.
- The python programming language is used as a development environment for this thesis.
- The development of EMT-TS co-simulation covers the design and implementation of master algorithm, PowerFactory interface, PSS/E interface, and PSSE Wrapper.
- The developed co-simulation tool is evaluated in terms of accuracy and execution time. The accuracy is assessed based on comparison with the result of EMT simulation in PowerFactory, and the execution time is evaluated from the time required for the simulation to finish.
- The test as well as the study cases is conducted in 2 balanced network. Therefore, the co-simulation only involves fundamental frequency positive sequence variables.

1.6. Outline of the Thesis

Following this chapter, this master thesis is organized with the following structure:

- In Chapter 2, a literature review and theoretical background about the co-simulation is presented to provide explanations of the technical aspects that are covered in this thesis.
- In Chapter 3, the design of the developed EMT-TS co-simulation is described. In this chapter, the implementation of the co-simulation tool is discussed in detail including the proposed architecture, interface in each simulators, and master algorithm.
- In Chapter 4, The test regarding the developed EMT-TS co-simulation is provided. Specifically, the test method, the test system, as well as the test result are explained.
- In Chapter 5, the application of the developed co-simulation using case studies is presented. In addition, the effect of simulator time step on the accuracy and execution time of the developed co-simulation are studied.
- In Chapter 6, the conclusion regarding the thesis project and recommendation for further research are discussed.

2
Literature Review

2.1. The Basics of Co-simulation

A co-simulation consists of different solvers that cooperate which each other [16]. Each simulator works in a different subsystem/domain and works simultaneously and independently with its solver and model. The simulators are coupled by exchanging variables and parameters between each other. Eg: the output from one simulator will be the input of the other simulator and vice versa. In order to function properly, the co-simulator usually is organized by a so-called master algorithm in which the purpose is to coordinate variable exchange, time synchronization, and execution coordination between solvers.

A basic composition of co-simulation is shown in Figure 2.1. It consists of simulators and master algorithm in which the simulators can be defined as a software composed of a solver and a model. The solver has a function to perform calculations based on its input and the equation embedded in its model. The model can be described in different equations depending on the complexity and the level of detail that want to be achieved. For example, the model of an electrical power systems can be described by an algebraic equation (in the case of a steady-state simulation), differential equation (in the case of an electromagnetic transient simulation) or a combination of both (in the case of transient stability simulation which adds the dynamic of the rotating electrical machine).

There are several functionalities provided by the master algorithm:

- Initialize the simulators. Eg: setting up initial condition for the model in each simulator and establishing communication between master algorithm and simulators.
- Synchronize the time and manage the execution of each simulator.
- Exchange the variables, parameters, and events between simulators.

The process involved in the co-simulation can be described as follows [16]:

1. At the beginning, the master algorithm initializes the models and establishes the communication link (interface) between simulators.
2. Once the initial condition is set, each of the simulators performs a full simulation to its next time step.
3. At a certain point in time called communication point, each of the simulators exchanges variables, parameters, and event data between each other. Each of the communication points is separated by a certain number of time steps depending on the size of the time step defined in each simulator. Usually, the size of the communication point is determined by the largest time step between the involved simulators. For example, in the case of EMT-TS co-simulation, the communication point in TS simulator is separated by one single time step whereas the communication point in EMT is separated in a range of hundreds of time step. This is because TS time step is typically larger than EMT time step. Therefore, the interval between communication point is constrained by TS time step.
4. The process of advancing simulation to the next time step, and the data exchange between simulators are repeated until the simulation reach the last communication point. Here, the sequence of the involved process is governed by a so-called interaction protocol.

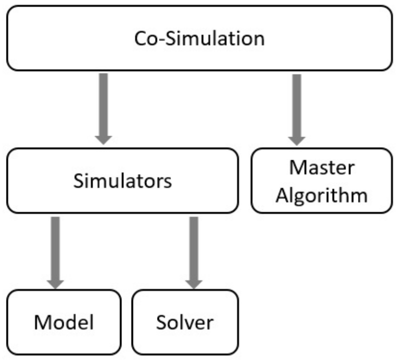

Figure 2.1: A basic composition of a master algorithm [16]

In EMT-TS co-simulation, the system is divided into two parts which are detailed system and external system. The detailed system is a domain where the component of interest is located. In this domain, the component is modeled in detail, and the EMT simulation is carried out to observe the system characteristic in as much detail as possible. On the other hand, the external system is the domain where the rest of the system is located. In this domain, TS simulation is performed due to its faster computation to simulate a larger system. The example of network separation between EMT and TS is previously depicted in Figure 1.1.

To obtain an accurate and efficient result, the appropriate interfacing techniques have to be considered in designing the co-simulation tool. The proper interaction between EMT and TS is determined by these factors [19]:

1. Modeling of an equivalent for the detailed system in the external system.
2. Modeling of an equivalent for the external system in the detailed system.
3. The interaction protocol between EMT and TS program.
4. Selection of interface location.
5. Data exchange between simulators.

Each of the factors is discussed in the next following subsections

2.2. Modeling of an equivalent for the detailed system in the external system

To obtain the proper co-simulation result, one simulation domain needs to represent the other domain by means of an equivalent model. Therefore, the EMT simulation which is executed in the detailed system needs to represent the external system in its model. In the other hand, TS simulation which is performed in the external system also needs to represent the detailed system in its diagram. It is important to represent the equivalent model correctly as the validity of the equivalent model determines the accuracy of the co-simulation.

There are numerous ways to represent the detailed system in the TS side. According to Reeve [19], the detailed system can be represented by:

1. Positive sequence voltage / current source
   Figure 2.2 shows the example of representation using this method. There are two voltage source which represents two EMT networks that is connected to the AC network. The voltage / current source value in Figure 2.2 can be determined according to the value obtained directly from the interface bus at EMT side.

2. Load model
   This model can specifically be represented by either PQ or PV load. There are two loads which represents two EMT networks that is connected to the AC network. The represented power is calculated from the measured voltage and current phasor from the interface bus at EMT side. Figure 2.3 depicts the implementation of this method.

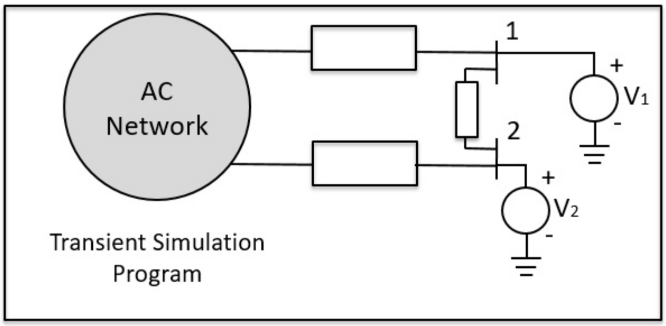

Figure 2.2: Voltage source as a representation of detailed system in TS side [19]

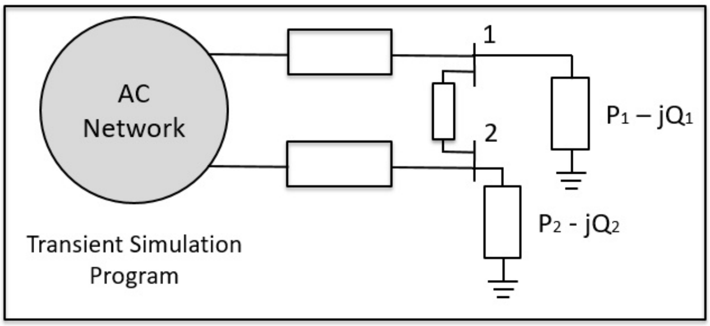

Figure 2.3: Load model as a representation of detailed system in TS side [19]

3. Thevenin / Norton equivalents
   This method requires the information regarding the equivalent impedance in the EMT side. Together with the obtained voltage and current value from the interface bus, the voltage / current source equivalent is calculated. The value of the source is updated at every TS time step. The value of the impedance remains constant as long as there is no change in the parameters of the other network. When there is a switching action in the detailed system, the zequivalent impedance needs to be updated. Example of research that uses this method are [29] [5] [31]. This research uses Norton equivalents to represent the detailed system in the external system. Apart from it, there is also research which uses Thevenin equivalents such as [7]. Figure 2.4 shows the implementation example of Norton equivalent form in the external system. In here, the current source value is calculated based on the variable obtained from EMT, and the equivalent impedance is obtained from the equivalent impedance of the detailed system.

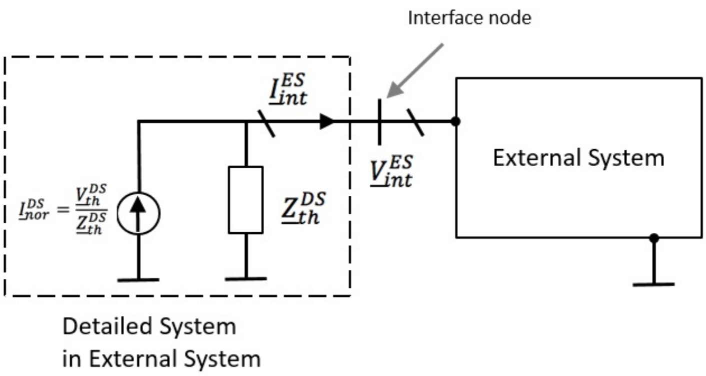

Figure 2.4: Norton equivalent as a representation of detailed system in TS side [29]

4. Decoupled time-varying load model

This method uses power as coupling variable between EMT and TS and has a similar approach to the load model. The difference is that in this model, the load is converted into a current source using the interface bus voltage on the TS side. The voltage and current from the interface bus on the EMT side are converted to power; then the power is converted into current source using the interface bus voltage on the EMT side and updated every TS time step. As power is used as a coupling variable, this method has a simpler way to exchange data between the two domains because there is no need to synchronize the reference point between the TS and EMT domain.

2.3. Modeling of an equivalent for the external system in the detailed system

In contrast with the modeling of the detailed system in the external system, all the proposed equivalents of external system in the detailed system use Thevenin/Norton equivalent circuits [10]. The equivalent circuit consists of an equivalent three phase impedance and three phase current/voltage source which is updated at every EMT time step. The equivalent impedance value is obtained from from the TS simulation and remains constant as long as the network on the TS side is unchanged. However, in the case when an event occurs on the TS side (e.g., short circuit), the equivalent impedance need to be updated. The example of research which uses Norton equivalent are [5] [31] [25] [30] and [13]. In the other hand, the example of research which uses Thevenin equivalent are [7] [29].

The formula to calculate the voltage source/current source phasor value is different depending on the coupled variable between both simulators. The variable options can be voltage, current, or power. Figure 2.5 shows an example of the external system equivalent in the detailed system. The system consists of a voltage source in series with an equivalent impedance that is connected to the interface bus. In this example, the value of voltage source is calculated using the quantities obtained from the interface bus in the external system. The equivalent impedance used in this example is an equivalent impedance of the external system.

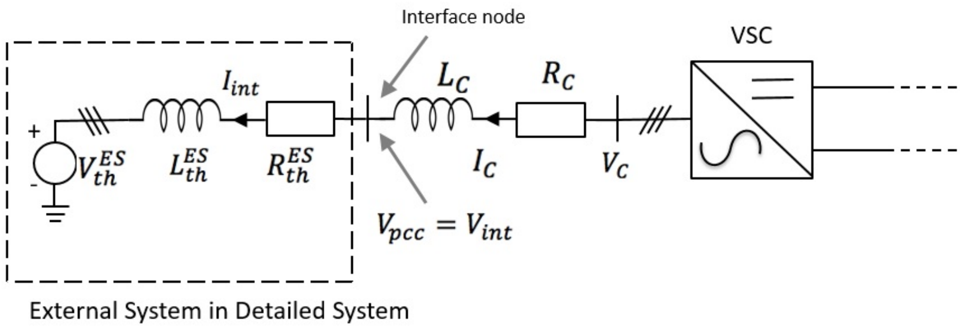

Figure 2.5: The equivalent representation of external system in the detailed system [29]

The simple representation of external system equivalent consists of impedance with R + jX value. In the case when the waveform at the interface bus is closely balanced, this representation is considered sufficient to give the proper response. However, this representation has a drawback as it is not sufficient to give a proper response from the signal over a wider frequency range, e.g., in the case when the waveform at the interface bus is unbalanced and contains a high level of harmonics.

In order to obtain a better EMT result when an event occurs, the equivalent circuit needs to accurately represent the dynamic characteristic of the external system, including the harmonics response. In this regard, a method using a frequency-dependent equivalent circuit is proposed by [2] [26]. A frequency-dependent equivalent has an advantage over a fundamental frequency equivalent by giving a more accurate representation of the system across a wider frequency spectrum. It is composed by a number of series RLC branches that is connected in parallel. The schematic of a frequency-dependent equivalent circuit is depicted in Figure 2.6. The method to derive this equivalent circuit and its application have been discussed in [20] [6] [14].

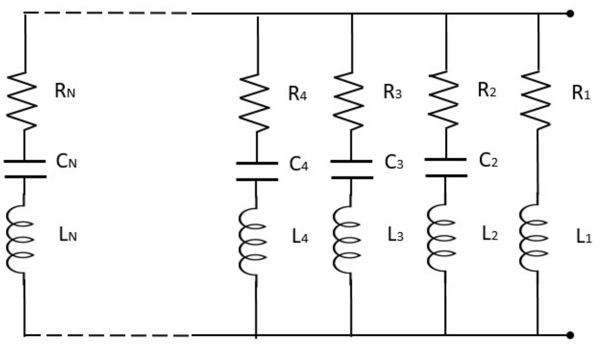

Figure 2.6: Frequency dependent equivalent circuit [26]

2.4. The Interaction protocol Between EMT and TS

As mentioned previously, EMT and TS simulators have different simulation time steps. An EMT simulator has a time step in the order of microsecond while a TS simulator has a time step in the order of millisecond. Therefore, the data exchange between both simulators can not be realized on every time step. Rather, it can only be executed on certain communication points. Usually, the communication point is defined for one TS time step or equal with hundreds of EMT time step.

The interaction involving the exchange of variables between simulators is governed by an interaction protocol. The functions of the interaction protocol are to determine which simulator that needs to perform calculation and to organize the data exchange [10]. There are two main interaction protocols: the serial and parallel protocol. Both interaction protocols are described as follows:

Serial interaction protocol

In a serial protocol, when one simulator performs the calculation for the next time step, the other simulator is idle. Once the simulator performing the calculation is done with its process, its variables are sent to the other simulator and then it is the other simulator's turn to start performing calculation while the previous simulator is idle. Several publications which implement serial protocol in the hybrid simulation for instance [7] [19] [2] [29].

Figure 2.7 shows the diagram representing the interaction protocol between EMT and TS. The process in the Figure can be explained as follows:

1. Both EMT and TS simulator advance from t_0 to t_1.
2. The equivalent of TS is calculated and sent to the EMT simulator.
3. The EMT simulator advances from t_1 to t_2 using the TS equivalent of TS at t_1. At this moment, the TS simulator is idle.

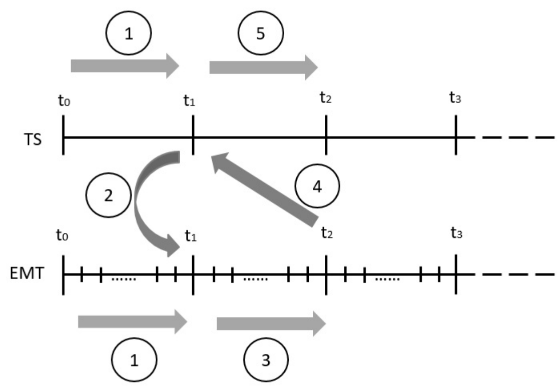

Figure 2.7: Serial Interaction Protocol [10]

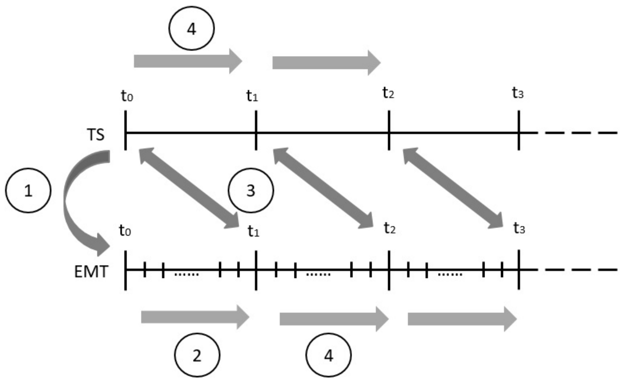

Figure 2.8: Parallel Interaction Protocol [10]

4. The equivalent of EMT is calculated and sent to the TS simulator.
5. The TS simulator advances from t_1 to t_2 using the equivalent of EMT at t_2. At this moment, EMT simulator is idle.
6. The step from 2 to 5 are repeated until the simulation reaches the end of simulation time.

Parallel protocol

In contrast with the serial protocol, in the parallel protocol, both simulators advance to the next time step in parallel without waiting for each other. The research which implements parallel protocol in hybrid simulation, for instance are [25] [5].

Figure 2.8 shows the sequence of parallel interaction protocol as mentioned from Fang 2005. The process can be explained as follows:

1. The TS equivalent is transferred to the EMT simulator at t_0.
2. Using the equivalent obtained from TS at t_0, EMT simulator advances to t_1.
3. The TS simulator transfers its equivalent at t_0 to EMT simulator, and EMT simulator transfers its equivalent at t_1 to TS simulator.
4. Using the newly obtained equivalent, both TS and EMT simulator advance to its next communication point. TS simulator advances to t_1 while EMT advances to t_2.
5. Step 3 and 4 are repeated until simulation reaches the end of simulation time.

Both interaction protocol have their own advantages and disadvantages. In the serial protocol, as each simulator needs to wait for another simulator to finish, there is an amount of time wasted resulting an inefficient simulation. Contrarily, in the parallel protocol, both simulators perform simulation at the same time. Thus, the simulation is more efficient, resulting in a faster computation time compared to a serial protocol. However, the advantage in the simulation time is traded with accuracy in the result. In the parallel protocol, one simulator advances to the next communication point by receiving the equivalent from the previous time step instead of the same time step as in the serial protocol. Therefore, the result obtained from the parallel protocol is less accurate compared to serial.

2.5. Data exchange between EMT-TS

In co-simulation, each simulation domain (TS and EMT domain) is solved by different numerical solver using differential algebraic equations. In the traditional simulation approach, the differential algebraic equations are composed within a single system. Therefore, the output and state equation of every devices are strongly coupled. However, in co-simulation, these equations are weakly coupled because each domain is solved independently and only exchanges output in a certain communication point. This process introduces an

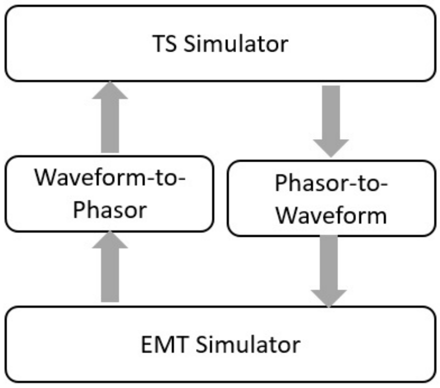

Figure 2.9: Data conversion between EMT-TS [10]

algebraic loop, which means each domain is coupled in the way that the output from one domain becomes the input to the other domain and vice versa. In this case, an extrapolation to the inputs is required at the beginning of the simulation in order for one simulation domain to advance to the next time step. This could potentially causes a numerical error which affects the accuracy and stability of the co-simulation [16].

There are two things that need to be considered regarding the data exchange in co-simulation. The first one is the choice of interface variables, and the second one is the data conversion between two domain.

2.5.1. Choice of interface variables

According to [2], the type of information transferred from one solver to the other must be sufficient to determine the direction of power flow, whether it is towards or outwards the interface. The choice of variables which can be measured, for instance are real power, reactive power, voltage, current through the interface, and phase angle information in the case of using different reference frame.

The direct use of voltage or current at the interface bus as exchanged variable needs an additional data processing to transfer the reference frame information between two domains, resulting in a more complex algorithm. The data processing can be made simpler by using power as exchanged variable as power information is independent to the reference frame.

Furthermore, as TS simulation is based on fundamental frequency positive sequence quantities, the fundamental frequency positive sequence power is more appropriate to be used as exchange variable. The use of RMS power as exchange variable is inappropriate because RMS power is not always the same with positive sequence power as it contains positive, negative, and zero sequence power. In order to obtain the correct value of power, the proper extraction of fundamental frequency positive sequence voltage and current from each simulator is required.

2.5.2. Data Conversion

As mentioned previously, TS and EMT simulation has different representation. TS simulation is based on phasor representation, and EMT is based on the three-phase instantaneous waveform. Therefore, data conversion is needed to exchange the data from EMT to TS and vice versa. As can be seen from Figure 2.9, the data conversion required to share information from EMT to TS is waveform to phasor conversion while the conversion required fro TS to EMT is phasor to waveform conversion. The method for each conversion process are discussed as follows:

1. EMT to TS
   There are two options of phasor extraction from EMT to TS which are: Fast Fourier Transform (FFT), and curve fitting method.

   (a) Fast fourier transform (FFT):
   FFT is a method based on Discrete Fourier Transform. This approach has an advantage over DFT that it can calculate the phasor information and the frequency of the sampled signal in a more efficient way, thus reducing the needed computation time [3]. However, this method has the limitation that it requires a number of samples of exactly one cycle to correctly produces the phasor

quantities [30]. The limitation has a consequence when an event occurs. As the FFT method needs a sampling period of one cycle, the sudden change of phasor quantities can not immediately be transferred to TS side, resulting a delay in information exchange and introduces an additional error in the co-simulation.

(b) Curve fitting:
Curve fitting is a method to fit a series of data points into a mathematical function. Compared to FFT, the curve fitting method does not have the limitation of a one-cycle data requirement. By using this method, the delay in information exchange from EMT to TS can be minimized. In comparison with the FFT method, this approach is considered simpler and has less computational burden [10] [13]. However, this method has the limitation that it is not effective to extract information of the signal when a DC offset occurs in the waveform.

The result of the extracted phasor is also determined by the quality of the sampled data. When an event occurs, high level of waveform distortion may exist at the interface bus. In this case, the use of low sampling frequency may result in inaccurate data processing, thus producing an inaccurate phasor extraction. It is advised to use the minimum sampling rate at twice fundamental frequency to obtain an accurate data extraction [18].

2. TS to EMT
The conversion between TS to EMT involves the conversion from fundamental frequency positive sequence phasor to three-phase waveform quantities as can be described by the following equation:

$$v_a = \sqrt{2}V_1 \cos(2\pi f t + \theta) \tag{2.1}$$

$$v_b = \sqrt{2}V_1 \cos(2\pi f t + \theta - \frac{2\pi}{3}) \tag{2.2}$$

$$v_c = \sqrt{2}V_1 \cos(2\pi f t + \theta + \frac{2\pi}{3}) \tag{2.3}$$

Where v_a, v_b, and v_c are the three phase voltage waveform at specific t and V_1 is the positive sequence voltage magnitude

It should be noted that TS has larger time step than EMT. Therefore, it is possible that the magnitude and the phase angle of TS quantities may change suddenly because of such event (e.g., short circuit in TS side). The sudden change of phasor information from TS, when exchanged to EMT, could result in a sudden change in waveform. A more continues waveform can be obtained by providing a transitional phasor using interpolation between two TS time steps. The intermediate phasor approximation can be implemented using First Order Hold (FOH) formula:

$$\theta_{(t_0+n\Delta t)} = \frac{\theta_{(t_0+h)} - \theta_{(t_0)}}{h} n\Delta t + \theta_{t_0} \tag{2.4}$$

Where h is the integration time step in TS, $\theta(t_0 + h)$ and $\theta(t)$ is the phase angle in the interface bus at $t + h$ dan t

Apart from the interpolation method, an alternative called frequency deviation method is proposed in [13]. This method interprets a phase angle deviation between each TS interval as a change in frequency. Therefore, instead of sending phasor information with different phase angle, this method sends the phasor information with the same phase angle as before, but with different frequency. By using this method, a continuous waveform between two TS time step can be obtained. The frequency deviation can be determined by using the following formula:

$$f_{(t_0+h)} = f_0 + \frac{1}{2\pi} \frac{\theta_{(t_0+h)}) - \theta_{(t_0)}}{h} \tag{2.5}$$

With $f(t_0 + h)$ represents the frequency of the phasor information exchanged to EMT. f_0 is the fundamental frequency, h is the integration time step in TS, $\theta(t_0 + h)$ and $\theta(t)$ is the phase angle in the interface bus at $t + h$ dan t. The comparison of waveform obtained by using fundamental frequency, frequency deviation method, and phasor interpolation can be observed in Figure 2.10.

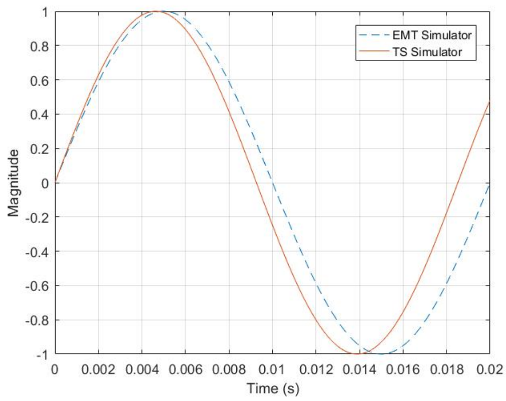

Figure 2.10: Comparison between fundamental frequency, stepwise phasor, and frequency deviation method [13]

2.6. Selection of interface location

The detailed and external system are separated in a location where the co-simulation interface is located. The role of the interface is to monitor the exchanged variables and send them to the other domain. Also, it serves as an equivalent of the other domain, providing the equivalent dynamic response from the other domain. As higher computation effort is needed in performing EMT simulation, it is important to determine the optimal interface location which separated two domain in order to obtain a more efficient co-simulation. There are no explicit rules to determine the interface location [10]. Generally, the point of the interface bus is optimally placed where the detailed system does not contain too many components while the equivalent of both domains still can be representative [25]. However, it should be mentioned that the location of the interface bus affects the accuracy of the monitored variables and the representation of system equivalent.

The size of the detailed system is affected by two factors that are the level of waveform distortion and phase imbalance at the interface bus [19]. The level of waveform distortion and phase imbalance in the interface bus affects the accuracy of the monitored variables. These factors have an impact in the case where the dynamic event takes place in the detailed system. When a balanced dynamic event (i.e., three phase bus fault) occurs, the level of waveform distortion and phase imbalance are low. However, in the case of an unbalanced dynamic event (i.e., Unsymmetrical fault), the level of the mentioned factors may be significant, especially in the location near the occurrence place of the dynamic event. Generally, the closer the location to the event location, the greater the level of distortion, and vice versa.

The history regarding the interface location issues in co-simulation can be summarized as follows: In the early attempts to couple EMT and TS simulation by Heffernan et. al [7] [28] [27], they proposed the model of HVDC system in EMT domain which interacts with AC system in TS domain. In their model, the interface is located at the terminal of the converter.

Further improvement was made by Reeve and Adapa in 1988 [19] [1] by altering the location of the interface bus. Instead of putting the interface in the converter terminal as in the Heffernan paper, they moved the interface location away from the terminal further into the AC network. The reason is that the farther the location from the terminal, the waveform distortion and the phase imbalance is less prevalent, resulting in more balanced network quantities. Hence, more appropriate fundamental frequency quantities can be obtained. In addition, the curve fitting method is used in their paper instead of FFT to allow the flexibility in alternating the simulation step size.

Anderson in 1995 again moved the interface to the converter bus [2]. He opposed the idea of moving the interface location away from the converter bus. He argued that by moving the interface location far from the converter bus, the detailed system and the interface technique could become more complex. To deal with the phase imbalance and wave distortion at the point near the converter bus, they used frequency-dependent equivalent network and use fundamental frequency positive sequence power as coupling variable. This solution solves the mentioned problem and improve the response of network equivalent towards the harmonic that occurs in the system. Therefore, the interface location can be moved closer to the location where the event occurred. However, it should be noted that the problem regarding the lack of accuracy in the data extraction still remains. A similar approach using frequency-dependent equivalent network also carried out by Sultan in 1998 [26].

If the variables monitored in the interface bus contain a high level of distortion, the number of samples obtained from the monitored variables may not be sufficient for extracting the fundamental components [25]. In addition, there is also a limitation in regards with the equivalent of the external system. If the external system is represented by a simple fundamental frequency equivalent, then the dynamic of the detailed system which contains the harmonics from a wide range of frequency spectrum can not be accurately represented.

From the mentioned history, there are two approaches that can be adopted to determine the interface location [24]. The first approach is by choosing the interface location near the occurrence of the dynamic event (i.e. the converter terminal). The main advantage of using this approach is that the computation time can be reduced due to the smaller size of the detailed system. In the other hand, this approach has the disadvantage which is the lack of accuracy in the extraction of the fundamental frequency component, and the inaccurate dynamic response from the equivalent of the external system. However, this limitation could be solved by using frequency-dependent equivalent network and use fundamental frequency positive sequence power as coupling variable [2].

The alternative is to place the interface location farther from the occurrence point of the dynamic event, thus extending the detailed system into the external system. The main advantage of this solution is that more balanced variables can be extracted at the interface bus. Therefore, the fundamental frequency component extraction can be more accurate. In addition, since the distortion level is also lower, the dynamic response using fundamental frequency equivalent is sufficient enough. The disadvantage of this solution is related to the computation time. As larger part of the external system is included in the detailed system, the number of component which needs to be modeled is also increasing. In addition, the farther the location is extended to the external system, the number of interface bus may increase, increasing the complexity of the detailed system. These factors lead to an increase of the required computation time.

2.7. Chapter summary

In this chapter, the literature review relating to the development of hybrid co-simulation is presented. The main purpose of this chapter is to review the ideas and methods related to co-simulation from literature. Furthermore, The review presented in this chapter is used as a basic foundation to develop co-simulation tool using PowerFactory and PSSE which is discussed in the next chapter.

The review is started by the basic explanation of co-simulation followed by the detailed explanation of the master algorithm and the process behind it. In co-simulation, the system is divided into two domains where each domain is simulated independently by two different simulators. Therefore, each domain needs the representation of the other domain by a form of equivalent model. As each simulator has different time step, such interaction protocol is necessary to coordinate the data exchange between two simulators. In addition, since each domain has a different type of signal representation (e.g., Waveform vs. phasor), then data conversion mechanism between each domain is required. Lastly, it should be mentioned that the selection of interface location could affect the simulation accuracy. All of these aspects are important to obtain the proper interaction in co-simulation. Therefore, in this chapter, these issues are reviewed in detail in each subsection.

3

Design of EMT-TS Co-simulation Using PowerFactory and PSS/E

One of the research's objectives in this thesis is to develop EMT-TS co-simulation between PowerFactory and PSS/E. In this chapter, the design of the developed EMT-TS co-simulation is presented. The design is defined by first describing the proposed architecture. Then, each of the elements in the co-simulation architecture is explained, started from the interface to PowerFactory, the interface to PSS/E, the master algorithm, and the PSS/E wrapper. In addtion, the previous design of master algorithm is also provided to give the insight about the design iteration used in this thesis.

3.1. Architecture of EMT-TS Co-simulation

One of the challenges in developing co-simulation is selecting the appropriate design architecture. The selection of co-simulation architecture is important because it affects the selection of communication method, interaction protocol, and extensibility in the future [8]. In this thesis, the design of the co-simulation is selected based on the conducted literature review considering the implementation practicality aspect. The proposed architecture of EMT-TS co-simulation is proposed as shown in Figure 3.1.

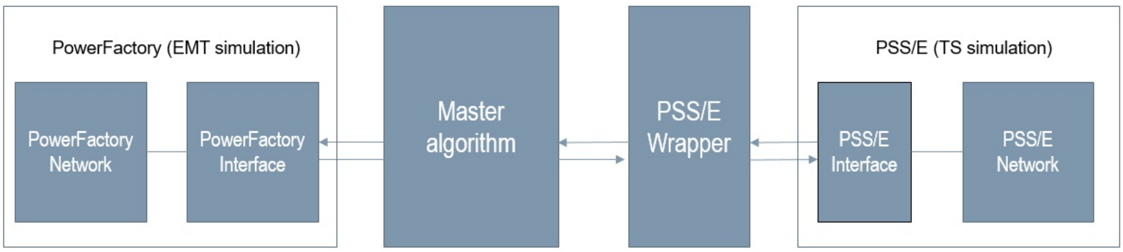

Figure 3.1: The architecture of EMT-TS Co-simulation

There are four main parts in the proposed architecture. They are Master Algorithm part, PowerFactory part, PSS/E part, and PSS/E wrapper part. EMT simulation is performed in PowerFactory whereas TS simulation is performed in PSS/EPowerFactory acts as an EMT simulator, PSS/E acts as a TS simulator, and the interaction between them is coordinated by the master algorithm.

The network in each simulator consists of power system model and an interface. The function of the interface is to obtain and set the variables in the simulator. The obtained variables are sent to the master. Conversely, the master also sends interface variables to the simulator. In here, the interface is responsible for settling its voltage and current according to the data sent by the master. Apart from these function, the interface also acts as an equivalent representation of the other part which is simulated in other simulator. Therefore, when the network on the other side is modified, the equivalent impedance should be updated as well.

EMT and TS simulators are connected with master algorithm block. The master algorithm plays an important role in the co-simulation. The functions of the master algorithm are as follows:

1. Orchestrate the co-simulation

   As two simulators are performing simulation independently, a coordination between them is needed. Master algorithm is responsible for managing the interaction between them. In addition, the master algorithm also coordinates both simulators in the case of event occurance.

2. Establish a connection and exchange variables between two simulators

   The master is responsible to create a connection with the same protocol to EMT and to TS. When the simulator sends the interface variables data, the master must able to accept the data, and vice versa.

3. Perform data processing

   As EMT simulation is based on point on wave and TS is based on phasor, a data processing is needed to enable data exchange between them. In the master algorithm, the conversions between waveform to phasor and phasor to waveform are implemented.

In the case of master algorithm to PowerFactory, the master communicates directly with the interface in PowerFactory, whereas in the case of master algorithm to PSS/E, the master communicates with the PSS/E wrapper, then the PSS/E wrapper communicates with the master. The functions of PSS/E wrapper are as follows:

1. Controlling PSS/E behavior during co-simulation

2. Obtain the data and modify the power set point of PSS/E interface

3. Enable data exchange between master and PSS/E interface

Among the coupling variables mentioned in the literature review, power is selected as the exchanged variable between EMT-TS because it is independent to the reference information. Using power as the coupling variable can be beneficial because there is no need to include the reference frame information every time the variables are exchanged. Thus, it could reduce the complexity and simplify the master algorithm.

In EMT, the power information is obtained from the instantaneous total power at the interface bus. On the other hand, in TS simulation, the power information is obtained from the positive sequence power phasor at the line connected directly to the interface bus.

In this thesis, the development of co-simulation is implemented using Python programming language. The Python language is selected because it provides the required Application Program Interface (API) for both PowerFactory and PSS/E. Three python scripts are developed which are:

1. emt_ts_convert.py : a python script which implements a library of functions used for the co-simulation. The functions that implemented in this script for instance are the script to convert waveform to phasor and the script to calculate EMT's voltage source phasor.

2. master.py: a python script for the master algorithm.

3. ts_wrapper.py : a python script for PSS/E wrapper.

The communication between PowerFactory, Master Algorithm, and PSS/E is implemented using socket-based communication. The socket communication is selected because its implementation has already been supported by the DSL model used for PowerFactory interface. Furthermore, it could enable the possibility of distributed simulation over Local Area Network (LAN) in future developments.

In the proposed architecture, there is no modification to PowerFactory and PSS/E. The modification is only on the interface which is based on the available component in the simulator. Therefore, The proposed approach and algorithm can be modified to be implemented on other EMT or TS simulation.

3.2. PowerFactory Interface

As power is selected as coupling variable, the selected interface design must be able to represent power information from the other simulator. In the literature review, the design to represent the other domain has been described. For representation of the external system in the detailed system, there is only one option mentioned in the literature review, that is using Norton/Thevenin equivalent. The equivalent in the detailed system can be modified to accommodate power as the coupling variable.

Using a Thevenin equivalent as the model representation, the design of interface bus in PowerFactory is shown in the Figure 3.2. From the figure, there are 6 variables that are sent to master algorithm which are the three phase voltage at the interface bus v_a, v_b, v_c, frequency, active and reactive power flowing at the interface bus. In the other hand, the number of variables that are received from master algorithm is 5 which are the three phase voltage of the voltage source e_a, e_b, e_c, and the impedance value of the series reactor R_{PF}, X_{PF}. These values are used to set the voltage and current at the interface bus so that the value is equal with the power sent from PSS/E.

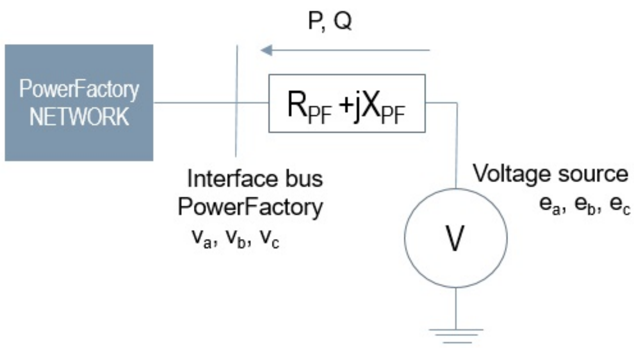

Figure 3.2: The design of the interface in PowerFactory

Figure 3.3 shows the realization of the interface design in PowerFactory in whih it consists of a voltage source connected with an equivalent impedance. The voltage source part is realized using *AC Voltage Source* component in PowerFactory which is controlled using external signals so that the voltage and current in the interface bus can represent the power informaton passed from TS. The equivalent impedance of the TS network is realized by using *Series Reactor* component in PowerFactory, which receives the impedance value from the master at every EMT time step.

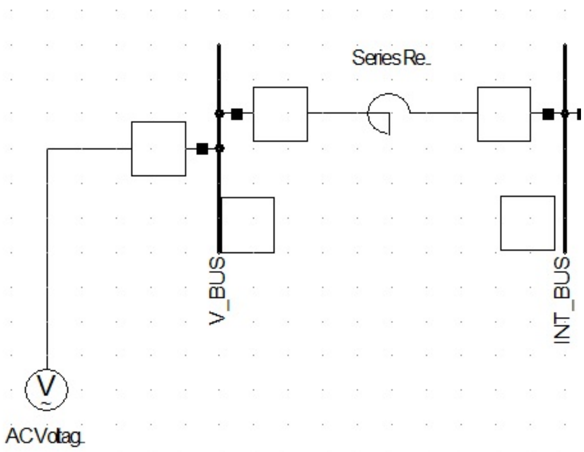

Figure 3.3: The design implementation of the interface in PowerFactory

The interface design should have capability to send and receives data to/from master. The interface must send the voltage and current at the interface bus to master. Then, the interface design must be able to receive the calculated voltage waveform for the next EMT timestep. The required capabilites to communicate between interface bus in PowerFactory to master is facilitated by API and External DLL that is developed by [23].

External Communication using API and External DLL

In co-simulation the interface variables need to be modifed at every time step. Howeverm, there is a limitation in the dynamic simulation in PowerFactory in the fact that the initial condition must be recalculated every time the calculation relevant model is modified. The mechanism to modify the dynamic simulation variables is provided by DSL in PowerFactory. It is developed to interact with the internal network equation system to create changes, for example to modify the generator voltage set points.

In co-simulation, the interface must be able to read and modify variables according to the calculated value from master. As mentioned from [23] The only method to modify variables in PowerFactory during EMT/RMS simulation is to communicate with a DSL block via external defined functions. In this co-simulation design, the external communication is enabled by API and external DLL that is developed by [23]. These features enable the data in the interface bus to be read and send to the master via socket communication. Similarly, the data from master can be sent to PowerFactory via socket communication and used to set the voltage source by the DSL block. Figure 3.4 shows the modified diagram from [23] that explains the interaction between PowerFactory, master, DLL, and DSL model in this thesis.

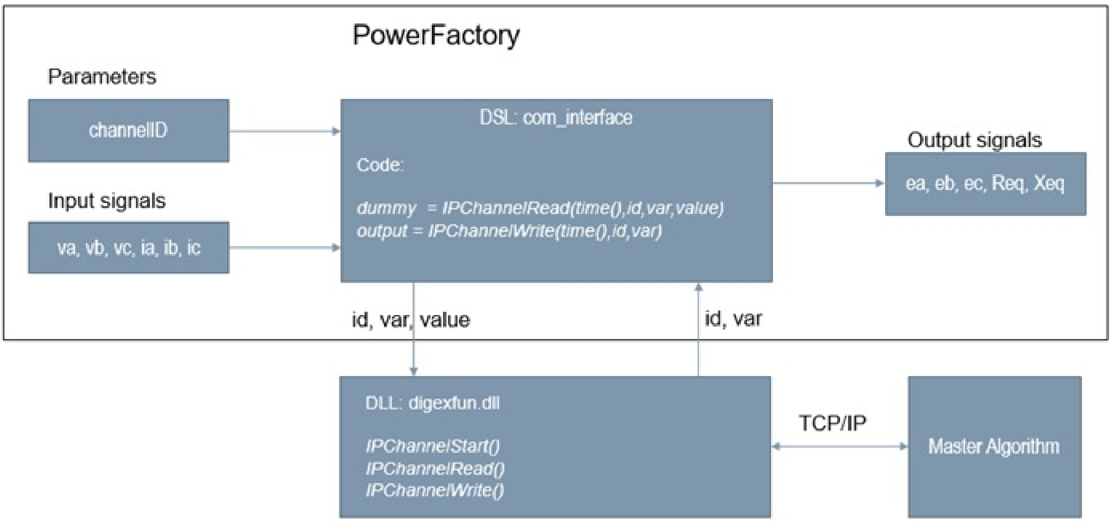

Figure 3.4: The interaction between PowerFactory, master, DLL, and DSL model in PowerFactory interface

The function of com_interface DSL model is to provide the communication link between the PowerFactory network and the external network. To perform the function, the DSL model need to define a parameter and connection to the input/output signal of PowerFactory component. In this co-simulation, the DSL model receives 5 input signals (v_a, v_b, v_c of the interface bus, and P, Q obtained from series reactor) and 5 output signals (e_a, e_b, e_c signal for the voltage source component, and R_{PF}, R_{PF} signal for the series reactor component). The input and output of the DSL model is defined in the cosim_interface frame model in PowerFactory in which the diagram is shown in Figure 3.5

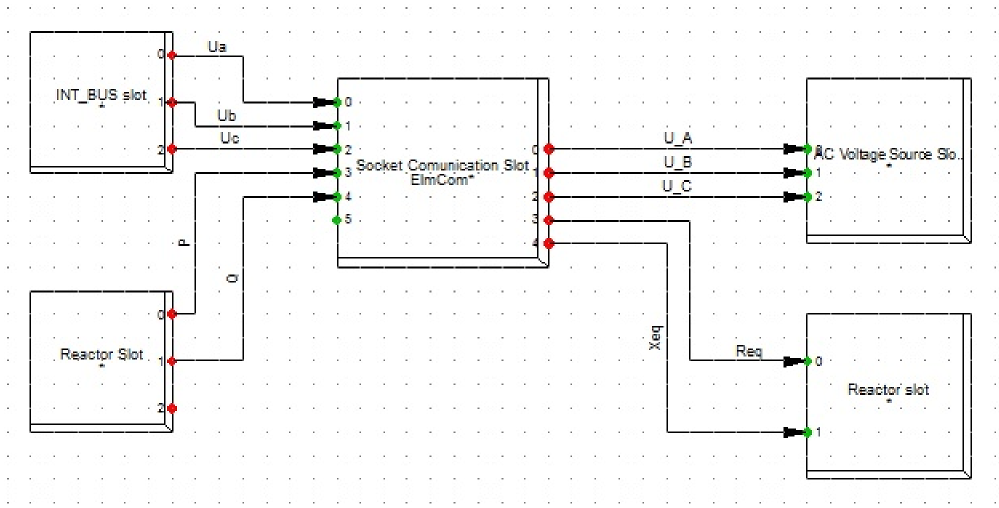

Figure 3.5: The composite model frame diagram of the co-simulation interface in PowerFactory

3.3. PSS/E Interface

For representation of the detailed system in the external system, the methods that can accommodate power as the coupling variable are the load model and decoupled-varying load model. As the interface must able to change its power set point during a dynamic event, then decoupled varying load model is more suitable. However, the power can not directly transferred to either EMT or TS because the differential equation involved in each simulator is not based on power. Therefore, the power needs to be converted to other quantities, e.g. voltage or current. The decoupled load model can be realized by a voltage source or current source in combination with an equivalent impedance.

The PSS/E interface is designed by the author of [29]. It is implemented in PSS/E by using a modified static generator. In this model, the static generator is able to receive power information from the master algorithm and based on that, it modifies the current injection to PSS/E interface bus. PSS/E models its static generator by a current source connected with a parallel impedance. Therefore, the interface is modeled using Norton equivalent to fit the model of static generator in PSS/E.

The PSS/E interface receives P and Q from the master algorithm via the PSS/E wrapper. The received P and Q are internally transformed into current source phasor using equation 3.1. After advancing to the next time step, PSS/E also needs to transfer power information to the master. The power information is obtained from the transmission line which is directly connected to the master.

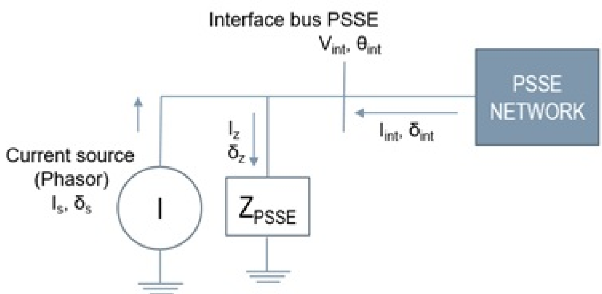

Figure 3.6: The internal model of the PSS/E interface

The internal model of the PSS/E interface is shown in Figure 3.6. In this figure, the interface is represented with a Norton equivalent that consists a current source connected in parallel with an impedance. The relation between the current source, the equivalent impedance, and the interface bus in the figure can be described by the following equation:

$$I_s\angle\delta_s = I_z\angle\delta_z + I_{int;PSS/E}\angle\delta_{int;PSS/E} \tag{3.1}$$

Where $I_s\angle\delta_s$ is a current source phasor, $I_z\angle\delta_z$ is the current flowing to the equivalent impedance, and $I_{int;PSS/E}\angle\delta_{int;PSS/E}$ is the current flowing towards/into the interface bus. Furthermore, the equation can be expanded by exploiting I_z and $I_{int;PSS/E}$. The terms I_z can be replaced by $Vint/Z$ and $I_{int;PSS/E}$ can be substituted by $S/3V$. Then, the equation becomes as follows:

$$I_s\angle\delta_s = \frac{V_{int;PSS/E}\angle\theta_{int;PSS/E}}{Z_{PSS/E}\angle\theta_{Z;PSS/E}} + \frac{S^*_{PF}\angle\theta_{SPF}}{3V^*_{int;PSS/E}\angle\theta_{int;PSS/E}} \tag{3.2}$$

where $V_{int;PSS/E}\angle\theta_{int;PSS/E}$ is the voltage phasor of the PSS/E interface bus, $Z_{PSS/E}\angle\theta_{Z;PSS/E}$ is the phasor of equivalent impedance, and $S_{PF}\angle\theta_{SPF}$ is the power from PowerFactory

To implement the interface in PSS/E, two files are needed which are DSUSRIEEEPWRDV33.dll and interface.dyr. The dll file is the file which modifies the static generator behavior during dynamic simulation. The dll file is similar with common model in PowerFactory; it contains a set of equations which determine the relationship between input, state, and output of the interface. The DSUSRIEEEPWRDV33.dll contains a set of equations which describe the behavior of the PSS/E interface during dynamic simulation. The dll file is obtained by compiling Fortran code which contains the above information. In this thesis, the DSUSRIEEEPWRDV33.dll has been developed by the author of [29]. Therefore, the dll and the Fortran source code is not described and documented in this thesis.

3.4. Master Algorithm

One of the function of master algorithm is to exchange variables between simulators. Since the data representation from EMT and TS are different, a data processing is needed to convert the data from one simulator to another . The data from EMT simulator is based on point of wave data whereas the data from TS is based on phasor. The informations which are received and sent to both instance are presented in the Table 3.1 and 3.2.

Table 3.1: The input and output of EMT to TS conversion in the master algorithm

EMT to TS			
Input	Remarks	Output	Remarks
t	time stamp EMT	tnext	next TS time
va(t)	interface bus voltage waveform phase a	P	the active power of PF
vb(t)	interface bus voltage waveform phase b	Q	the reactive power of PF
vc(t)	interface bus voltage waveform phase c		
P(t)	the active power flowing at the PF interface bus at particular t		
Q(t)	the reactive power flowing at the PF interface bus at particular t		
f	system frequency		

Table 3.2: The input and output of TS to EMT conversion in the master algorithm

TS to EMT			
Input	Remarks	Output	Remarks
P	the active power of PSS/E	ea(t)	voltage source waveform phase a
Q	the reactive power of PSS/E	eb(t)	voltage source waveform phase b
		ec(t)	voltage source waveform phase c
		R	real part of equivalent impedance
		X	imaginary part of equivalent impedance

The conversion process and the interaction between EMT-TS and TS-EMT are managed by the master algorithm. In this section, the data processing involved in the master algorithm which is implemented using functional blocks are presented. Next, the interaction protocol that manages the data exhange between them are described.

3.4.1. Data Processing Inside the Master Algorithm

The master algorithm consists of functional blocks which has different function to facilitate the data conversion process. There are two main process in the master algorithm. The conversion between EMT to TS, and from TS to EMT. The explanations of each process are as follows:

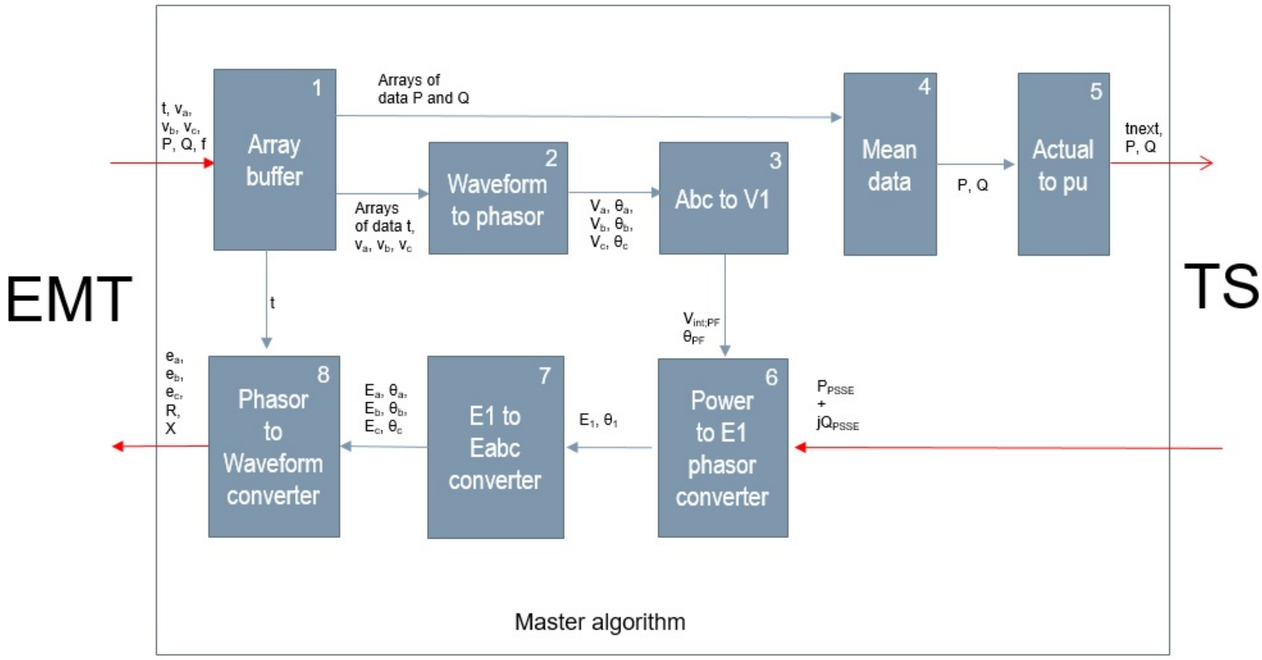

Figure 3.7: The functional blocks inside master algorithm

Data Conversion from EMT to TS

For the conversion from EMT to TS, firstly, the power informations obtained from EMT are stored in an *array buffer* block until it reaches the same time position with TS time stamp. Next, the power informations in the array are averaged in the *mean data* block. Then, The averaged power is converted to its per unit value with *actual to pu* block. Finally, the power informations are sent to PSS/E wrapper along with the information of the next PSS/E time step.

Data Conversion from TS to EMT

For the conversion from TS to EMT, the process involves the PowerFactory interface bus's voltage phasor. Since the EMT is waveform based, the conversion between waveform to phasor is needed. First, The obtained voltage waveforms received by the master at every EMT time step are stored in the *array buffer* block until the PowerFactory time stamp is the same with TS time stamp. Next, the stored data is processed using the *waveform to phasor* block to obtain the voltage phasor in each phase of the PowerFactory interface bus. Since TS is based on positive sequence fundamental frequency, it is needed to convert the phasor from each phase into a positive sequence phasor. The obtained phasor is converted into positive sequence phasor by *abc to V1* block. The positive sequence voltage phasor, together with the power received from PSS/E wrapper, are used to compute the positive sequence voltage phasor of the interface bus's voltage source via *Power to E1 phasor converter* block. Then, the obtained positive sequence voltage source phasor is used to calculate three phase voltage source phasor using *E1 to Eabc converter* block. The waveform of each EMT time step is calculated using the obtained three phase phasor with *Phasor to Waveform converter* block. Finally, the voltage waveform informations together with the value of equivalent impedance (Req and Xeq) are sent to the PowerFactory interface.

The interactions between each of the blocks composing the master algorithm are shown in Figure 3.7. The description of each of the mentioned blocks inside master algorithm are described as follows;

1. **Array Buffer**

The block has the function to store the waveform data from EMT. It is realized using a numpy array in python programming language. There are 7 variables that are stored in the buffer which are PowerFactory time stamp, three phase voltage at the interface bus v_a, v_b, v_c, frequency f, active and reactive power flowing at the interface bus P and Q. The number of data that are stored in the array depends on the EMT time step. For a time step of 50 μs, the array size is 400 whereas for a time step of 25 μs, the array size is 800.

2. **Waveform to Phasor**

   Using the availabe set of datas in the buffer, the waveform information can be processed to yield phasor data. The *Waveform to Phasor Conversion* receives the array of time stamp t and waveform informations v_a, v_b, v_c from the *array buffer* block and calculate the complex phasor and its frequency. The FFT method is selected for the waveform to phasor method in the master algorithm design because it is more reliable than the curve fitting method in the performed co-simulation test. The FFT used in the co-simulation design is implemented using *fftpack* from *Scipy* Python module based on [4].

   The FFT method is further improved by using a moving-window FFT. Using this method, when a new waveform informations are coming from PowerFactory, the data stored in the waveform is shifted to the left. Then, the last data in the array is replaced by the new arrived waveform information. Using this method, the FFT method can be used in a smaller co-simulation integration time, which could enable a faster data synchronization between both simulators.

   The curve fitting method has been implemented and tested in the master algorithm source code. Although the curve fitting method is more flexible due to the absence of one-cycle data requirement, the curve fitting method failed when being used in the co-simulation test. The reason is expected because of the improper code implementation or could also because the method failed to compute the phasor information from the waveform data.

3. **ABC to V1**

   The block has the function to compute a positive sequence phasor from three phase quantities. It receives a complex voltage phasor from phase a, b, and c and returns a positive sequence phasor using the following equation:

   $$V_1 = \frac{1}{3}(V_a + aV_b + a^2 V_c) \tag{3.3}$$

   Where $a = e^{\frac{2\pi}{3}j}$, V_1 is the positive sequence voltage phasor, and V_a, V_b, V_c represent voltage phasor at each phase of the interface bus.

4. **Mean data**

   In this block, the P and Q array data from *array buffer* block is averaged to obtain the power information which will be sent to PSS/E wrapper.

5. **Actual to p.u.**

   The power obtained from the *Mean data* block is expressed in MVA. However, the power that is sent to PSS/E interface must be expressed in per unit. Therefore, a conversion from actual value to per unit value is needed. In this block, the power obtained from *Mean data* block is divided by power base value and then the result is forwarded towards PSS/E wrapper. The equation involved in this block is as follows:

   $$S_{pu} = \frac{S_{actual}}{S_{base}} \tag{3.4}$$

6. **Power to E1 phasor converter**

   The block has the function to calculate the phasor for the interface bus's voltage source. The function receives 3 phase power phasor from PSS/E Wrapper and positive sequence interface bus's voltage phasor from *ABC to V1* block and returns the positive sequence phasor used for setting up the voltage source in EMT simulator.

Using the representation of the interface bus in Figure 3.2, the relation between the voltage source, the equivalent impedance, and the interface bus can be described by the following equation:

$$E_{PF}\angle\delta_{PF} = V_{int;PF}\angle\theta_{int;PF} + I_{PF}\angle\delta_{PF}.Z_{PF}\angle\theta_{Z;PF} \tag{3.5}$$

Where $E_{PF}\angle\delta_{PF}$ is the positive sequence voltage source phasor, $V_{int;PF}\angle\theta_{int;PF}$ is the voltage phasor of PowerFactory interface bus, $I_{PF}\angle\delta_{PF}$ is the current flowing into/towards the interface bus, and $Z_{PF}\angle\theta_{Z;PF}$ is the equivalent impedace at PowerFactory interface. The equation can be expanded by replacing I_{PF},

$$I_{PF}\angle\delta_{PF} = \frac{S^*_{PSS/E}\angle\theta_{PSS/E}}{V^*_{int;PF}\angle\theta_{int;PF}} \tag{3.6}$$

Where $S_{PSS/E}\angle\theta_{PSS/E}$ is power information received from PSS/E. The final equation becomes:

$$E_{PF}\angle\delta_{PF} = V_{int;PF}\angle\theta_{int;PF} + \frac{S^*_{PSS/E}\angle\theta_{PSS/E}}{V^*_{int;PF}\angle\theta_{int;PF}}.Z_{PF}\angle\theta_{Z;PF} \tag{3.7}$$

7. **E1 to Eabc converter**

   Using the positive sequence voltage obtained from *Power to E1 phasor converter* block, the three phase phasor for the voltage source can be calculated using the dollowing equations:

$$V_a = V_1 \tag{3.8}$$

$$V_b = a^2 V_1 \tag{3.9}$$

$$V_c = aV_1 \tag{3.10}$$

   With $a = e^{\frac{2\pi}{3}j}$

8. **Phasor to Waveform converter**

   In this block, the phasors obtained from *E1 to Eabc converter* block are converted into a waveform in each EMT time step. The equations involved in this block are as follows:

$$e = E_{PF}\cos(2\pi f t + \theta_{PF}) \tag{3.11}$$

   where e is the waveform that will be sent to PowerFactory, E_{PF} and θ_{PF} are the magnitude and phase angle of the voltage source phasor respectively.

3.4.2. Interaction Protocol

In the developed co-simulation design, the data exchange between EMT and TS is implemented using serial protocol. In this protocol, when one simulator perform its simulation, the other simulator is idle. The reason of using the serial protocol instead of using parallel protocol is due to its simpler implementation. In addition, at the first attempt of the developing the co-simulation, the accuracy of the result is more concerned than the simulation speed. Therefore, the serial protocol which has more advantage in the accuracy is selected.

The interaction protocol of the developed co-simulation can be summarized in Figure 3.8. The numbers in each arrow on the figure are explained as follows:

1. PSS/E and PowerFactory do load flow and determine initial condition.
2. The initial condition from PowerFactory are sent to PSS/E.
3. PSS/E advances to the next time step.
4. PSS/E sends interface variables to master, and master sends interface variables to PowerFactory.

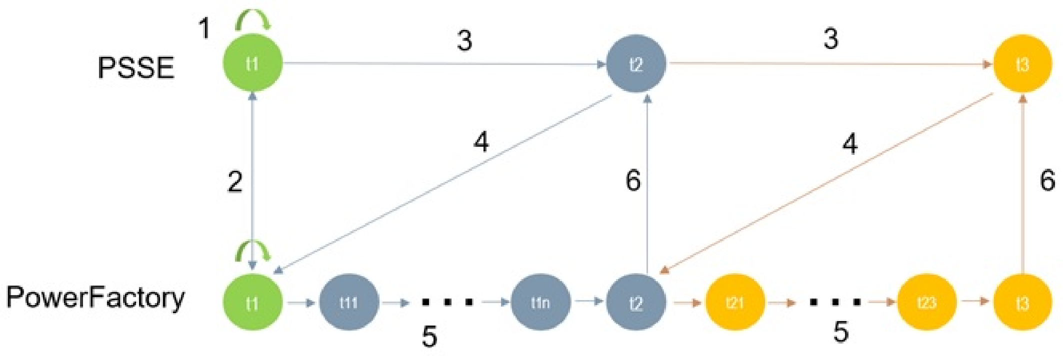

Figure 3.8: The interaction protocol of EMT-TS Co-simulation

5. PowerFactory receives waveforms from master, advances to next step, and sends interface variables to master. The process repeated until it reaches the same time as PSS/E.
6. The waveforms from PowerFactory are converted to phasor and the power information is sends to PSS/E.

3.5. PSS/E Wrapper

As mentioned at the beginning of this chapter, the PSS/E Wrapper has three functions which are controlling behavior during co-simulation, obtain the data and modify the power set point on the PSS/E interface, and enable data exchange between master algorithm and PSS/E interface. The further explanations of each functions are described as follows:

1. **Controling PSS/E behavior during co-simulation**

   Using the Python API provided by PSS/E, most of the command in PSS/E can be executed. The PSS/E wrapper developed in this thesis uses the provided API to control PSS/E during co-simulation. The API used in the developed co-simulation refers to [21] and [22]. In the PSS/E wrapper, the API is used for the following purposes:

   - Initiate the simulator at the beginning of the co-simulation by loading the required file, setting the monitored variables during co-simulation, and set up the output file.
   - Advance the PSS/E simulation to the next time step.
   - Apply the event inside PSS/E at the specified time.

2. **Obtain the data and modify the power set point of PSS/E interface**

   When PSS/E finishes advancing to its next time step, the PSS/E wrapper obtains its result by using the Python API. The power information is retrieved from the flow informations of the line connected to the PSS/E interface.

   When the power information is received from the master algorithm, the PSS/E wrapper also needs to update the power set point of the PSS/E interface. To perform this process, the index of PSS/E interface's static generator needs to be found. Then, using the relative index, the P and Q index of the static generator can be determined. Finally, The received value from the master is used to replace the previous P and Q value inside the static generator which will further modifies the current injection at the PSS/E interface bus.

3. **Enable data exchange between master and PSS/E interface**

   The data exchange between PSS/E wrapper and master algorithm is established using socket communication. The master algorithm acts as a server whereas the PSS/E wrapper acts as a client. PSS/E wrapper establishes the socket communication link with the master at the beginning of the co-simulation. Then, for each of PSS/E time step, PSS/E wrapper sends the obtained variables to the master. When the master finishes its data processing, PSS/E wrapper is also in charge of receiving the variables from master.

Looking at the functionalities mentioned above, these functionalities can be embedded inside the master algorithm as well. However, these functionalitis are separated into different instance so that the co-simulation can be performed in a different hardware, eg: PowerFactory is simulated in one hardware and PSS/E is simulated in the other hardware. By this consideration, the co-simulation could be improved by separating the computation for each simulator into different hardware. In addition, this consideration could also enable the possibilities of joint co-simulation in the future in which multiple stakeholders could work together to perform a co-simulation.

3.6. Previous Design of EMT-TS Co-simulation

In the previous design of EMT-TS Co-simulation, the power information exchanged by each simulator is obtained by multiplying voltage and current phasors. In EMT, the voltage and current phasors are obtained by converting the voltage and current waveform informations stored in the *buffer array*. In the other hand, the voltage and current phasor in TS are obtained directly from the variable inside PSS/E interface.

The reason of the design modification is due to the inaccuracy of the obtained power information. It is found that the calculated power from multiplying the voltage and current phasors has a slightly different result compared to the power observed directly from each of internal simulators, causing an incorrect information exchanges. This leads to a decrease of power flow in each simulator at every time step and yields a completely different result compared to benchmark value. The comparison of the result using the previous design and the result using the current design is presented at the additional discussion section in the chapter 4.

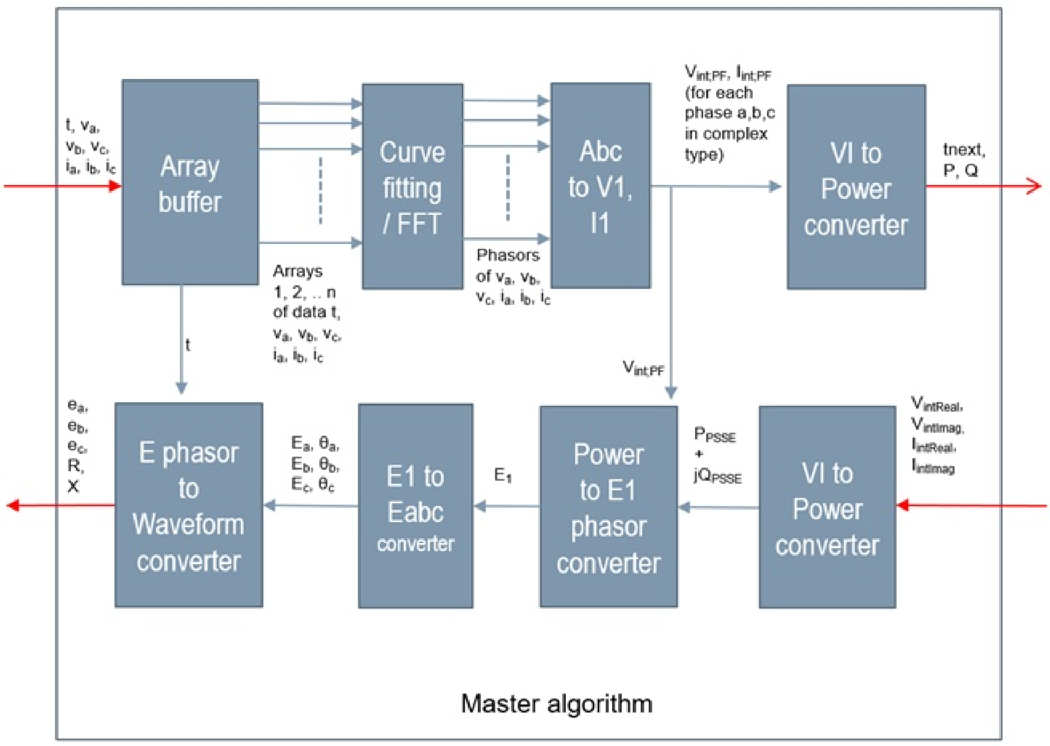

Figure 3.9: The previous design of EMT-TS Co-simulation

Figure 3.9 shows the design of the previous master algorithm. In the design, the master algorithm receives voltage and current waveforms from PowerFactory interface instead of power and voltage. The conversion process from EMT to TS and TS to EMT are explained as follows:

Data Conversion from EMT to TS

In the process of exchanging data from EMT to TS, The power is calculated by multiplying the voltage and current phasors from EMT simulator. Since EMT is based on waveform, the conversion between waveform to phasor is needed. First, the waveform informations sent at every EMT time step are stored in an *Array* *buffer* block. Then, after the number of data inside the buffer reaches aa certain number, the stored data is processed using the *waveform to phasor* block to obtain the voltage and current phasor in each phase. Since TS is based on positive sequence fundamental frequency, the phasor from each phase also needs to be converted into a positive sequence phasor. The process is performed by *ABC to V1 I1* block followed by *VI to Power converter* block to yield three phase positive sequence power. Finally, the three phase power together with the tnext are sent to PSS/E wrapper.

Data Conversion from TS to EMT

In this conversion process, the master algorithm receives the voltage and current phasor from PSS/E wrapper at the end of each PSS/E time step. Then, the phasors are multiplied to yield three phase power by using the *VI to Power converter* block. The obtained power, together with the positive sequence voltage of EMT interface bus, are used to calculate the voltage source's positive sequence phasor using *Power to E1 phasor converter* block. Next, The obtained positive sequence phasor is used to calculate the three phase voltage source phasors with the *E1 to Eabc converter*. For every EMT timestep, the voltage source's waveform values are calculated using the *E phasor to Waveform converter*. Finally, The calculated waveform information together with the equivalent impedance informations are sent to the PowerFactory interface.

3.7. Chapter Summary

In this chapter, the design of EMT-TS co-simulation using PowerFactory and PSS/E is presented. This chapter starts by describing the architecture of the co-simulation. Then, the main components are presented. The first and the second components are PowerFactory interface and PSS/E interface, whose functions are to obtain and set the variables at the point of interconnection, and to act as an equivalent system representation of the other simulator. The third component is the master algorithm, the function of which are orchestrating the co-simulation, establishing a connection and exchange variables between simulators, and performing data processing. Lastly, the fourth component is the PSS/E wrapper whose functions are to control PSS/E, obtain and modify the data variables from PSS/E and enable data exchange between the master and PSS/E interface. Each of the main components and the design consideration for each of them are described more detail in a separate section. Apart from that, the previous EMT-TS cosimulation design is also provided to give more informations regarding the design iteration that has been performed during this thesis.

4

Testing of EMT-TS Co-simulation

In chapter 3, the design of the EMT-TS co-simulation has been described. To test whether the developed co-simulation is able to function properly and to verify the obtained result, several tests need to be performed before the co-simulation is applied to study cases. This chapter aims to provide the documentation, result, and discussions of the performed tests.

The tests presented in this chapter aims to give a firsthand check to the developed EMT-TS co-simulation to ensure that the master algorithm, the interface in PowerFactory, the interface in PSS/E as well as the PSS/E wrapper are able to function properly in performing co-simulation. For this purpose, the network used in this test is created as simple as possible. The description regarding the used test network is presented in section 4.1. Based on the results obtained in the tests, the developed co-simulation is evaluated. If the results of the co-simulation tests are satisfactory, then the developed co-simulation is ready to be applied in a study case.

Ideally, there are many tests required for properly testing the developed co-simulation. However, since the aims of the tests are to give a first-hand check, the tests performed in this chapter are considered sufficient for this master thesis. There are three tests that have been performed which, are:

1. Test 1: PowerFactory interface test
2. Test 2: PSS/E wrapper + PSS/E interface test
3. Test 3: PowerFactory and PSS/E Integration test

The first test aims to test the function of PowerFactory interface. The second test aims to test the function of PSS/E wrapper and PSS/E interface. And the third tests aims to test the integration of EMT and TS with co-simulation. The scope in each of the tests is shown in Figure 4.1. In the figure, the scope of each test is marked with red dotted line.

In this chapter, the test network that is used is described in section 4.1. Then, the documentation of the test 1 is presented in section 4.2, followed by the documentation of test 2 in section 4.3, and test 3 in section 4.4. Apart from the tests, this chapter also provides additional discussion in section 4.5 to give the explanation of the phenomena that are observed during the test. The supplementary discussion is not the main content that wants to be presented in this chapter. However, the discussion is considered beneficial because it can provide more insight of the phenomena observed in the co-simulation and can be useful for the continued development of EMT-TS co-simulation. Finally, the summary of this chapter is presented in section 4.6.

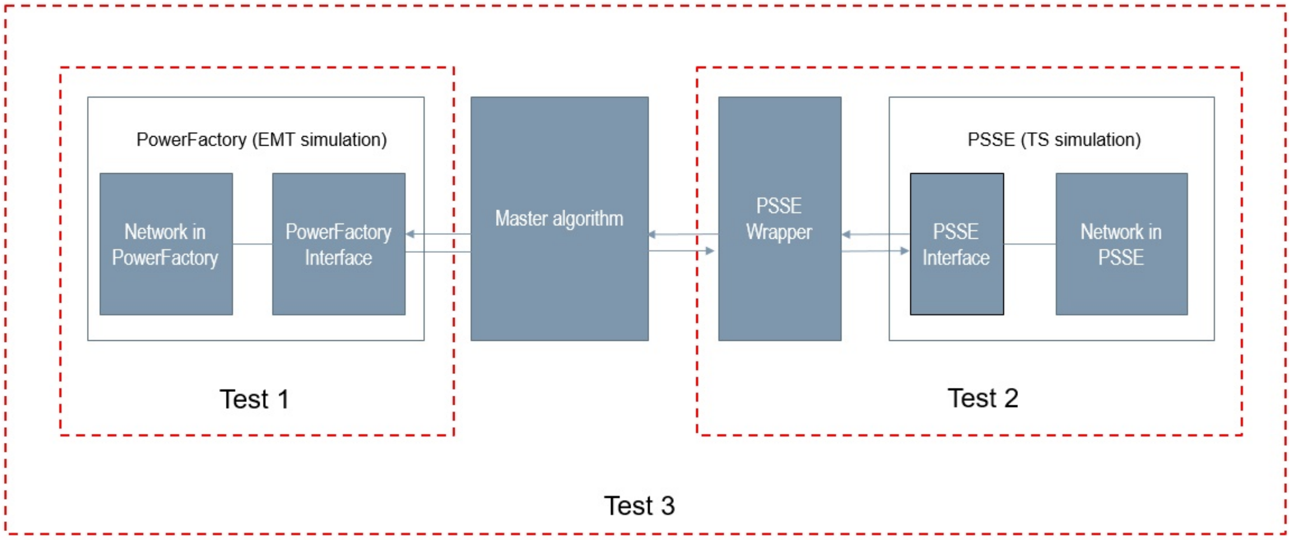

Figure 4.1: Scope of the tests performed in chapter 4

4.1. Test Network

In the initial tests, the network used in the simulation is created as simple as possible. The reason is to minimize potential problems or errors occurred in the simulation which is caused from the improper parameters inside components. Therefore, by using a simple test network, the analysis and troubleshooting of any misbehavior or the error in the simulation can be performed easier.

The network in this initial test consists of a generator connected in series with line and loads. To test the co-simulation in this network, the system is divided into two parts. One part which consists of generator and half of the line is simulated in PowerFactory using EMT simulation while the other part which consists of loads and the remaining half of the line is simulated in PSS/E using TS simulation. The test network and the separation in PowerFactory and PSS/E are shown in figure 4.2.

The part of the network that is simulated in PowerFactory (generator and line) are connected in series with interface bus and Thevenin equivalent. In the other hand, the part of the network that is simulated in PSS/E is connected to the interface bus and a custom static generator which has a representation as a current source in PSS/E. Before performing co-simulation test, each of these two parts is examined. The network part which is simulated in PowerFactory is examined in test 1 while the other part that is simulated in PSS/E is examined in test 2. After both tests are performed, the integration test by using co-simulation between PowerFactory and PSS/E is performed in test 3.

The reason why the generator is simulated in PowerFactory using EMT is because it includes a differential equations in its modeling. Therefore, the dynamic phenomena from the generator can be observed in more detail if the generator is simulated using EMT. In PSS/E, two loads are used in this simulation for the reason that one of the loads can be disconnected during the dynamic simulation. Thus, a loss of load event to observe the dynamic condition of the system can be applied to the test network.

In the tests performed in this chapter, a network model which serves as a benchmark is created. The purpose of the benchmark network is to evaluate the accuracy of the co-simulation result. The benchmark network, which consists of the same network used in co-simulation, is simulated in monolithic EMT simulation. To evaluate its accuracy, the co-simulation result is compared with the result obtained from the benchmark network simulated in full EMT simulation.

To ensure that the benchmark result is correctly representing the network simulated in PSS/E and PowerFactory, it is important that the benchmark network has the same parameters and modelling with the network in both simulators. However, it is practically difficult to implement the same parameters for PowerFactory and PSS/E as both simulators do not exactly model the network in the same way. In this thesis, a specific procedure is applied to create the network as identical as possible between the benchmark network, the network simulated in PowerFactory, and the network simulated in PSS/E. The procedure can be summarized in figure 4.3.

First, the benchmark network created in PSS/E. Then, the network files created in PSS/E are imported

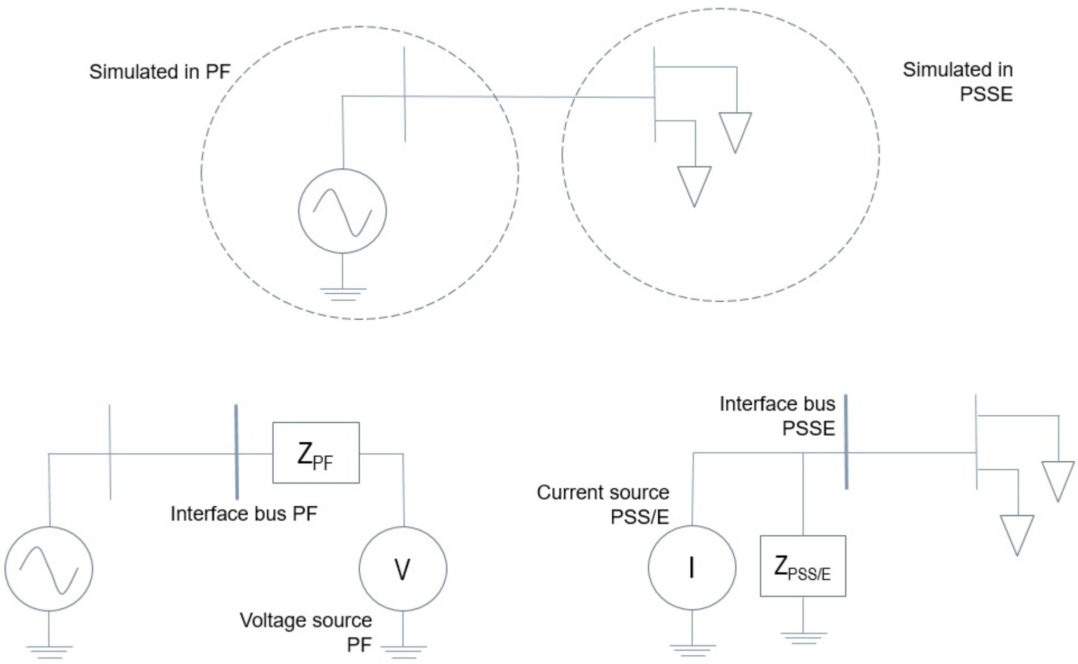

Figure 4.2: The test network and its separation in PowerFactory and PSS/E

Table 4.1: The comparison between the power flow result of benchmark network in PowerFactory and PSS/E

	PowerFactory		PSS/E	
Bus	Voltage (p.u)	Angle (deg)	Voltage (p.u)	Angle (deg)
1	1.0	0	1.0	0
2	0.99545	-0.65	0.99568	-0.65
3	0.99181	-1.31	0.99149	-1.31

into PowerFactory project file. Therefore, two similar benchmark networks in PowerFactory and PSS/E are obtained. To ensure that the benchmark network in PowerFactory and PSS/E behaves similarly, a powerflow simulation and a dynamic simulation is performed in both network. The result of the simulation is used to justify that both of them has similar network characteristic. Further, The benchmark in PowerFactory is modified by removing the load to obtain the network which will be simulated in PowerFactory. Similarly, the benchmark network in PSS/E is modified by removing the generator to obtain the network which will be simulated in PSS/E. Lastly, a co-simulation interface is added to both networks to enable co-simulation.

The network described in figure 4.2 has been implemented in PowerFactory and PSS/E. The single line diagram as well as the power flow result for both simulators are illustrated in figure 4.4 and 4.5. In addition, the bus voltage result from the power flow is summarized in table 4.1. The figures and the table show that both networks have the same power flow solution. Therefore, it can be concluded that both networks have the same steady state characteristic.

Apart from power flow results, the dynamic behavior on each of the networks during transient is also compared. In this regard, a dynamic simulation is performed in both PowerFactory and PSS/E. The TS simulation is performed in PSS/E while in PowerFactory both EMT and TS are performed. The dynamic behavior of the network is observed by applying a load event by disconnecting one of the loads. The result of the dynamic simulation from each simulator is then compared. Figure 4.6 and 4.7 show the comparison result of the performed dynamic simulation in PowerFactory and PSS/E.

In figure 4.6, the comparison between the INT_BUS voltage in PowerFactory and PSS/E is presented. In addition, the active and reactive power observed at the INT_BUS can be observed in figure 4.7. The results show that there is a slight difference in the observed dynamic. As the input parameters of the system are the same, the differences are probably caused by the way the simulator solves the equation involved during the dynamic simulation. In this thesis, the differences in the dynamic of PowerFactory and PSS/E is not the main

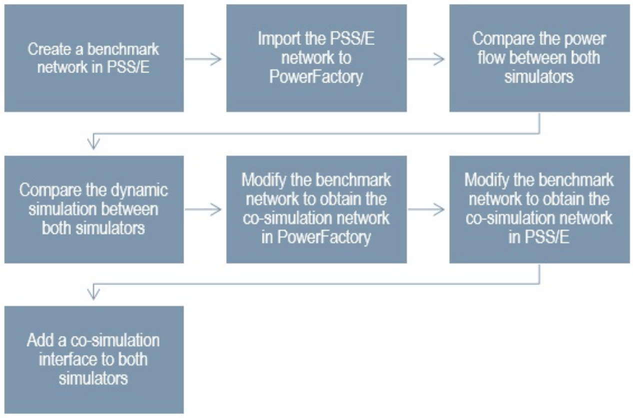

Figure 4.3: The process to obtain the test network used in the EMT-TS co-simulation

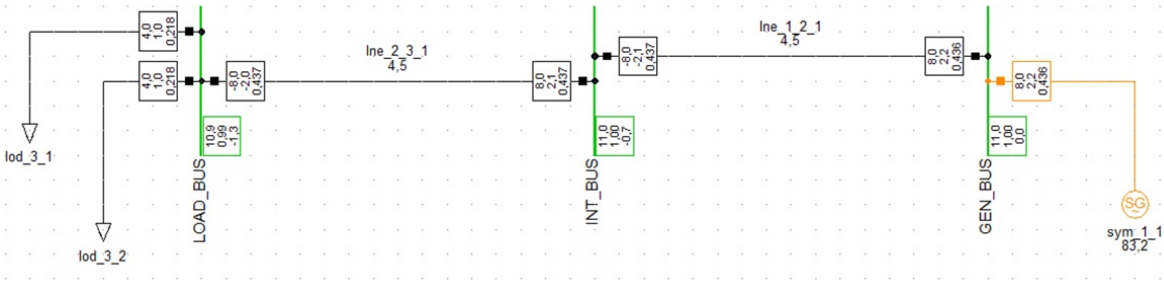

Figure 4.4: The single line diagram of the benchmark network in PowerFactory with the power flow result

concern. As the differences between the results are not large, the result is considered adequate to conclude that the benchmark network in PowerFactory and PSS/E has similar behavior in dynamic simulation.

In this test, an excitation and governor system is installed in the generator so that the network could returns to a stable condition after the disturbance occured. In PSS/E, the load model used in the dynamic simulation are transformed to a certain composition of constant power, constant current, and constant impedance load model. In this test, the load is remodelled into 100% constant current for active power and 100% constant impedance for reactive power. This proportion of load is adopted from [11] to ensure that the same load behavior in both simulator is obtained during dynamic simulation.

In this chapter, the description regarding the test network and the benchmark network have been presented. For the next section, the documentation regarding each of the performed tests is presented.

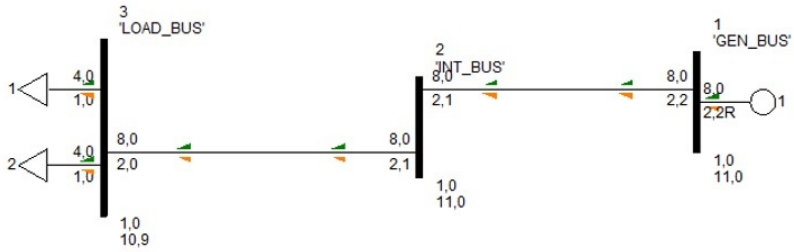

Figure 4.5: The single line diagram of the benchmark network in PSS/E with the power flow result

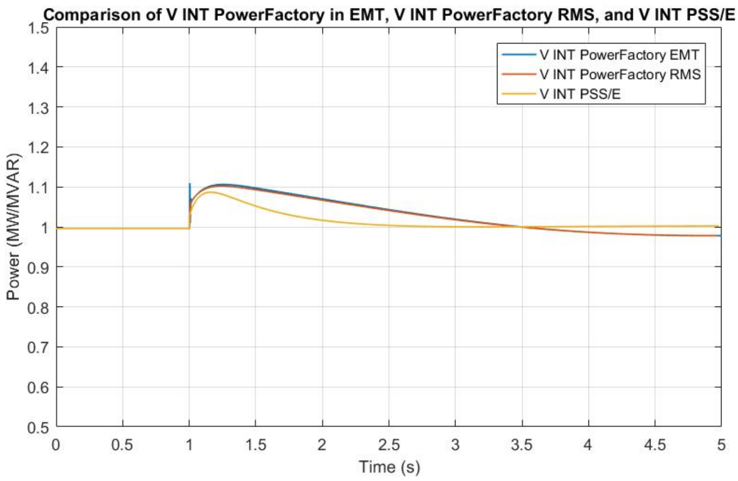

Figure 4.6: The comparison of the voltage magnitude observed in the interface bus between a monolithic EMT in PowerFactory, monolithic TS in PowerFactory, and monolithic TS in PSS/E

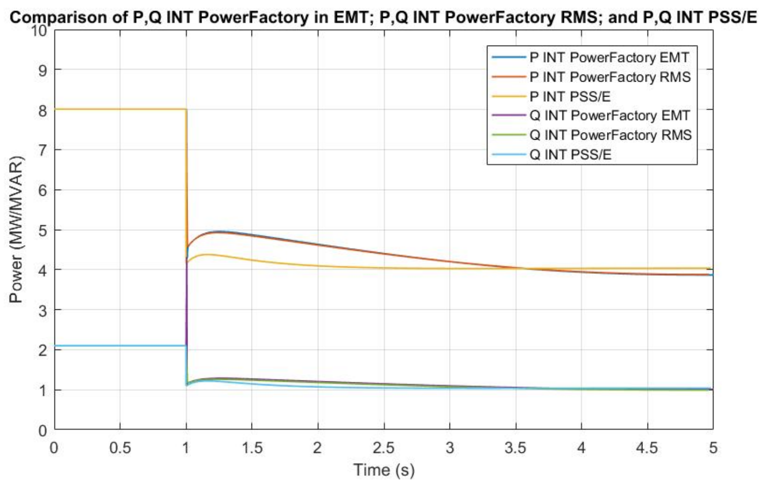

Figure 4.7: The comparison of the voltage magnitude observed in the interface bus between a monolithic EMT in PowerFactory, monolithic TS in PowerFactory, and monolithic TS in PSS/E

4.2. Test 1: PowerFactory Interface

When PSS/E sends power information to PowerFactory, the PowerFactory interface must be able to receive the power information and then set the same amount of power at the PowerFactory interface bus. To assess this functionality, the PowerFactory interface is examined with the test 1.

4.2.1. Method

In the test 1, a network in PowerFactory which contains a generator, line, and PowerFactory interface is created. The implementation of the single line diagram in PowerFactory is depicted in figure 4.8. PowerFactory interface communicates with the master algorithm via a socket connection. Instead of using PSS/E, the master algorithm is connected with a PSS/E dummy, in which the function is to send a constant PSS/E power information to the master. The connection from the master to the PSS/E dummy is also established using a socket connection. The block diagram describing the components involved in test 1 is illustrated in figure 4.9

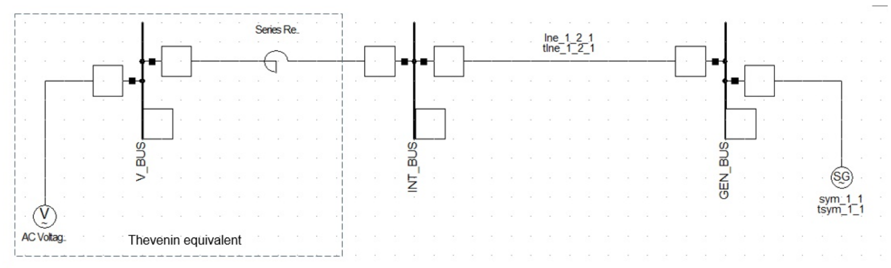

Figure 4.8: The single line diagram of the co-simulation network in PowerFactory used in test 1

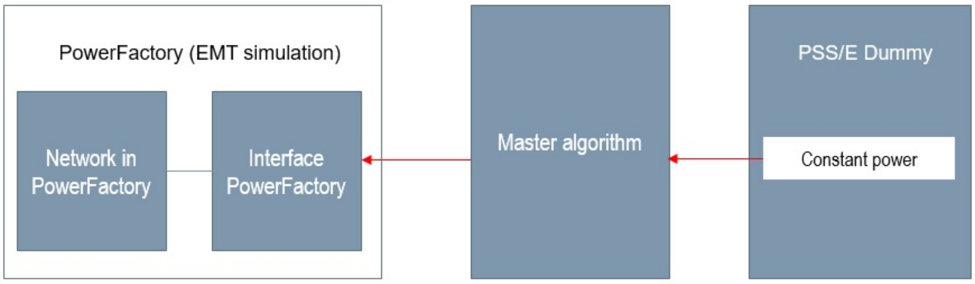

Figure 4.9: Blocks diagram involved in test 1

During the test, the PSS/E dummy sends a constant power information to the master. Based on it, the master sends point on wave data for the voltage source in PowerFactory. After receiving the data from the master, PowerFactory advances to the next time-step, resulting in new calculation results. In this test, the power at the interface bus is observed. The obtained value is compared with the power sent from the PSS/E dummy. Then, based on the comparison, it is evaluated whether the PowerFactory interface is able to function properly or not. In this test, only the data at the point when PowerFactory reaches stable condition until the simulation end, is evaluated.

At the beginning of the first test, a constant power information is sent from the PSS/E dummy to PowerFactory until the network in PowerFactory reaches steady state. The value of the constant power is the same as the value of INT_BUS power obtained from the power flow simulation of the benchmark network. Further, the power sent from PSS/E dummy is reduced into half a moment after the system reaches steady state. This is to test whether the PowerFactory interface is able to follow the changing of power from PSS/E. When the power from PSS/E dummy is halved, it is expected that the power observed at the interface bus is also reduced by half.

When the power set point is changed, the equivalent impedance in the PowerFactory network is also modified. The reason is to replicate the condition when the power is suddenly changed. The drastic change of power in most cases is caused by a network modification. For instance, short circuit or a loss of load. In this test, it is assumed that when the power setpoint is reduced, a change of network properties is occurred at PSS/E dummy. Therefore, the equivalent impedance needs to be updated at the PowerFactory interface in order to adapt to the change of power from the PSS/E dummy.

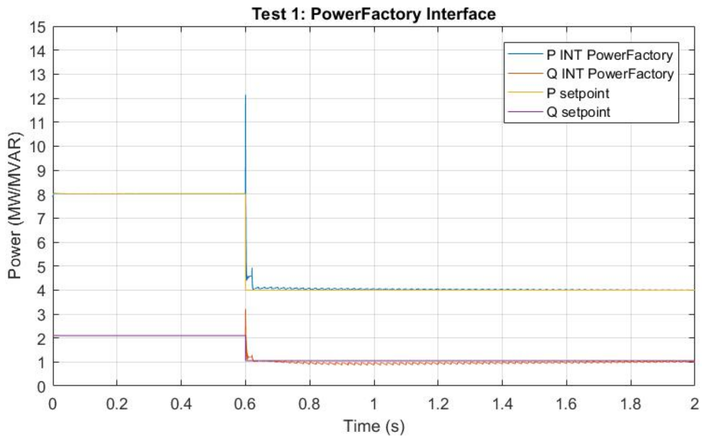

Figure 4.10: Comparison of the power observed in interface bus with the power setpoint from PSS/E dummy

Aside from testing the PowerFactory interface, a part of the master algorithm is also tested in this test. The master algorithm is needed in this test to handle the conversion between power to PowerFactory variables. Therefore, the master can not be separated from the PowerFactory interface. Before the first test is performed, the master algorithm has been tested using pytest, a standard testing procedure in the Python development environment. From the point of view of software development, the testing of the master algorithm is considered sufficient.

4.2.2. Result and Discussion

The result of test 1 is presented in figure 4.10. The figure consists of four graphs which aim to compare the power observed in PowerFactory and the power set-point sent from the PSS/E dummy. It is shown in the figure that the power in PowerFactory is nearly aligned with the power setpoint. When the power setpoint is changed, the interface in PowerFactory is also able to react accordingly and produces the similar value of power output.

When the setpoint is changed, a transient is observed in the interface bus. The transient occurs because the system is in the process towards reaching a new solution. The ripple observed after the change of power set-point is keep decreasing until the power reaches the same value with the power set point. In this test, it is shown that the interface in PowerFactory is able to arrive at a stable condition after the change of power setpoint.

From Figure 4.10, the PowerFactory interface is able to set the proper amount of power according to the power setpoint, and when the power is changed, the interface is able to converge into a stable condition. Therefore, it can be concluded that the interface in PowerFactory works properly in the test case.

4.3. Test 2: PSS/E Interface

Similar with the PowerFactory interface, the PSS/E interface must also be able to set the power at its interface bus according to the power sent from PowerFactory. The second test in this chapter specifically examines this PSS/E interface functionality. In this thesis, the writer's contribution in the PSS/E interface is in developing the PSS/E wrapper. However, the test of PSS/E wrapper can not be done separately from the PSS/E interface. Therefore, the test of these two instances is performed together.

4.3.1. Method

In the second test, three parts are involved. They are master dummy, PSS/E wrapper, and PSS/E. In PSS/E, a test network according to section 4.1. which contains 2 identical loads, a line, and a PSS/E interface is created. The implementation of the single line diagram in PSS/E is illustrated in figure 4.11.

The PSS/E interface is controlled by the PSS/E wrapper. The PSS/E wrapper is connected with the master dummy via a socket connection. Similar to the function of PSS/E dummy in the previous section, the function of master dummy is to send a constant PowerFactory power information to PSS/E wrapper. The master dummy is used instead of the real master algorithm to simplify the implementation of the test. Using this scheme, there is no need to establish a connection other than PSS/E wrapper and eliminate unnecessary

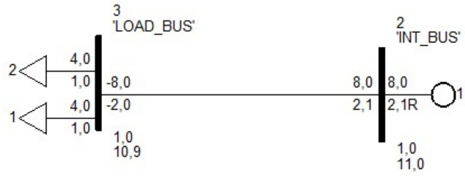

Figure 4.11: The single line diagram of the co-simulation network in PSS/E used in test 2

computation inside the master algorithm such as waveform to phasor conversion. The relation between the master dummy, PSS/E wrapper, and PSS/E can be seen in figure 4.12.

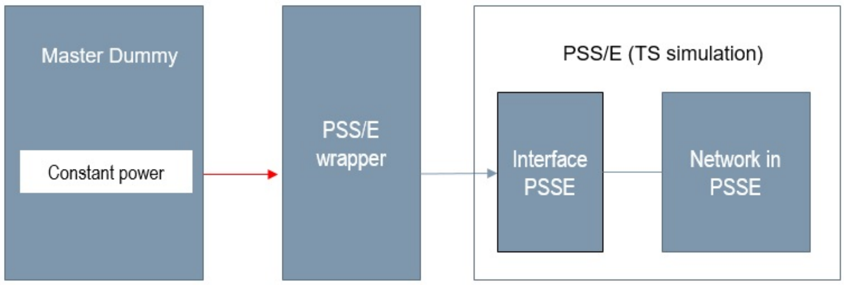

Figure 4.12: Blocks diagram involved in test 2

During the second test, the master dummy sends a constant power information to the PSS/E wrapper. Based on the received power information, the PSS/E wrapper modifies the variables inside the static generator model to change the current injection, which will further modify the power at PSS/E interface bus. The resulted power at the PSS/E interface bus is compared with the power sent from master dummy. From the comparison, it is evaluated whether the PSS/E interface is able to function properly or not.

Similar to the test 1, a constant power with the same value obtained from the power flow is applied at the beginning of the test until the network reaches steady state. Then, the power set point is changed a moment after. The power sent from the master dummy is reduced into half, then the power at the interface bus is observed. By doing this, it is examined whether the PSS/E interface is able to follow the change of power from the master dummy. When the power from the master dummy is halved, it is expected that the power observed at the interface bus is also reduced by half. In this test, the data that is analyzed is only the data at the point when PSS/E network reaches stable condition until the simulation end.

When the power setpoint is reduced to half, one of the loads in the network is also disconnected. The reason is to balance the current flowing in the network. As mentioned in the previous section, the active power of the load is modeled with a constant current. Therefore, the power at the interface bus is proportional to the voltage at the interface bus. If the power at the interface bus is reduced to half, and current to the load is constant, then the system needs to adjust the voltage at the interface bus to match the power set point. This may cause a mismatch in the system and could affect the accuracy of the result. Therefore, when the power set point is reduced to half, one of the loads needs to be disconnected so that the amount of current drawn to the load bus is also reduced to half.

4.3.2. Result and Discussions

The result of test 2 is presented in figure 4.13. It aims to compare the power observed in PSS/E and the power set-point sent from master dummy. It is shown in the figure that the power in PSS/E is nearly aligned with the power setpoint. When the power setpoint is changed, the interface in PSS/E is also able to react accordingly and produces the similar value of power output.

In the figure, there is no transient phenomena observed. The graph obtained from the simulation is flat without a ripple or a dip. The reason is that the network in PSS/E only contains a line and loads, which are a component with a simple representation in the system. The equation involved in the line and the loads do not include a differential equation unlike the modeling of generators and its controller. Therefore, there is no transient phenomena observed, which usually happens in the system which involves a component with complex modeling.

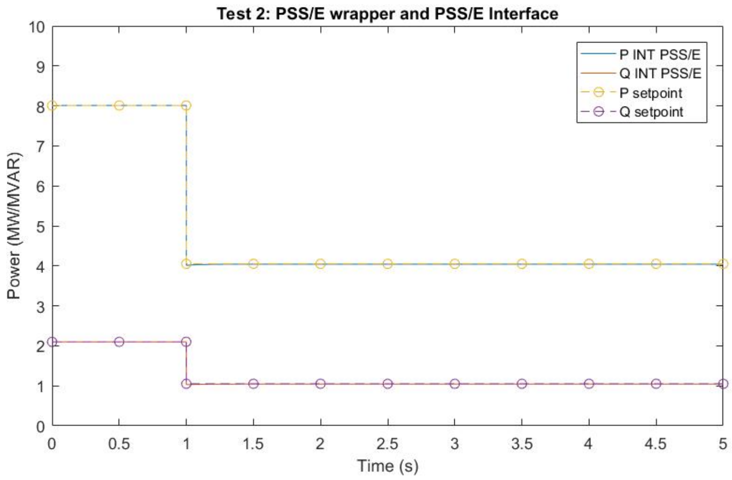

Figure 4.13: Comparison of the power observed in interface bus with the power setpoint from master dummy

From the figure, the PSS/E interface is able to set the proper amount of power according to the power setpoint, and when the power is changed, the interface is able to converge into a stable condition. Therefore, it can be concluded that the interface in PSS/E functions correctly in the test case.

4.4. Test 3: Integration of EMT and TS Co-simulation

4.4.1. Method

In the first and the second test, the co-simulation components in PowerFactory and PSS/E have been tested. The third test is the combination of the first and the second test. The objective of this test is to evaluate whether the PSS/E and PowerFactory part of the co-simulation are able to perform a co-simulation together. In this test, all the compositions of EMT TS co-simulation are integrated to perform a co-simulation together. Then, based on the result, its performance will be evaluated.

To assess its performance, the network as described in section 4.1. is used in the co-simulation. The EMT TS co-simulation is executed until it reaches a steady state condition. To obtain a steady state condition, both simulators are fed by a constant power value from the master and the TS wrapper until t=1s. The synchronization between both simulators is begun at this point and the co-simulation is run until it reaches steady state condition. At t=2s, a loss of load event is applied by disconnecting one of the loads in PSS/E network. The sudden change of power flow will cause a transient in EMT network. Here, the dynamic phenomena occurred in EMT and TS are observed, and the results are compared with the same simulation event performed in the benchmark network.

In this test, the behavior of the system at the initial condition, and the behavior when the load event occurred are observed. Further, two variables obtained from PowerFactory, PSS/E, and benchmark network are monitored which is power and voltage at the interface bus. Here, the results obtained from PowerFactory and PSS/E are evaluated at how close these results compared to benchmark network.

4.4.2. Result and Discussions

Figure 4.14, 4.15, and 4.16 show the behavior of the system at the moment when the event is applied in test 3. In the benchmark network, when a loss of load occurred at t=2s, the system impedance changed suddenly. Since the current in the system can not change immediately, the sudden change in the impedance resulted in a sudden change in the voltage and power. Due to the action of generator voltage controller, the voltage is decreasing, and eventually, the voltage is back to around 1 p.u.

In the co-simulation, the result is closely matched with the benchmark result at the beginning. The result obtained between EMT, TS, and benchmark are nearly coincident. However, the result starts showing differences a moment after the event is applied (around t=3s). The noticeable difference is, while the flow of power from the benchmark is decreasing, the flow of power from the co-simulation keeps increasing as observed in Figure 4.14 and 4.15. The phenomena is caused by two reasons. The first one is due to the inaccuracy of the resulted power at the interface bus, and the second one is the absence of voltage controller in PSS/E side.

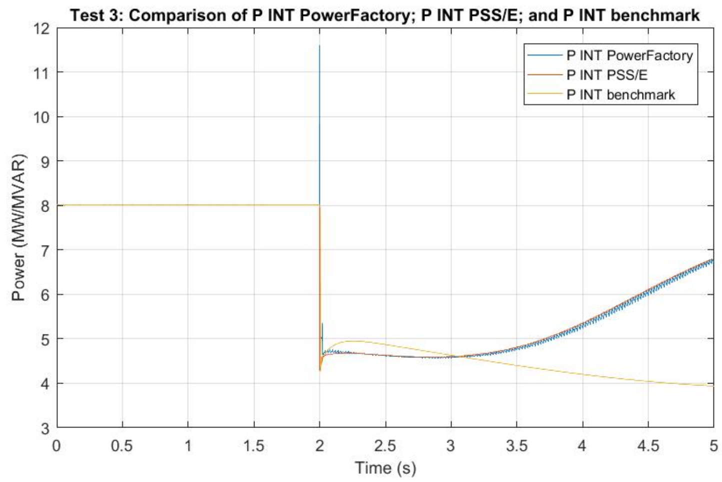

Figure 4.14: The comparison of the P INT in PowerFactory, PSS/E and benchmark network during load event

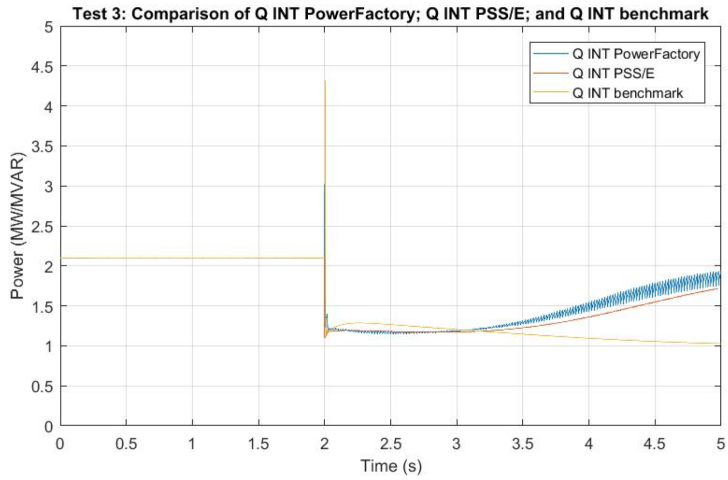

Figure 4.15: The comparison of the Q INT in PowerFactory, PSS/E and benchmark network during load event

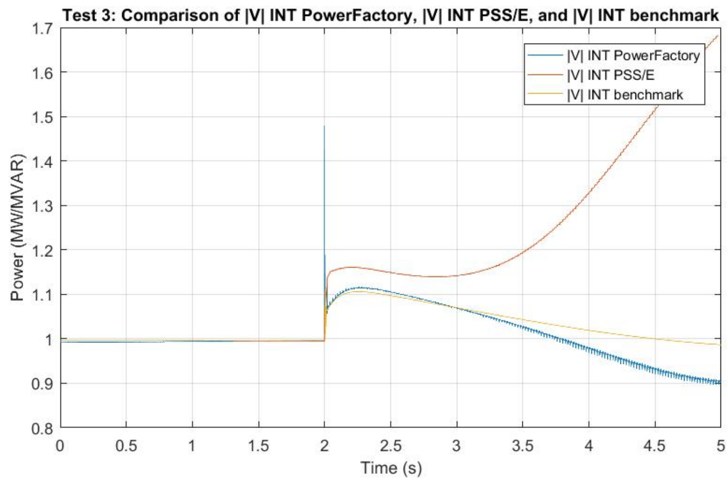

Figure 4.16: The comparison of the V INT in PowerFactory, PSS/E and benchmark network during load event

Regarding the inaccuracy of the resulted power, it is further analyzed from the recorded data that there is a noticeable mismatch occurred after the event applied. For example, it is observed at t=3s that the nominal power sent from PowerFactory is 4.537+1.168j MVA, then at the next time step the power sent from PSS/E to PowerFactory is 4.555+1.161j MVA, which differs by 0,018-0.007 MVA. Ideally, It is expected that the power exchanged between two simulators is equal if there is no event applied. However, due to the numerical error and the difference in the solver between both simulator, a mismatch occurred in the co-simulation is unavoidable.

The slight mismatch of the exchanged power resulted in a small voltage increase in PSS/E. Due to the absence of a voltage controller, the voltage in PSS/E keeps growing. As the load in PSS/E is converted into a constant current, the power drawn from the source has a linear relationship with the voltage. Therefore, when the voltage increases, the power supplied to the load also increases. The mismatch of the exchanged power with the absence of voltage controller lead to a gradual increase of the exchanged power, which can be observed in the figures.

In the beginning, the mismatch between the power set from the master and the power observed at the interface is small. Therefore, the power exchange between PowerFactory and PSS/E could still result in a balance power flow between both simulators. However, after the event occurred, the mismatch becomes larger. It is observed that the larger the power deviates from the initial power setpoint, the larger the mismatch occurred between both simulators. Figure 4.17 and 4.18 give a comparison of the power exchange between both simulator at before and after the event applied.

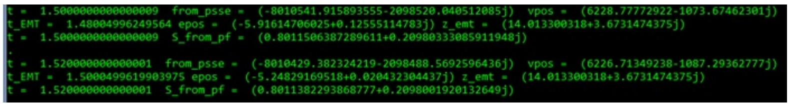
```
t =  1.5000000000000009  from_psse =  (-8010541.915893555-2098520.040512085j)  vpos =  (6228.77772922-1073.67462301j)
t_EMT =  1.48004996249564 epos =  (-5.91614706025+0.12555114783j) z_emt =  (14.013300318+3.6731474375j)
t =  1.5000000000000009  S_from_pf =  (0.8011506387289611+0.20980333085911948j)
.
t =  1.520000000000001  from_psse =  (-8010429.382324219-2098488.5692596436j)  vpos =  (6226.71349238-1087.29362777j)
t_EMT =  1.5000499619903975 epos =  (-5.24829169518+0.020432304437j) z_emt =  (14.013300318+3.6731474375j)
t =  1.520000000000001  S_from_pf =  (0.8011382293868777+0.2098001920132649j)
```

Figure 4.17: The co-simulation cmd report before the event is applied

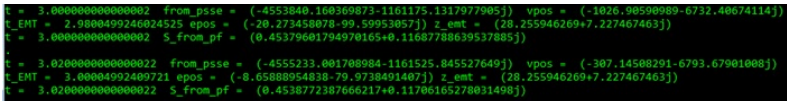
```
t =  3.000000000000002  from_psse =  (-4553840.160369873-1161175.1317977905j)  vpos =  (-1026.90590989-6732.40674114j)
t_EMT =  2.9800499246024525 epos =  (-20.273458078-99.59953057j) z_emt =  (28.255946269+7.227467463j)
t =  3.000000000000002  S_from_pf =  (0.45379601794970165+0.11687788639537885j)
.
t =  3.0200000000000022  from_psse =  (-4555233.001708984-1161525.845527649j)  vpos =  (-307.14508291-6793.67901008j)
t_EMT =  3.00004992409721 epos =  (-8.65888954838-79.9738491407j) z_emt =  (28.255946269+7.227467463j)
t =  3.0200000000000022  S_from_pf =  (0.4538772387666217+0.11706165278031498j)
```

Figure 4.18: The co-simulation cmd report after the event is applied

Although the result of active and reactive power is different, the voltage result at EMT simulation shows similar behavior with the result from the benchmark. In the benchmark network, when a loss of load occurred, the system impedance is changed suddenly, resulting in an observable voltage dip in the graph. The similar situation also happened in the EMT network. In the EMT network of co-simulation, the system impedance in PSS/E is represented by the equivalent thevenin impedance. The nominal value of the thevenin impedance is also changed when the event in PSS/E occurred. Therefore, the EMT experienced the similar impedance change as the benchmark network, resulting in the similar voltage graph between both. However, since the power from PSS/E keeps increasing, the voltage drop in EMT eventually becomes lower than the voltage observed in the benchmark.

From the result of test 3, it can be concluded that the developed co-simulation is able to produce a similar behavior with the benchmark network only in a particular period of time. At 1s<t<3s, the resulted power and voltage graph is similar to the result from the benchmark. However, due to the accumulated power inaccuracy at each time step, the longer the co-simulation is performed, the farther the result deviates from the benchmark. After 3s, the result is no longer similar to the result from the benchmark. Therefore, the co-simulation is not suited to be performed for long simulation time.

4.5. Additional Discussion from the Test

4.5.1. The Effect of Delaying Synchronization in the Developed Co-simulation

In test 3, a synchronization delay is applied at the beginning of the co-simulation. The reason for the synchronization delay is to give a more proper initial starting point when the co-simulation begins. At the moment when the co-simulation is started, there is a ripple observed in the system because the system tries to find a solution between the input from the master and the other simulation variable in the system. If the information is exchanged directly, the ripple will be included in the exchanged information, resulting in an inaccurate power exchange between both simulators.

A more accurate representation of the simulation can be obtained by delaying the synchronization between both simulator. In this method, a constant power, in which the value is obtained from power flow, is fed into each simulator. After the co-simulation reaches a stable power flow condition, each simulator starts exchanging data. By this method, the inclusion of ripple information at the beginning of co-simulation can be avoided, resulting in a more identical result with the benchmark simulation.

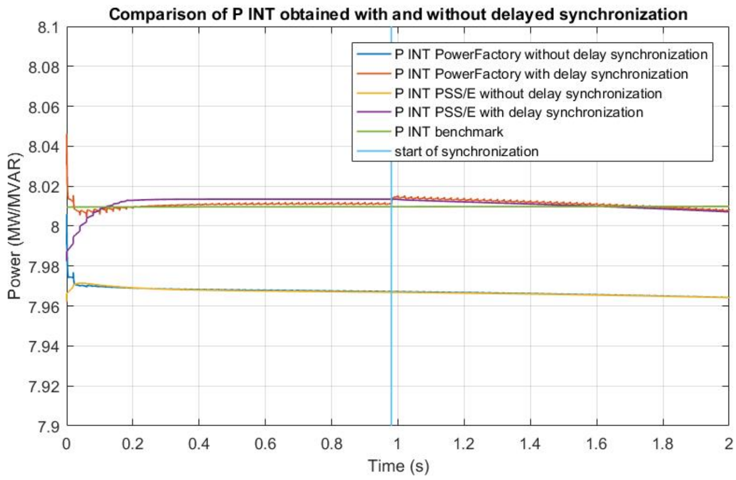

Figure 4.19: Comparison of P INT obtained with and without delayed synchronization

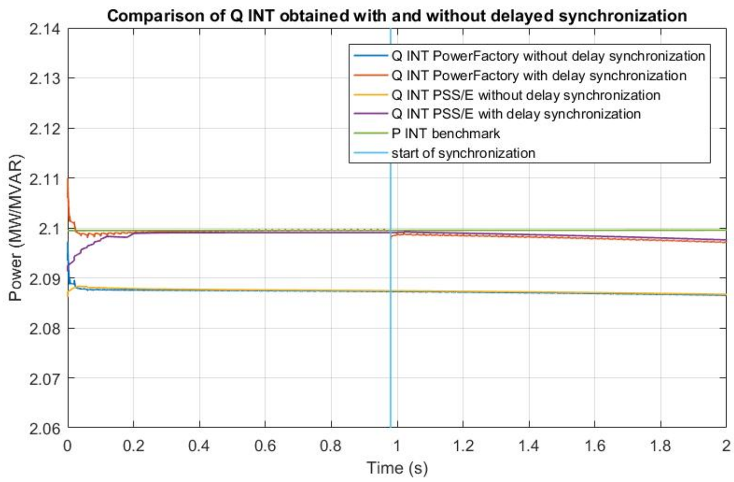

Figure 4.20: Comparison of Q INT obtained with and without delayed synchronization

Figure 4.19 and 4.20 show the active and reactive power comparison from the co-simulation without delayed synchronization and with delayed synchronization. The figures are obtained based on the result of test 3. From these figures, it can be observed that the result without delay synchronization is slightly below the benchmark result whereas the result with delay synchronization is a nearly coincidence with the benchmark result. Based on this result, it is shown that the delay synchronization helps the co-simulation to obtain a more accurate behavior of the system at the beginning of the co-simulation before the event is applied.

The reason of the less accurate result from the method without delayed synchronization is due to the transient that occurs at the beginning of co-simulation. At this moment, the simulator tries to reach a stable simulation condition. Since the power set point sent from the master may not be similar with the solution achieved from simulator initialization, a small transient occurs at this moment. If the synchronization is started at this point, an incorrect value may be sent to other simulator. Then, it will further causes an incorrect starting condition.

4.5.2. Method to Extract Power Information from Simulator

In the process of designing the co-simulation, previously, the power information is obtained by multiplying the voltage and current phasor from both simulators. In EMT, the voltage and current phasor are obtained by applying waveform to phasor conversion to the collected waveform. In TS simulation, the voltage and current phasor are obtained directly from the interface variable. However, the calculated power information from this method has slightly different values from the power set point, resulting in a decrease of power at every time step. The phenomena can be observed in figure 4.21 which shows the result if the power is obtained by multiplying voltage and current phasors. In the figure, it is seen that power is kept decreasing until it reaches a certain point and then starts oscillating.

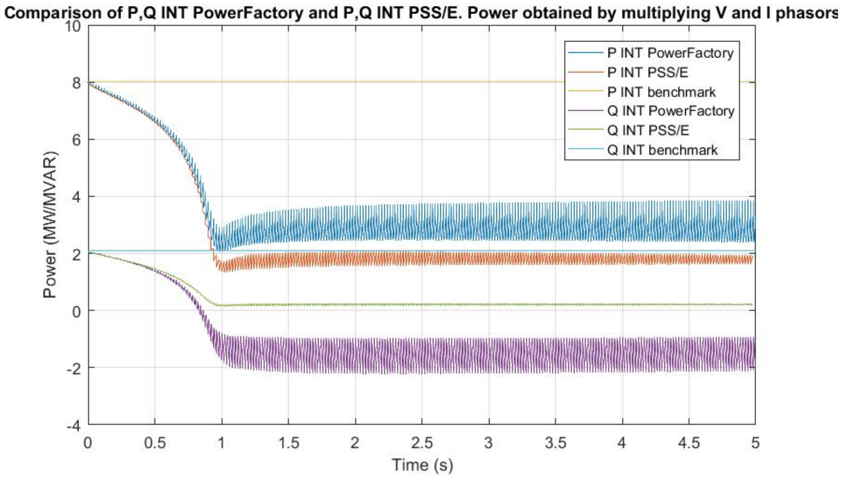

Figure 4.21: Comparison of P,Q INT PowerFactory and P,Q INT PSSE when the power is obtained by multiplying V and I phasors

The solution of the problem is to modify the way to extract the power information from the simulator. Instead of obtaining power from voltage and current phasor, the power is obtained directly from the simulator result. It is possible to be realized both in PowerFactory and PSS/E as they provide the power information in its component at every time step. It is further investigated that the power obtained from simulator result has similar quantities with the power set point. Therefore, the usage of power variable from the simulator could result in a more balanced power exchange between both simulators as can be seen previously from figure 4.14 and 4.15.

The inaccuracy reason of the power obtained by multiplying voltage and current phasor has not been further investigated. It may be due to the numerical error that is happening in the process of waveform to phasor conversion, or in the calculation process to obtain the power information. An attempt to investigate the reason of the error can be considered for further research on this topic.

It is further investigated that different voltage source initialization in PowerFactory could affect the steady state solution of the co-simulation result. Figure 4.22 and 4.23 present the comparison of different co-simulation results (in which the power is obtained by multiplying voltage and current phasors) with different initial voltage source magnitude. It is seen from the figure that the different voltage magnitudes causes the power exchange between both simulators to end up in a different steady state solution. It shows that different initial condition affects the behavior of the co-simulation. The detailed reason has not been further investigated. However, it is an interesting phenomenon that can be considered for further research on this topic.

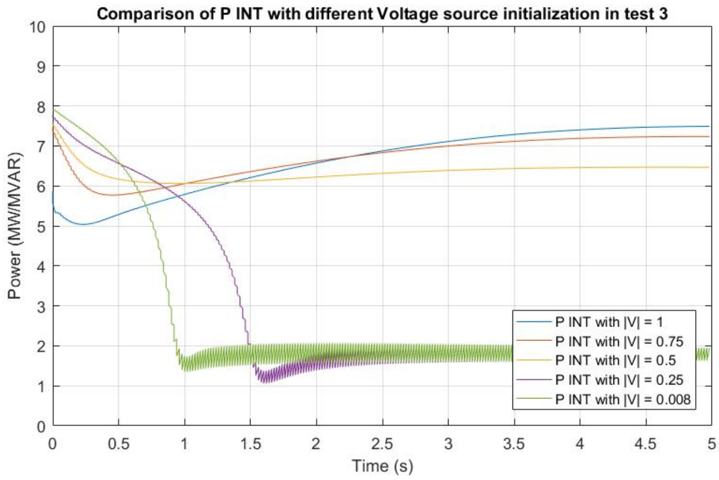

Figure 4.22: Comparison of P INT with different voltage source initialization in test 3 (using voltage and current phasor to obtain power information)

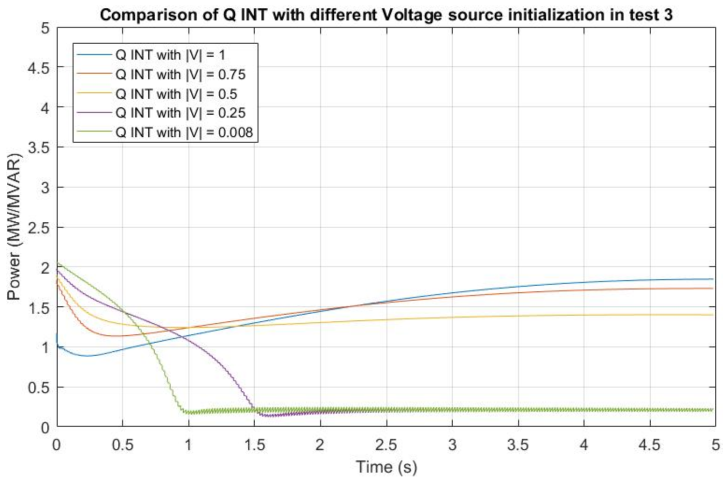

Figure 4.23: Comparison of Q INT with different voltage source initialization in test 3 (using voltage and current phasor to obtain power information)

4.6. Chapter Summary

In this chapter, the initial tests for EMT-TS co-simulation using PowerFactory and PSS/E have been presented. The summary of this chapter is as follows:

1. At the beginning of the chapter, the test network used in the test as well as the method to create it has been described
2. From the test 1, it is shown that the PowerFactory interface is able to function properly to set the same amount of power controlled by the PSS/E dummy
3. From the test 2, it is shown that the PSS/E interface is able to correctly set the power according to the power set point from the master dummy
4. In test 3, the integration of EMT-TS co-simulation test has been performed. From the result, it is shown that the composing components of the developed co-simulation is able to work together to perform a co-simulation
5. It is also shown in the test 3 that the developed co-simulation is able to produce similar value with the benchmark result before the load event is applied. After the load event is performed, the co-simulation

is able to produce the similar power magnitude with the benchmark. However, it is observed that the power obtained from co-simulation keeps increasing. The phenomena is caused by two reasons, the first one a mismatch between the power sent from master and the resulted power at the interface bus, and the second is due to the absence of voltage controller in PSS/E side

6. The developed co-simulation is able to produce a similar behavior with the benchmark network only in a particular period of time. Due to the accumulated power inaccuracy at each time step, the longer the co-simulation is performed, the farther the result deviates from the benchmark. Therefore, the co-simulation is not suited to be performed for a long simulation time

7. In the additional discussion section, the comparison between the result with delayed synchronization and without delayed synchronization is presented. It is shown that delaying the synchronization could improve the co-simulation result at the beginning of the simulation

5

Study Case

In this chapter, the developed co-simulation is applied to several study cases with an aim to give more insight on how the developed co-simulation performs under different circumstances. There are five study cases presented in this chapter:

1. Loss of load in TS Area
2. Loss of transmission line in TS Area
3. Loss of transmission line in EMT Area
4. The effect of different TS time step to the co-simulation result
5. The effect of different EMT time step to the co-simulation result

The chapter can be divided into two main parts. The first part consists of study case 1, 2, and 3 in which the aim is to fulfill the fourth objective of this thesis. The second part which consists of study case 4 and 5, aims to fulfill the fifth objective in this thesis.

This chapter begins by describing the test network used in the benchmark and in the co-simulation. Then, each of the study cases is presented in a different section. For each study case, the objective, method, as well as the discussion is presented. At the end of this chapter, a summary is provided to sum up what has been achieved.

5.1. Study Case Network

The Kundur 2 Areas 4 Generators (2A4G) system based on [12] is used for the study case in this chapter. The Kundur 2A4G system is selected for the study cases in this thesis because of the following reasons:

- The network consists of two areas and is symmetrical. Therefore, the system can be easily separated in the middle of the system to obtain two similar areas.
- As both areas in the system contain the same network elements, the same study case in one area can also be implemented in the other area
- Since the system does not have a large number of power system components, the system is easy to be implemented and the co-simulation result is easy to be analyzed

Two types of network are used in this chapter, which are benchmark network and co-simulation network. The co-simulation network is the network used in the co-simulation's study cases whereas the benchmark network is the network used to evaluate the co-simulation result. In each study case, the same simulation is applied to both network. Then, the result from both networks are compared to evaluate the performance of the developed co-simulation. The description of both networks as well as the procedure to create them are described as follows:

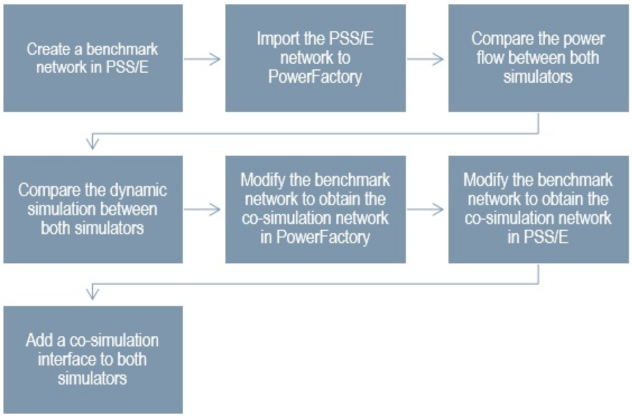

Figure 5.1: Process to obtain the test network used in the EMT-TS co-simulation

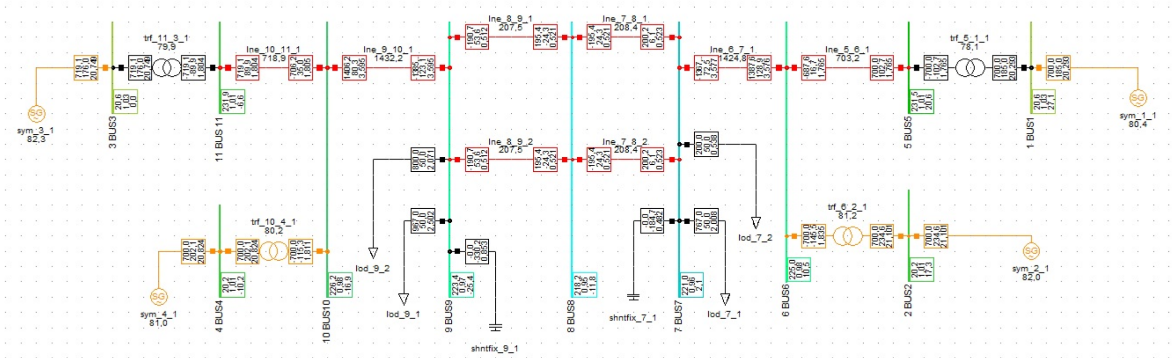

Figure 5.2: Single line diagram of the benchmark network in PowerFactory with its power flow result

5.1.1. Benchmark Network

The study cases in this chapter use the Kundur 2A4G as the benchmark network. For each of the performed case studies, a benchmark result is provided to evaluate the accuracy of the co-simulation result. The benchmark result is obtained by performing the same study case in the Kundur 2A4G system with a monolithic EMT simulation. To assure that the benchmark result is precisely representing the co-simulatio network simulated in PSS/E and PowerFactory, it is necessary that the benchmark network has the same parameters as the network in both simulators. However, it is practically difficult to implement the same parameters for PowerFactory and PSS/E as both simulators do not exactly modeled the network in the same way. In this thesis, a procedure is applied to create as similar as possible network between the benchmark network, the co-simulation network simulated in PowerFactory, and the co-simulation network simulated in PSS/E. The procedure is the same with the method described in the chapter 4 section 4.1 and is summarized in Figure 5.1

The Kundur 2A4G system has been implemented both in PowerFactory and PSS/E. The Kundur schematic file in PSS/E is based on the Kundur system file retrieved from [11]. The single line diagram as well as the power flow result for both simulators are illustrated in figure 5.2 and 5.3. In addition, the bus voltage results from the power flow are summarized in Table 5.1. The figures and the table show that both networks have the same power flow solution. Therefore, it can be concluded that both networks have the same steady state characteristic.

Apart from the power flow result, the dynamic behavior on each of the network during a transient is also compared. In this regard, a dynamic simulation is performed in both PowerFactory and PSS/E. The TS simulation is performed in PSS/E and the EMT simulation is performed in PowerFactory. The dynamic behavior of the network is observed by disconnecting one of the loads that is connected to BUS 9. Then, the result of the dynamic simulation from each simulator is compared. Figure 5.4 and 5.5 show the comparison result of the performed dynamic simulation in PowerFactory and PSS/E. In these figure, the comparison of power flow observed at BUS 8 and the comparison of voltage magnitude at BUS 9 are presented. From both result,

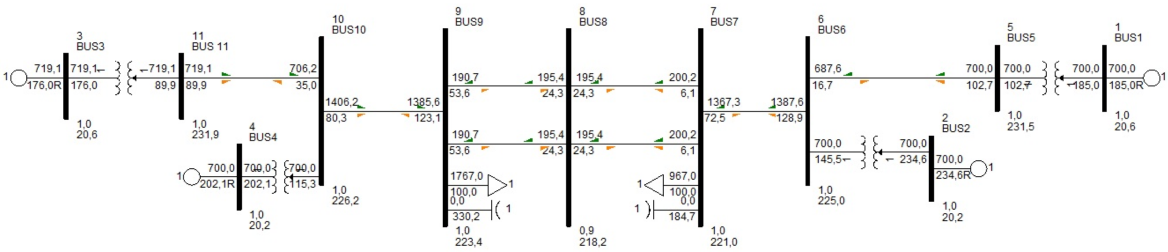

Figure 5.3: Single line diagram of the benchmark network in PSSE with its power flow result

Table 5.1: Comparison of bus voltages obtained from power flow in PowerFactory and PSS/E

	PowerFactory		PSS/E	
Bus	Voltage (p.u)	Angle (deg)	Voltage (p.u)	Angle (deg)
1	1.03	27.07	1.03	27.07
2	1.01	17.31	1.01	17.31
3	1.03	0	1.03	0
4	1.01	-10.19	1.01	-10.19
5	1.01	20.61	1.01	20.61
6	0.98	10.52	0.98	10.52
7	0.96	2.11	0.90	2.11
8	0.95	-11.76	0.95	-11.76
9	0.97	-25.35	0.97	-25.35
10	0.98	-16.94	0.98	-16.94
11	1.01	-6.63	1.01	-6.63

it is shown that the network created in PowerFactory and PSS/E has a similar characteristic in this dynamic simulation test. This result is considered adequate to justify that both networks more or less have the same network characteristic.

5.1.2. Co-simulation Network

To perform a co-simulation, the Kundur 2A4G system is symmetrically divided into two parts, one part is simulated in PowerFactory using EMT simulation and the other part is simulated in PSS/E using in TS simulation. The partition of the network can be seen in Figure 5.6. From the figure, it is shown that the system is equally divided, resulting in a two similar areas. In the co-simulation network, BUS 8 is selected as the interface bus due to its location at the middle of the network.

To realize the co-simulation network in PowerFactory, the PowerFactory benchmark network that has been created before is modified by removing the part which is supposed to be simulated in PSS/E. Then, BUS 8 as the interface bus is connected in series with a PowerFactory co-simulation interface. The single line diagram realization of the co-simulation network simulated in PowerFactory is presented in Figure 5.7.

On the other hand, to realize the co-simulation network in PSS/E, the PSS/E benchmark network that has been created before is modified by removing the part which is supposed to be simulated in PowerFactory. Then, BUS 8 as the interface bus is connected with a PSS/E co-simulation interface. The single line diagram realization of the co-simulation network simulated in PSS/E is presented in Figure 5.8.

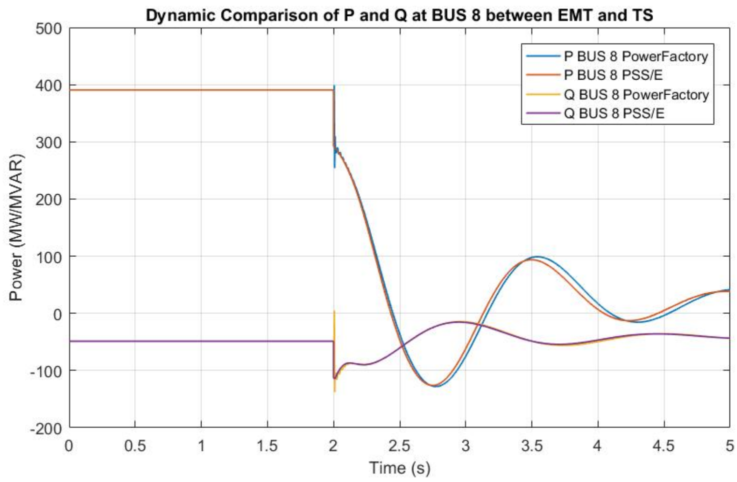

Figure 5.4: Comparison of the total power flow observed at BUS 8 between EMT and TS

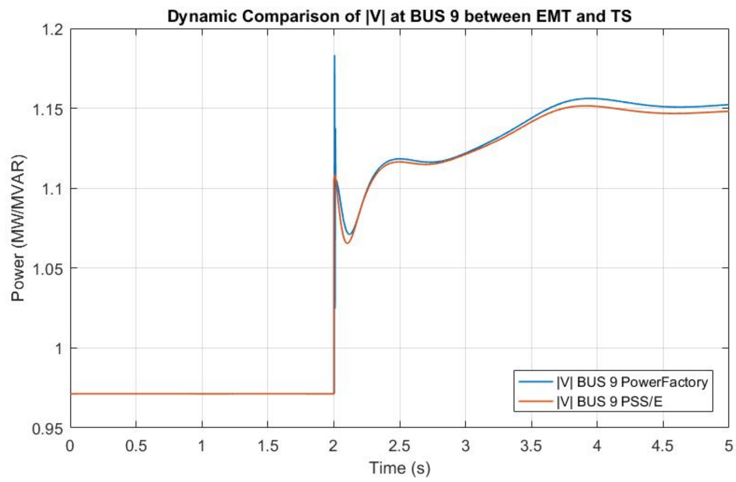

Figure 5.5: Comparison of the voltage magnitude observed at BUS9 between EMT and TS

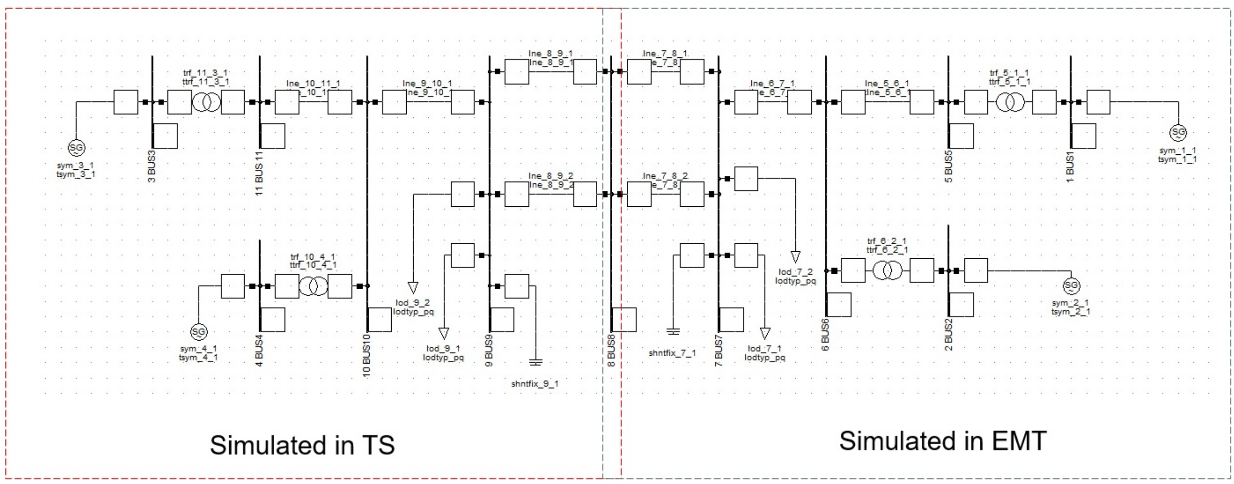

Figure 5.6: Kundur 2A4G system and its separation in EMT and TS

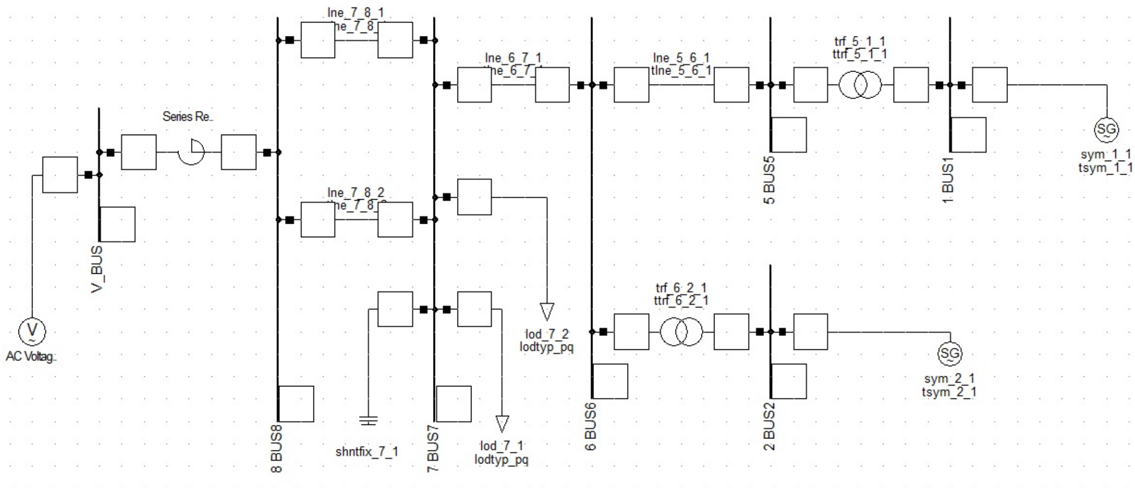

Figure 5.7: Single line diagram of the co-simulation network in PowerFactory during case studies

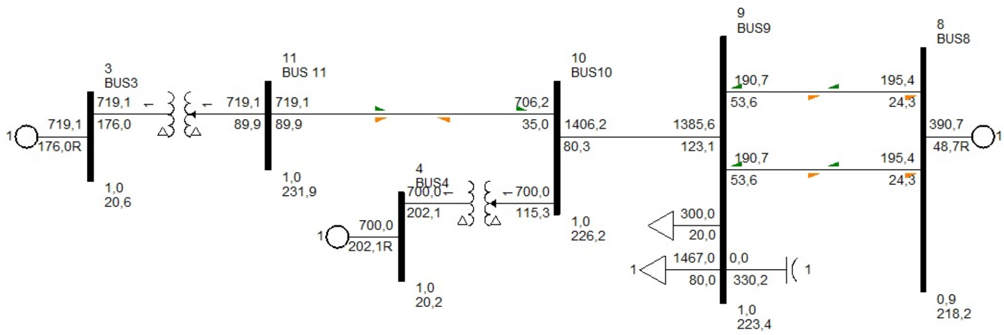

Figure 5.8: Single line diagram of the co-simulation network in PSS/E during case studies

5.2. Case 1: Loss of Load Event in TS Area

Case 1 aims to fulfill the fourth objective in this thesis. In the first case, a loss of load event on the TS side is performed. The load event is selected because this event does not cause a substantial transient which may lead to an unstable co-simulation result. The method of this case is as follows:

5.2.1. Method

The first case uses the co-simulation network based on the Kundur 2A4G system which has been defined in the previous section. Using a TS time step of 0.02s and EMT time step of $50\mu s$, the EMT-TS co-simulation is executed until it reaches a steady state condition. First, both simulators are fed by a constant power value from the master and the TS wrapper until t=1s. Then, the synchronization between both simulators begins at this point. Next, the co-simulation is run until it reaches a steady state condition.

In this case, the load connected at the BUS 9 in the Kundur system is split into two loads with different power. Load 1 has a nominal power of 987+50j MVA and load 2 has a nominal power of 800+50j MVA. At t=2s, a loss of load event is applied by disconnecting the second load in the PSS/E network. Then, the simulation is continued for 3s. The sudden change of power flow will cause a transient in the EMT network. Here, the dynamic phenomena that occurs in EMT and TS are observed, and the results are compared with the same simulation event performed in the benchmark network.

In this test, two variables obtained from PowerFactory, PSS/E, and benchmark network are monitored which are active and reactive power at the interface bus. Here, the results obtained from PowerFactory and PSS/E are evaluated at how close these results are to the benchmark network, and how much the execution time differs between both.

5.2.2. Result and Discussions

The results of the simulation are presented in Figure 5.9 - 5.14. In these figures, the comparison of the active and reactive power in bus 8 (interface bus) obtained in PowerFactory, PSS/E, and benchmark result are depicted respectively. The total execution time of the co-simulation is 23.30 minutes while the total execution time of the benchmark is 12s. From the comparison of each graphs, it is observed that the result of active power between PowerFactory, PSS/E, and benchmark are similar. However, the result of reactive power at the interface bus is different.

Benchmark Result

From the result showed in Figure 5.11 and 5.14, it is observed that the loss of load occurred at t=2s causes a transient in the power system. When a loss of load occurs, the system impedance changes suddenly. The change in impedance causes the sudden change in voltage and power during a short period of time, resulting in a steep decrease of active power transferred to the TS side. Since a shunt capacitor is connected to the same bus with the load, the sudden increase of voltage causes a sudden increase in the reactive power flow to the interface bus. After this point, the generator controllers try to control its output power towards the new solution. An oscillation of power flow between two areas is observed. However, the oscillation is kept constrained. It can be seen in the figure that the power observed at the interface bus converges towards the new power flow solution.

Active Power Result

The active power result in Figure 5.9 and 5.12 shows an identical result. It means that the power flow between both simulator is equal. Although the graphs are similar, it is observed that there is no sudden drop of active power in the EMT result when the even is applied at t=2s. Although the result in TS shows a sudden drop of active power, the curve is forced back to the original value. This is caused by the discretization of power exchange between simulators. Figure 5.15 shows the phenomena a moment after the load event is applied. When the load event happens in TS, the power flow drops suddenly. But, since the active power from EMT is kept constant during one TS time step, the power flow in TS is forced back to its previous value again. This resulted an incorrect power information value to be sent to EMT side. Therefore, the EMT simulator did not experience the sudden drop at its timestep.

The other thing that is observed in the active power result is the difference in its oscillation when it converges towards the new power flow solution. In the benchmark, it is observed that between t=2s to t=5s, 1.5 sinusoidal cycle is observed whereas in co-simulation, only 1 sinusoidal cycle is noticed. It shows that the co-simulation result has slower dynamic compared to the benchmark result. This is also caused by the discretization of power transfer between both simulators. Since the information exchange does not happened

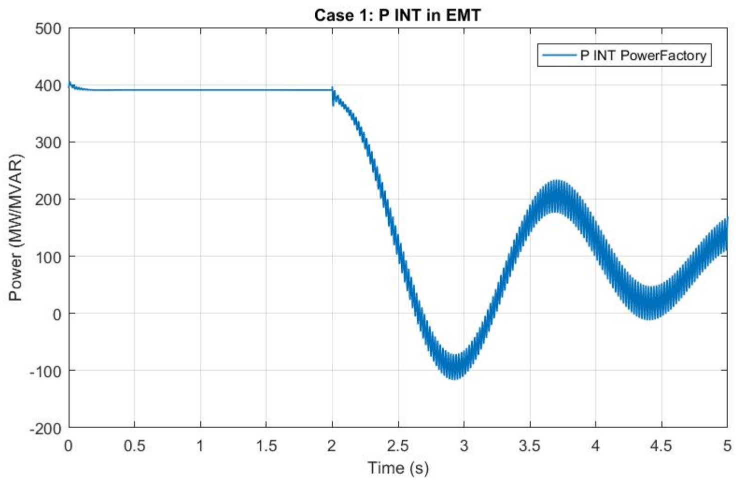

Figure 5.9: Result of Case 1: PINT in EMT

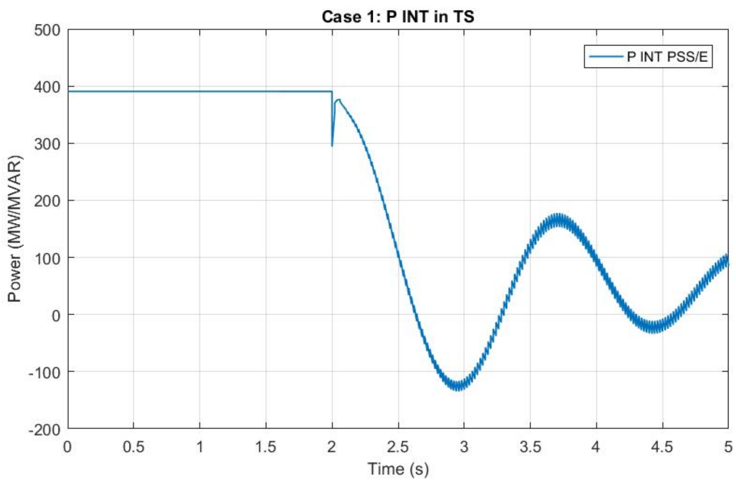

Figure 5.10: Result of Case 1: PINT in TS

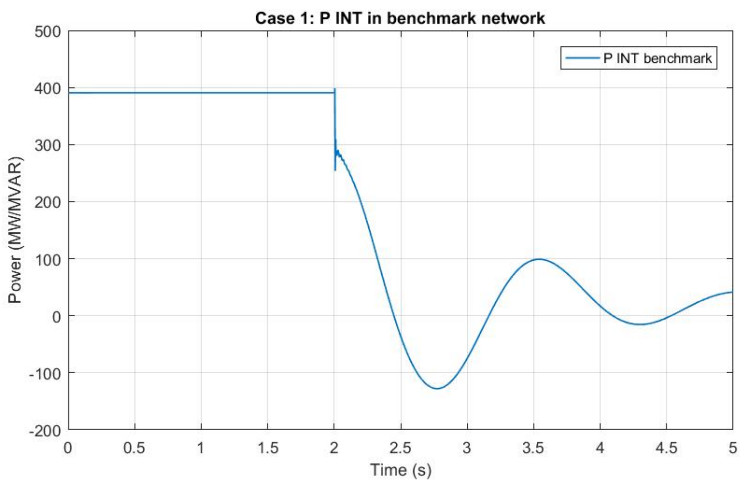

Figure 5.11: PINT in the benchmark Result

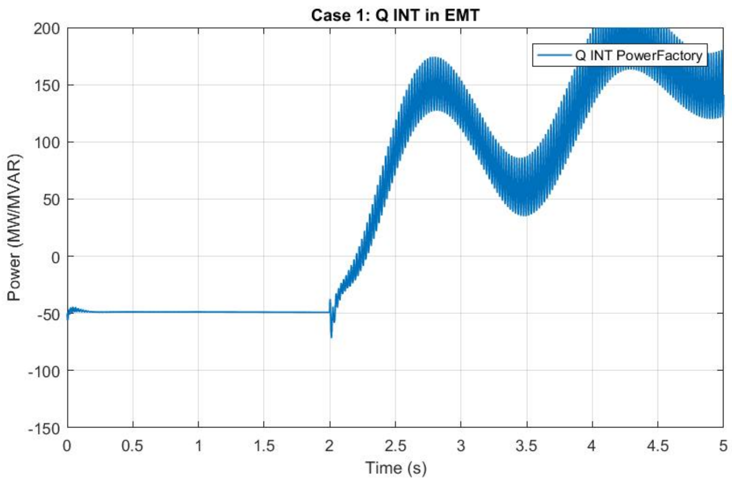

Figure 5.12: Result of Case 1: QINT in EMT

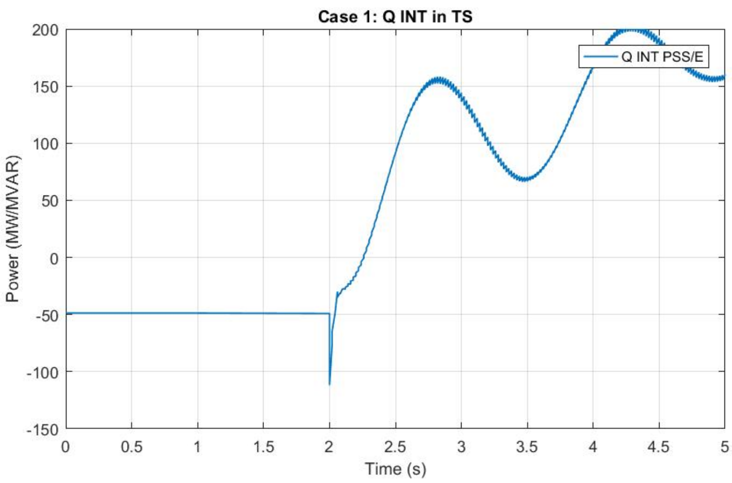

Figure 5.13: Result of Case 1: QINT in TS

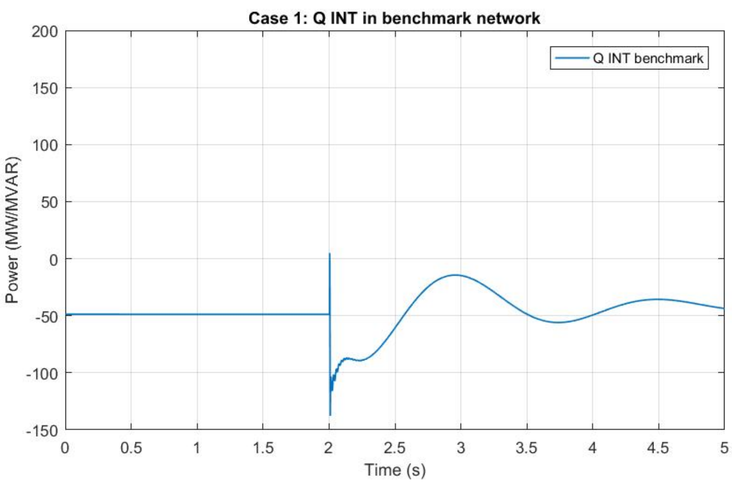

Figure 5.14: QINT in the benchmark Result

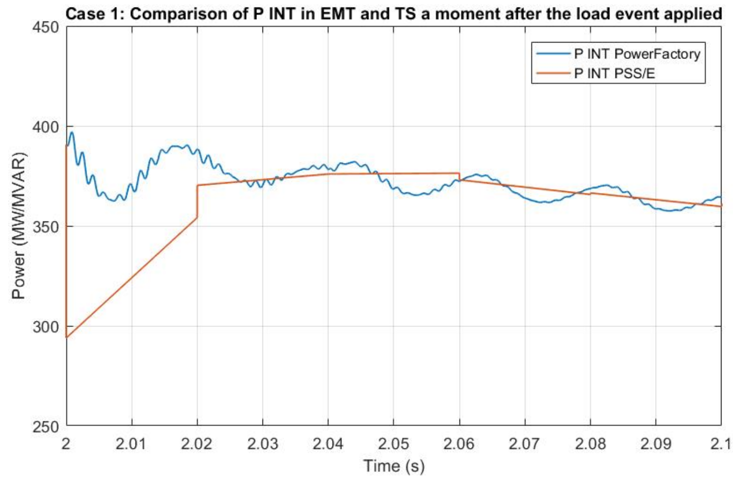

Figure 5.15: Case 1: Comparison of P INT in EMT and TS a moment after the load event applied

simultaneously, there is a delay in the way each simulator responds to the other, causing a slower transient in the co-simulation result.

Reactive Power Result

In the case of reactive power, the result obtained from co-simulation is in contrast to the benchmark. Although both figures show an oscillation of reactive power, but the magnitude in each result is different. The oscillation of reactive power in the benchmark network is able to converge into a new value. However, the reactive power in co-simulation result is oscillating in a different dirrection. Instead of directing reactive power to the EMT side, the power flow is directed to the TS side. In addition, it is not shown that the oscillation converges to a new value.

The reason could be because of the incorrect system solution when the load event occurs. It is observed from the benchmark result that when a load event occurs, the voltage at BUS 8 is slightly below the voltage at BUS 9. However, from the co-simulation result, the voltage at BUS 8 is nearly the same with the voltage at BUS 9, causing the reactive power flow to drop. The drop of reactive power keeps decreasing and eventually, this leads to the flow of reactive power reverted to the TS side. The comparison of voltage at BUS 8 (INT BUS) and BUS 9 in the benchmark network and in the co-simulation at PSS/E side can be seen in Figure 5.16 and 5.17.

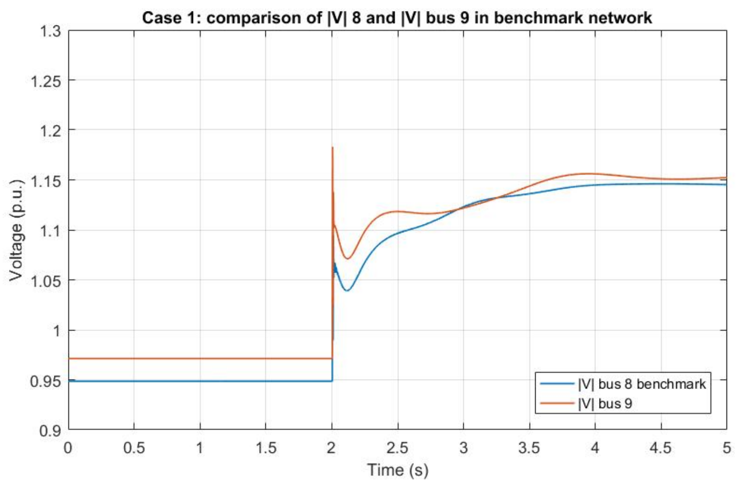

Figure 5.16: Case 1: comparison of |V| BUS 8 and |V| BUS 9 in benchmark network

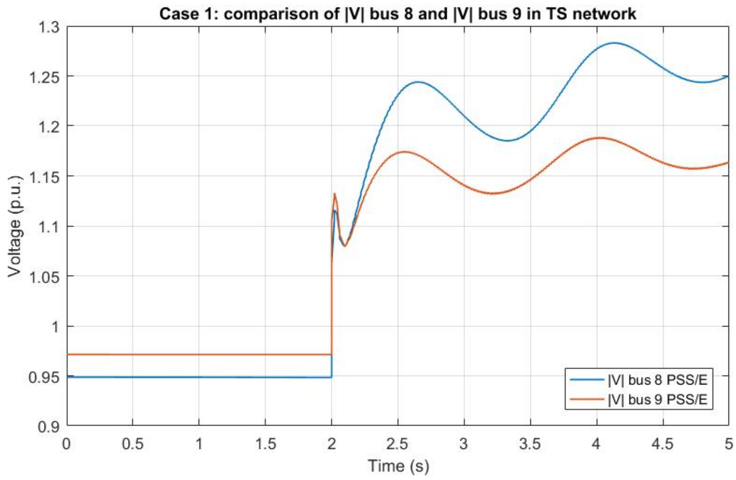

Figure 5.17: Case 1: comparison of |V| BUS 8 and |V| BUS 9 in TS network

5.3. Case 2: Loss of Transmission Line in TS Area

Similar with the first study case, the second study case also aims to provide the study regarding the fourth objective in this thesis. In this case study, a loss of transmission line event in TS is performed to give more insight on how the developed co-simulation performs in a different type of event. Apart from that, an additional discussion regarding the effect of equivalent impedance modification is presented following the discussion of the result.

5.3.1. Method

For this case, a co-simulation network based on Kundur 2A4G system defined in the previous section is adopted. A TS time step of 0.02s and EMT time step of 50μs is used. Initially, the interface in both simulators are fed with a constant power set point until t=1s. From that point, both simulators start synchronizing their power information.

In Kundur's system, there are two transmission lines connecting BUS 8 and 9. In this study case, a loss of transmission line event is performed by disconnecting one of these two lines once the co-simulation reaches steady state. Then, the simulation is continued for 3s. From the obtained result, the total execution time is compared between the co-simulation result and the benchmark. Also, the active and reactive power at the interface bus are evaluated to observe how the co-simulation handles the power information exchange during this study case.

5.3.2. Result and Discussion

The result of the simulation is presented in Figure 5.18-5.23. In these figures, the comparison of the active and reactive power in bus 8 (interface bus) obtained in PowerFactory, PSS/E, and benchmark result are depicted respectively. The simulation is done in 22.40 minutes. From the comparison of each graph, it is observed that the results of active and reactive power are similar with the results from the benchmark network a moment after the event is applied. However, the result becomes more different than the benchmark result when the simulation is run for longer simulation time.

Benchmark Result

The benchmark result in Figure 5.20 and 5.23 shows the behavior of the Kundur area system when the loss of line event happened. From the figure, it is shown that when line 8-9-2 goes offline, the power which is previously transmitted through it is redirected to line 8-9-1, causing a sudden increase of power flow in that line. It means that after the event, line 8-9-1 handles twice the active power flow from before. This cause the line to need more reactive power. This causes the flow of reactive power which is previously flowing to EMT area is reverted into flowing to the TS area to supply the reactive power need of line 8-9-1.

Active Power Result

The active power observed in Figure 5.18 and 5.19 shows identical result. It means that the power flow

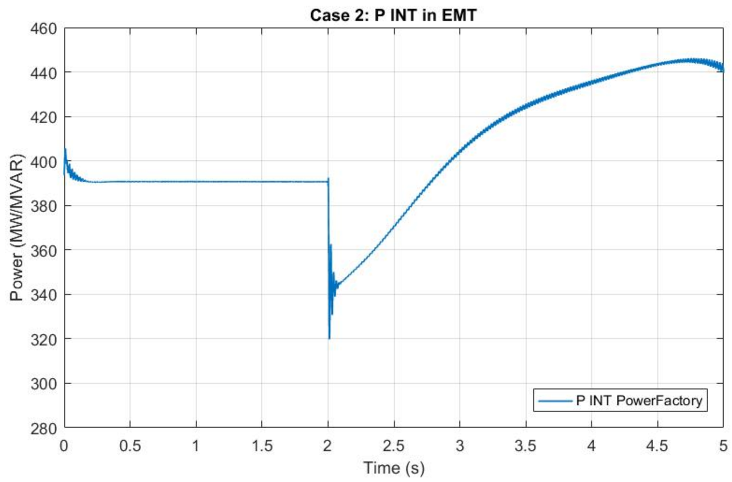

Figure 5.18: Result of Case 1: PINT in EMT

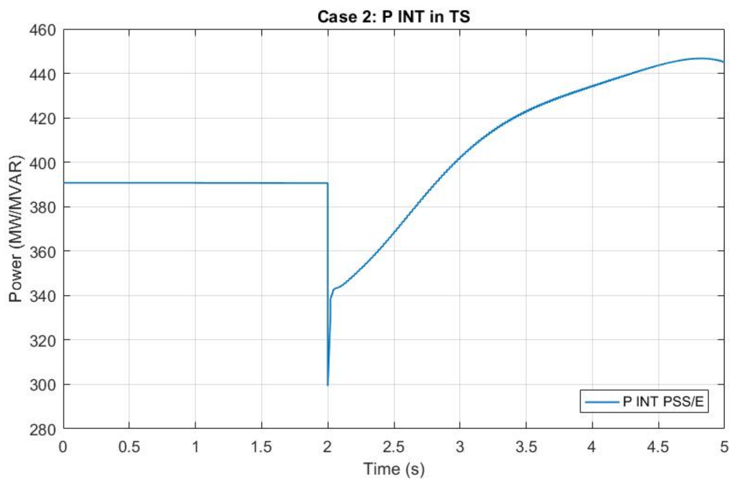

Figure 5.19: Result of Case 1: PINT in TS

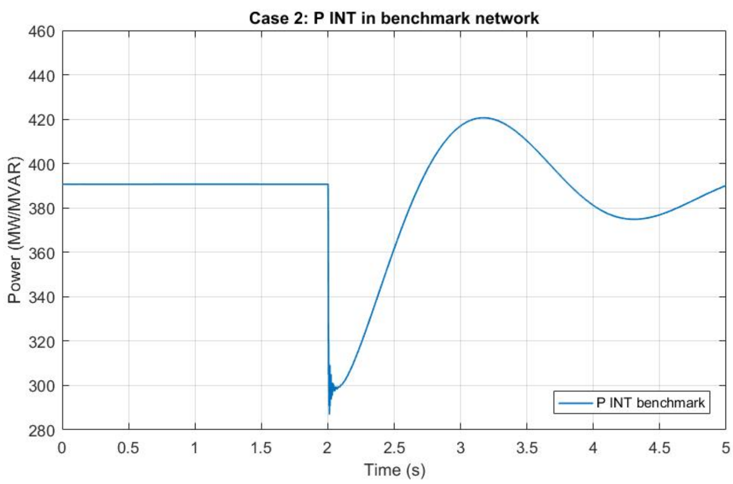

Figure 5.20: PINT in the benchmark Result

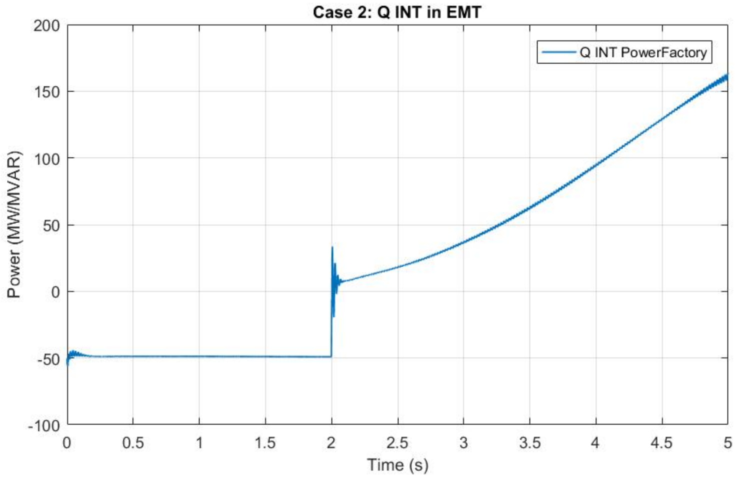

Figure 5.21: Result of Case 1: QINT in EMT

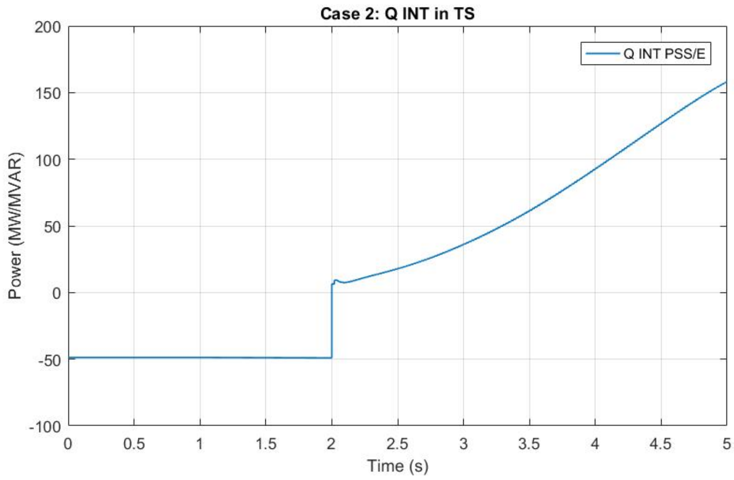

Figure 5.22: Result of Case 1: QINT in TS

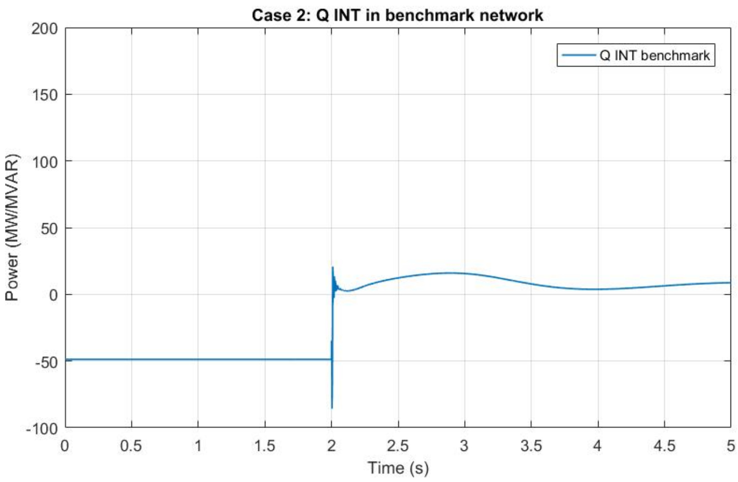

Figure 5.23: QINT in the benchmark Result

between both simulator is equal. It is further analyzed that a moment after the event is applied, both simulators responded with a sudden drop of active power. However, it is observed that there is a sudden step in TS result, showing that the power in TS is forced back to go up. The reason is while the power flow from TS is reduced, the power supplied from interface is kept constant during one TS time step. This constant power forced the power at the interface to increase, causing the PINT at TS change from 300 to 340 MW. This phenomena caused the inaccurate result at the beginning of the event and eventualy leads to a higher peak value of active power.

The second thing observed from the active power result is that the transient in the co-simulation is slower than the transient observed in the benchmark. The result from the benchmark reached its peak value at t=3.2s. However, the result from the co-simulation shows that it reaches its peak at 4,7s. The reason of the slower transient in co-simulation is the discrete power exchange between both simulator. Since the network in EMT and TS are separated, the transient in one side can not immediately affects the other side. The information between both simulator is transferred only at particular time, causing a delayed response of one side to the other side, and as a result, the transient observed in the co-simulation appears delayed compared to the benchmark network.

Reactive Power Result

For the reactive power, the result in EMT and TS also shows identical result. Therefore, the power flow between EMT and TS are equal. When the line event happens at t=2s, both result from co-simulation and benchmark also experience a sudden change in power. Both result has a step change from around -50 MVA to around 10 MVA. However, while the benchmark reactive power oscilates and reaches a stable value, the co-simulation reactive power keep increasing until the end of simulation.

The difference between the benchmark and the co-simulation is caused by the slow transient of active power. In the benchmark result, the active power peaked at t=3.1s then the value went down afterwards. However, in the co-simulation result, the power reached its peak later at t=4.9s because of the slow transient phenomena. Since the active power keep increasing the amount of reactive power used to supply the transmission line is also increasing. This causes the continuous increase of reactive power.

5.3.3. The Effect of Equivalent Impedance Modification to the Simulation Result

The PowerFactory interface consists of a voltage source connected in series with an equivalent impedance representing TS side. When the line event occured in the TS side, the equivalent impedance in PowerFactory interface needs to be updated. In this additional discussion, the effect of equivalent impedance modification when the event occurs is studied. To examine it, the second study case is re-simulated without changing the equivalent impedance when the line event occurs. Then, the obtained result is compared with the result obtained from the second study case that includes equivalent impedance modification, and the result from the benchmark network.

Figure 5.24 and 5.25 show the active and reactive power result observed at EMT side. For active power graph, both results show a similar curve. However, the result obtained with impedance change is slightly closer to the benchmark result. Also, while the result obtained with the impedance change reaches its peak at around 4.8s, the result obtained without impedance change keeps increasing until the simulation ends. For reactive power graph, both results also show an identical curve. However, the result obtained without impedance change is surprisingly closer than the result with impedance change.

To further analyze the result, an additional figure is presented. Figure 5.26 shows the voltage magnitude result at BUS 9 that is located at the end of the disconnected line. From the result, it is shown that the result with impedance change is closer to the benchmark result than the result without impedance change at the moment after the event occurs.

From the comparisons, there is no firm conclusion that can be drawn regarding how the equivalent impedance modification affects the co-simulation result. In the active power and voltage at bus 9 result, it is shown that modifying the impedance slightly improve the accuracy of the co-simulation result. However, the reactive power result contrastly shows that the result without the equivalent impedance change is better.

The difference of active and reactive power result could be related to how large the impedance modification happened during the event. For the second case, the nominal of equivalent impedance used before the event occurs is 14.00953 + 42.9524j Ohm while the nominal used after the event occurs is 16.99614 + 71.24613 Ohm. From these value, the modification of the real part is not as large as the modification to the imaginary part of the impedance. Therefore, this could explain why the difference in the reactive power result is larger than the difference in the active power result.

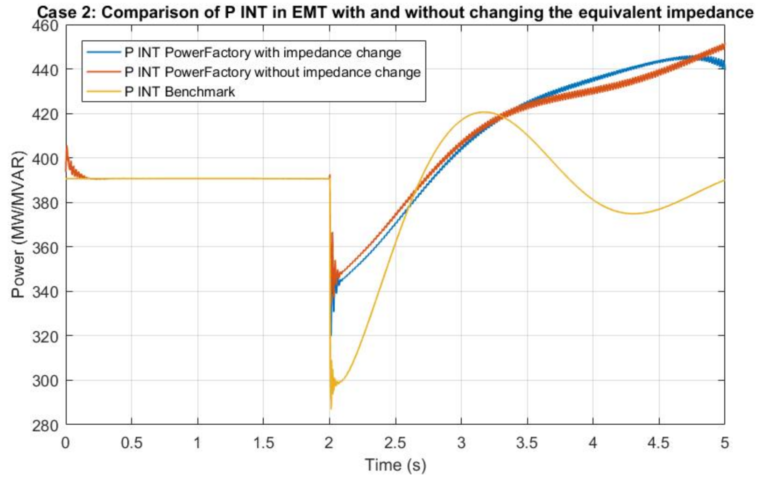

Figure 5.24: Comparison of PINT in EMT between with and without updating the equivalent impedance

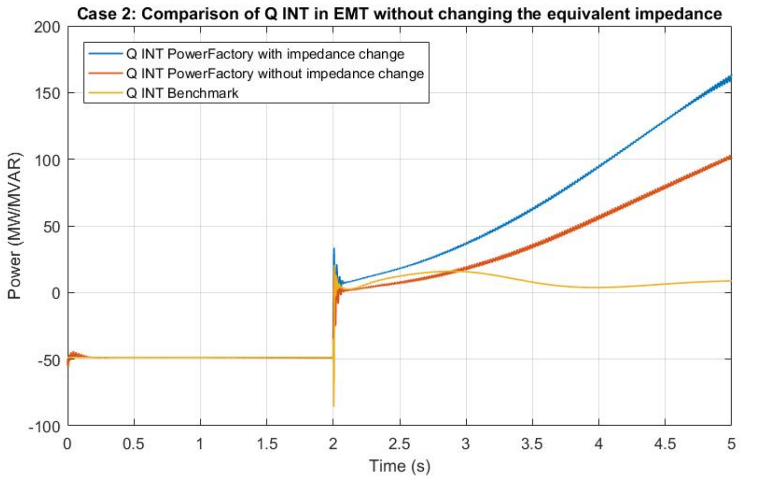

Figure 5.25: Comparison of QINT in EMT between with and without updating the equivalent impedance

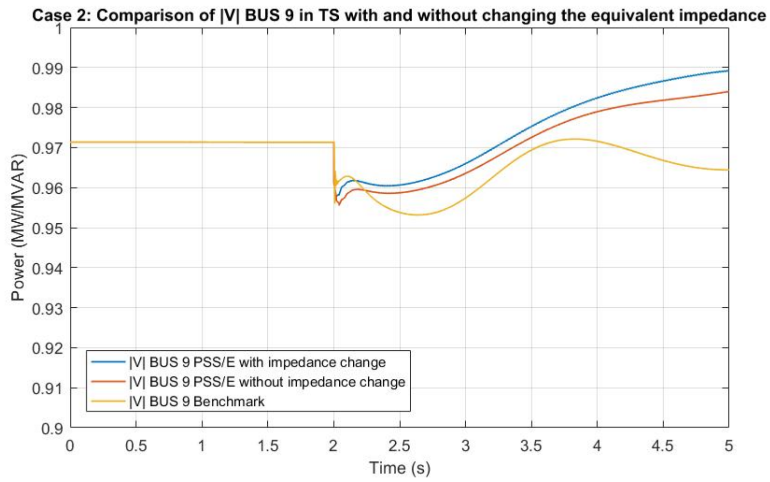

Figure 5.26: Comparison of the Voltage in BUS 9 obtained in PSS/E between with and without updating the equivalent impedance

To further examine the effect of equivalent impedance to the co-simulation, more simulation cases is required. The simulations must involve an event which causes a change in total system impedance, e.g. loss of load event. The simulation network is advised to be made as simple as possible to eliminate the effect of other components in the system. In each simulation, the amount of system impedance change is varied and the result between with and without changing the equivalent impedance is observed. For example, in one case such event is applied which causes the amount of the total real impedance change is increased while the imaginary impedance is fixed. Then, two co-simulations are made. One with modifying the equivalent impedance, and the other without modifying the equivalent impedance. By performing this experiment, the difference of the result between with and without modifying the real equivalent impedance to the active power result can be observed. The same approach can also be used to examine the effect to the reactive power result. The examination of the effect of the equivalent impedance is an interesting topic that can be recommended for the further research in this topic.

5.4. Case 3: Loss of Transmission Line in EMT Area

In the third study case, a loss of line event in EMT side is performed. This study case also have the similar aims with the first and the second study case that is to provide the study regarding the fourth objective in this thesis. In addition, this case study also provide an insight on how the co-simulation performs when the event is applied in EMT instead of in TS.

5.4.1. Method

Similar to the case 1 and 2, a co-simulation network based on Kundur 2A4G system defined in the previous section is used in this case. the co-simulation is executed using TS time step of 0.02s and EMT time step of $50\mu s$. At the beginning of the simulation, both simulators are fed with a constant power set point until t=1s. Then the synchronization between simulator is begun at this point. When both simulator reaches steady state, a loss of transmission line is applied in EMT side. Then, the simulation is run for the next 3s.

In Kundur's system, there are two transmission lines connecting BUS 8 and 7. In this study case, a loss of transmission line event is performed by disconnecting one of these two lines when the co-simulation has reached steady state. In this study case, the active and reactive power at the interface bus is evaluated to see how the co-simulation handles the power information exchange during this specific case.

The co-simulation interface in PSS/E is based on static generator which has internal impedance inside it. Since the internal impedance is used as an equivalent impedance, modifying the internal impedance of the static generator during dynamic simulation is not possible. Ideally, the equivalent impedance in TS needs to be modified when the event occurs to adapt with the change of network in EMT. However, in this case the equivalent impedance of the interface inside PSS/E is not modified when the line event occurs due to the mentioned limitation.

5.4.2. Result and Discussions

The simulation result for case 3 are shown in Figures 5.27 - 5.32. In these figures, the comparison of the active power, reactive power in the INT BUS (Bus 8) obtained in PowerFactory, PSS/E, and benchmark result are depicted respectively. For this case, the simulation finished in approximately 24 minutes. The discussions regarding each of the results are as follows:

Active Power Result

Figures 5.27 and 5.28 show the active power result at EMT and TS. Both figure shows identical result, indicating that the power flowing in EMT and TS are the same. When compared to the benchmark result in Figure 5.29, the active power shows similarity until t=3,5s. However, after this point the result from co-simulation keep dropping and then at t=4s the active power start to oscilate.

It is observed that a moment after the event is applied, the active power is going down to 340 MVA. At the same time in the benchmark result, the power is going down to 300 MVA. The reason of this difference is caused by the averaging of active power result when sending the power information to PSS/E. It is observed from Figure 5.33 that up until t=2.02s, the active power in EMT is similar with the active power from the benchmark. However, since the value that is sent to PSS/E is the average value, the value returned from PSS/E at t=2.02 s is higher than PowerFactory previous value, resulting a ramp up in power and inaccurate co-simulation result.

The reason why the active power keeps going down at t=3,5s is because of the slower transient in the co-

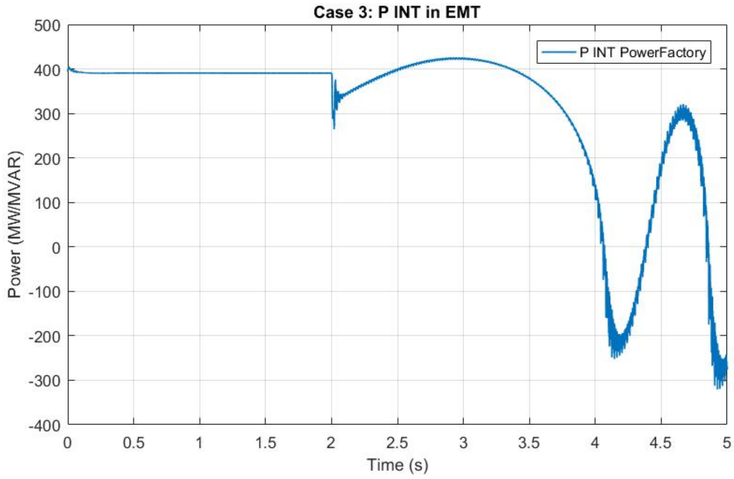

Figure 5.27: Result of Case 3: PINT in EMT

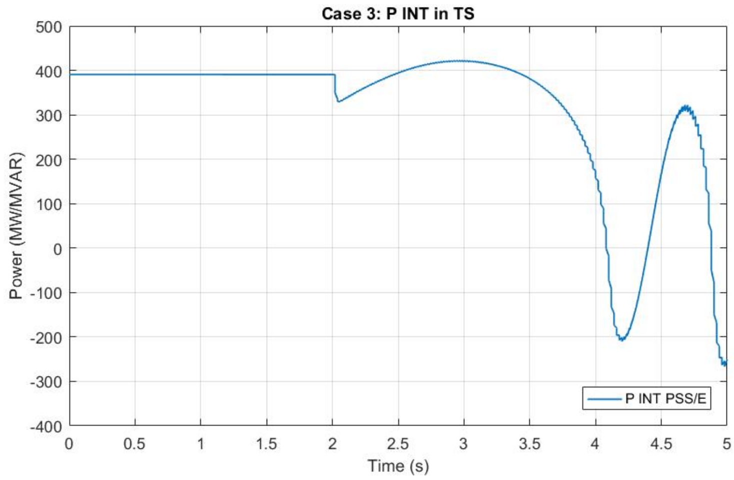

Figure 5.28: Result of Case 3: PINT in TS

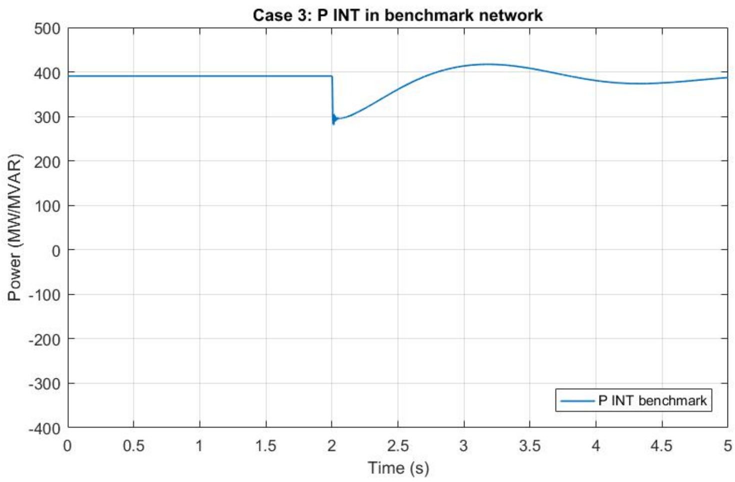

Figure 5.29: PINT in the benchmark Result

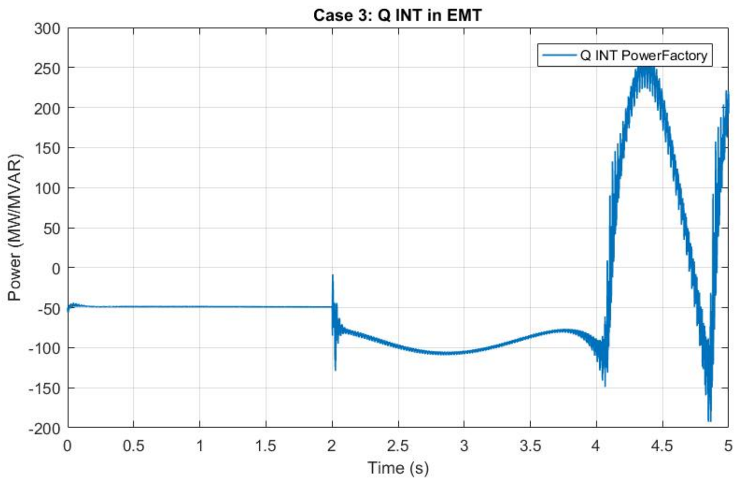

Figure 5.30: Result of Case 3: QINT in EMT

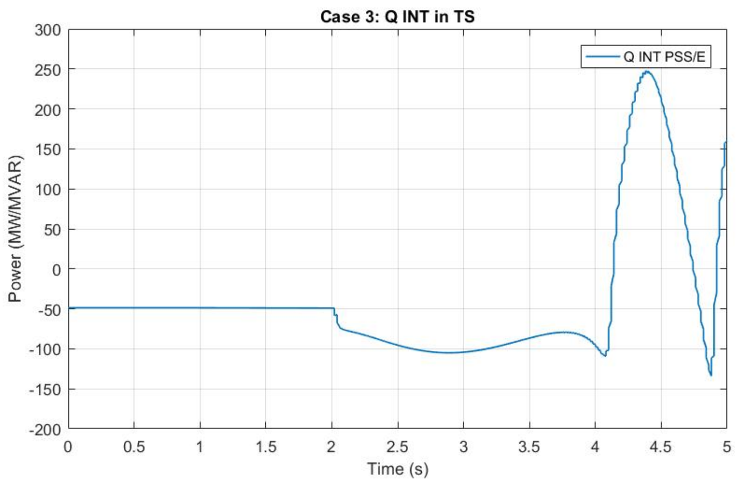

Figure 5.31: Result of Case 3: QINT in TS

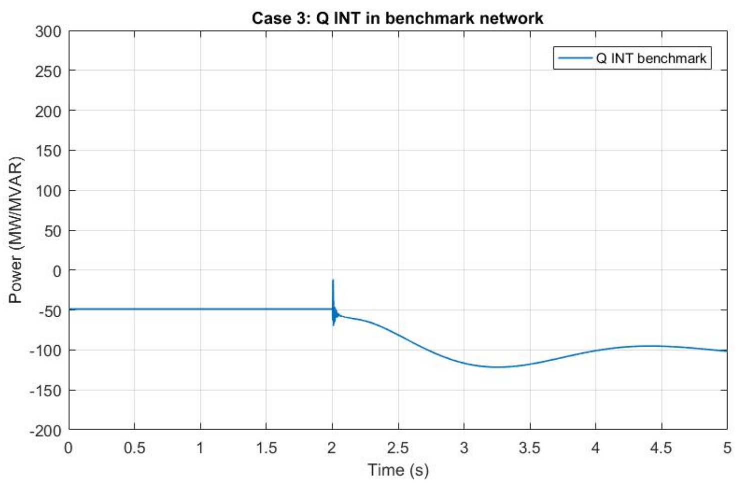

Figure 5.32: QINT in the benchmark Result

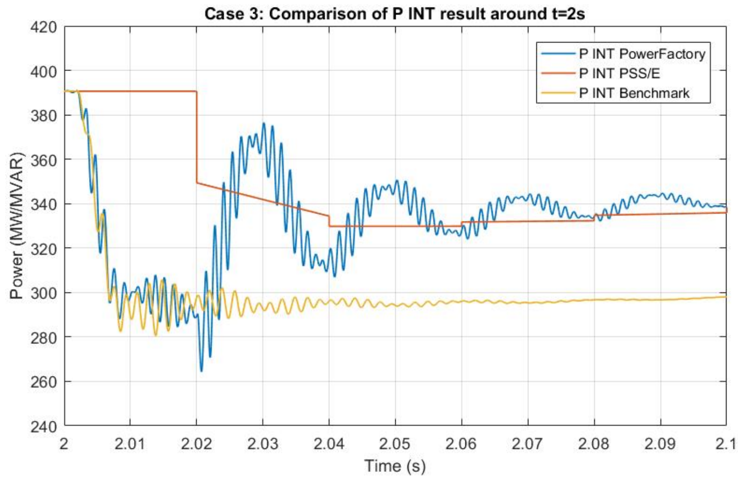

Figure 5.33: Result of Case 3: The comparison of PINT a moment after the line event occured

simulation. In the Kundur system, there is a power flow from the EMT to the TS area because the load in TS are larger than the load in EMT. When the line in EMT is disconnected, the active power flow is interrupted in a moment. Since the load in TS is supplied by the generator from both areas, ideally, when one line is disconnected, the generators in both areas responded at the same time to the transient caused by the disconnection of the line. However, in the co-simulation, the discretization of power exchange caused the dynamic response from the other system to be slower. Due to the reason, the response of the generator to return its active power supply to the load in TS is delayed, causing the generator in TS to increase more of its power output to supply the load in TS side. It can be observed in figure 5.34 that the Power from LINE 10-9 (the line which carries the power from the generator in TS side) is increasing to fulfill the demand of TS load. Since the power demand in TS area is fulfilled, the power flow from EMT is reduced, causing the active power at the interface is going down. Eventually, the power is kept reduced until the active power direction reverse into EMT side and causing a power oscillation a moment after.

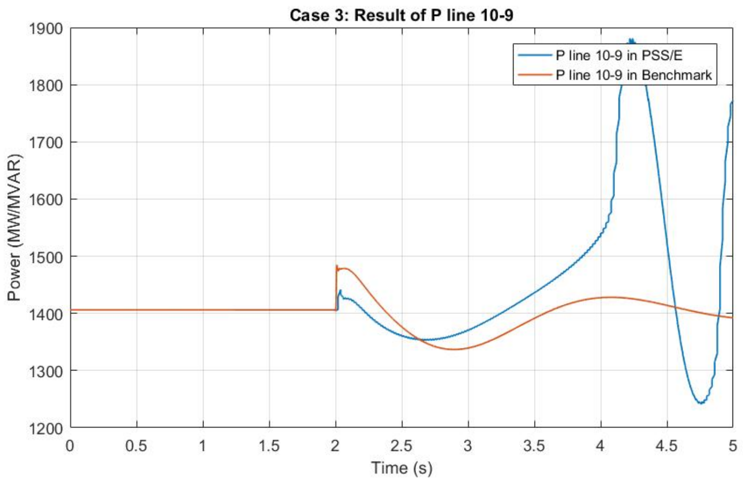

Figure 5.34: Result of Case 3: Comparison of LINE 10-9 active power between TS and benchmark

Reactive Power Result

Figure 5.30 and 5.31 shows the reactive power result at EMT and TS. The identical result shown by the two figures indicates that the power flowing in EMT and TS are the same. When compared to the benchmark result in Figure 5.32, the reactive power shows a similar result with the benchmark. The reactive power result start to diverge at t=3s. In addition, it is also observed that at t=4s, the reactive power starts oscillating. This is due to the oscillation of active power.

5.4.3. Attempt to Modify the Equivalent Impedance Inside PSS/E

An attempt to modify the equivalent impedance inside PSS/E has been made. However, the result is not as expected. To modify the equivalent impedance, the idea is to add a shunt impedance at PSS/E interface bus. Since the interface in PSS/E is represented by a current source connected in parallel with a shunt equivalent impedance, the addition of another shunt impedance could modify the value of the total equivalent impedance of the interface. The result of the attempt are depicted in Figure 5.35 and 5.35.

The explanation of why the attempt failed has not been further investigated. The reason could be because of the method to add a shunt impedace to the interface bus. In this attemp, the way to add a shunt impedance is realized by creating a short circuit to the interface bus with a certain value of impedance. A further investigation to find out why the idea failed can be started by comparing the system impedance matrix in PSS/E before and after the short circuit is applied. Then, from the obtained matrix, the total impedance at the interface bus can be evaluated whether it changes or not.

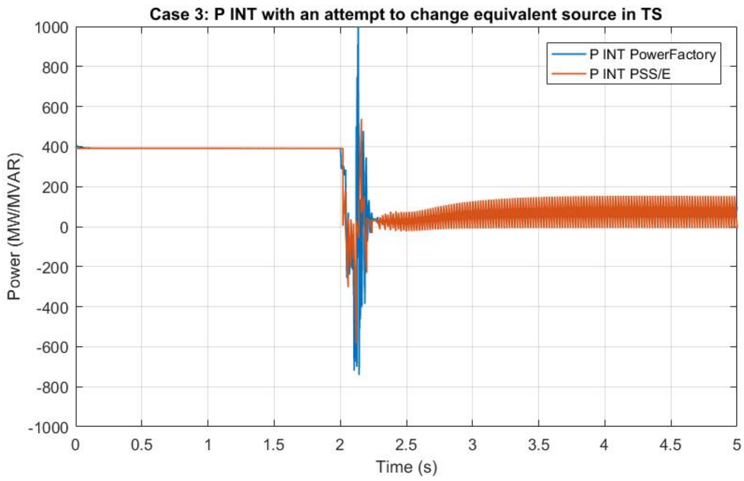

Figure 5.35: Result of Case 3: PINT in EMT and TS with an attempt to change the equivalent source impedance in TS side

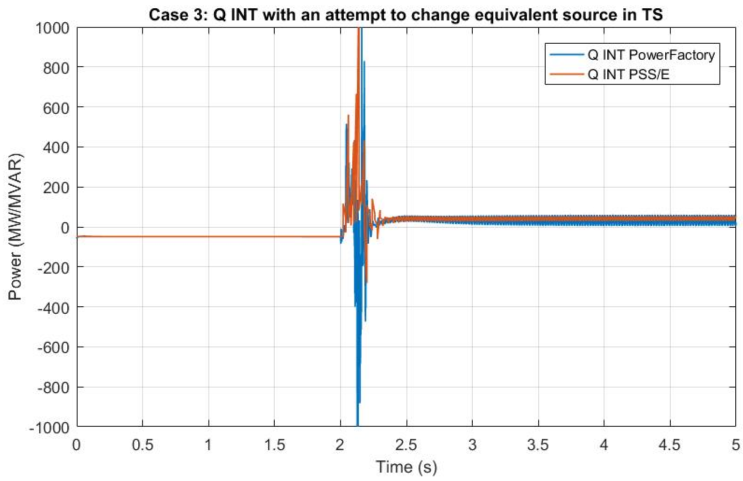

Figure 5.36: Result of Case 3: QINT in EMT and TS with an attempt to change the equivalent source impedance in TS side

5.5. Case 4: Effect of Different TS Time Step in EMT-TS Co-simulation

In the fourth study case, a comparison between different TS time step used in the co-simulation is presented. The aim of this study case is to examine how does the TS time step parameter affects the result accuracy and the total simulation time of the developed co-simulation as corresponds with the fifth objective in this thesis.

5.5.1. Method

To perform the comparison, the TS time step parameter in the master algorithm is modified. Then, the modified master algorithm is used to re-simulate a loss of transmission line event at TS side which has been performed in the case 2 section. The method to perform the loss of transmission line event is the same with the method defined in section 2. The result from the modified time step simulation and the result from case 2 simulation are compared and further, two variables which are active and reactive power, are evaluated.

Two TS time steps are compared in this study case which is 0.02s and 0.01s. The attempt for a TS time step of 0.04s previously has been tried. But, due to the simulation showed an error in the middle of simulation, the result is not included in this comparison. To perform a co-simulation with a TS time step smaller than 0.01s, a modification in the master algorithm which include a phase compensation (also called time-delay compensation) in the process from TS to EMT is required [15]. This recommendation to include this modification is included in the chapter 6 of this thesis.

In this study case, the EMT time step used for both 0.01 and 0.02 case is 50 μs. The co-simulation integration time is changed according to the TS time step. For the TS time step of 0.01s, the integration time is 0.01s and for the TS time step of 0.02s, the integration time is 0.02s. The reason is because the integration time step is constrained by the TS time step. If TS time step is smaller, then the data exchange between both simulator can also be performed in a smaller interval, and vice versa.

5.5.2. Result and Discussions

The simulation result for case 4 are shown in Figure 5.37 - 5.42. In these figures, the comparison of the active power, reactive power in the INT BUS (Bus 8) obtained in PowerFactory, PSS/E, and benchmark result with different TS time step are depicted respectively. The discussions regarding each of the results are as follows:

The Effect of TS Time Step to the Accuracy of the Result

From the figures, it is shown that the result obtained from 0.02 and 0.01 TS time step is not significantly different. The results from both case are similar in the shape. However, the result from the case of 0.01s TS time is slightly below the result of 0.02s. When compared to the result from the benchmark, the active and reactive power result of 0.01 second TS time step does not show a significant accuracy improvement compared to the result from 0.02s TS time step.

The result of 0.01s and 0.02s TS time step start showing a difference a moment after the event is performed. To examine further, the result of active power from both case are observed at around t=2s right after the event is applied. Figure 5.43 shows the comparison of different time step in EMT simulation and Figure 5.44 shows the comparison in TS simulation. From both figures, the process of each case can be observed in more detail.

It is shown in the figures that the result of 0.01s time step is higher than the result obtained from 0.02s. This is also related to the way PSS/E perform the dynamic simulation. It is observed that the calculation result of the next time step between 0.01 and 0.02 integration time are the same at the moment right after the event is applied. From Figure 5.44, it is shown that both cases resulted 330 MW at its next time step. Since PSS/E intrapolate the result between its time step, this causes the result obtained from 0.01s time step appears higher than the result from 0.02s time step.

It is deducted from these figures that the reason of the difference is partially related to the averaging process of power information from EMT to TS. Between each integration time step, the power informations from EMT in its time step are stored in a data array. The power information that is sent to TS is the average of the stored data. Since the average of the power information is different in both case, this could cause a different result in the simulation.

The Effect of TS Time Step to the Total Simulation Time

The co-simulation with a TS time step of 0.02s finished in approximately 23 minutes whereas the co-simulation with a TS time step of 0.01s finished in approximately 26 minutes. From this comparison, it is shown that reducing the TS time step increases the total co-simulation time. The reason of the increase of co-simulation time is due to the more calculation performed in TS and more process involved in the master algorithm.

In a smaller TS time step, there is more calculation involved in TS. The number of calculation in TS simulation with time step of 0.01 is twice the number of calculation performed in TS simulation with time step of 0.02s. Therefore, the time simulation in the case of 0.01s integration time step is longer. However, The difference between both case is considered small (3 minutes) because there is more calculation involved in EMT

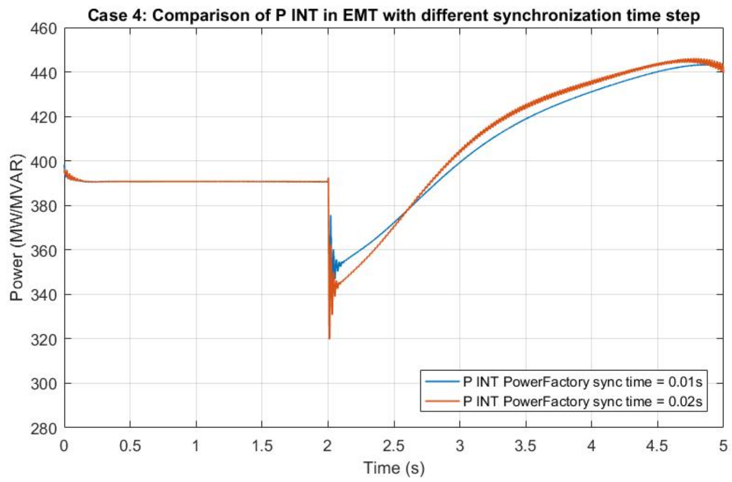

Figure 5.37: Result of Case 4: PINT in EMT

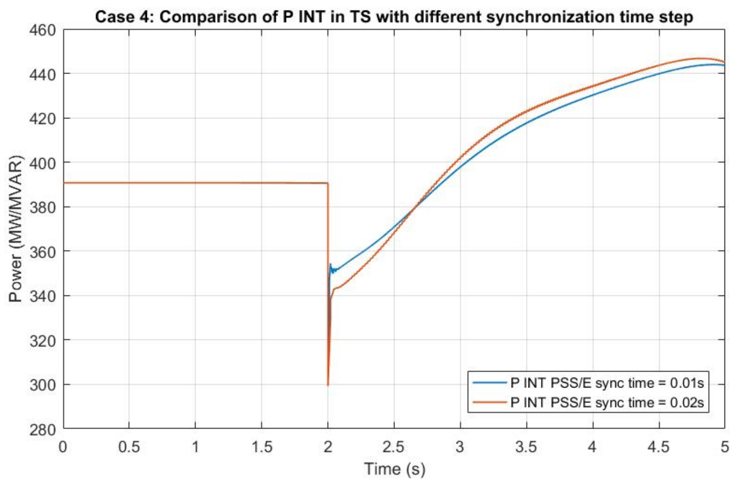

Figure 5.38: Result of Case 4: PINT in TS

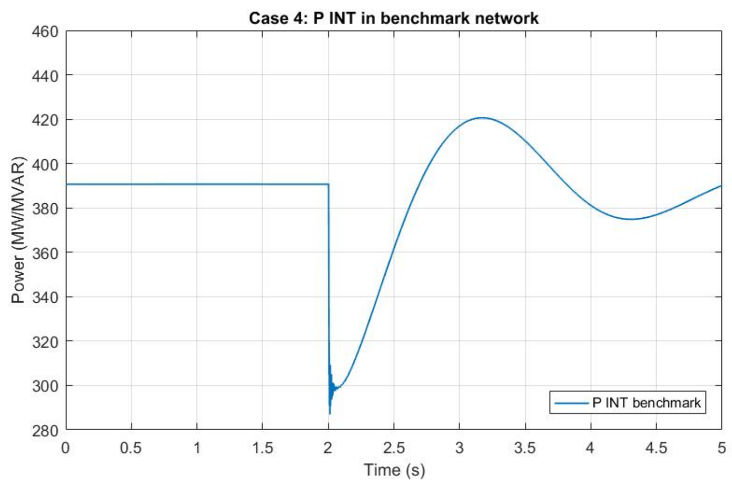

Figure 5.39: PINT in the benchmark Result

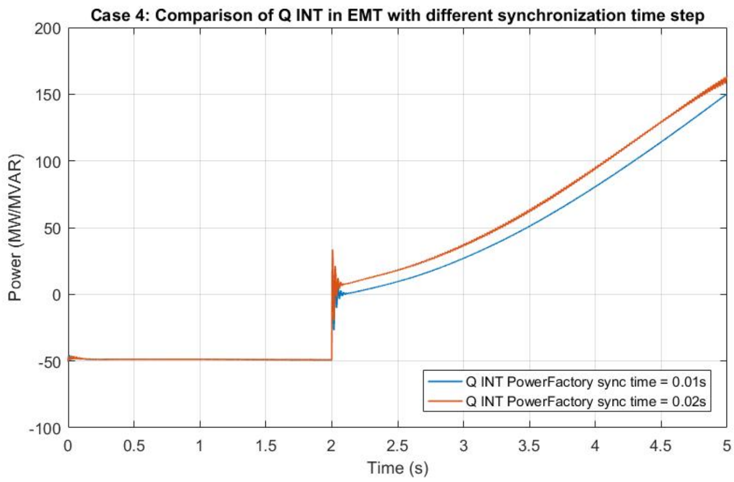

Figure 5.40: Result of Case 4: QINT in EMT

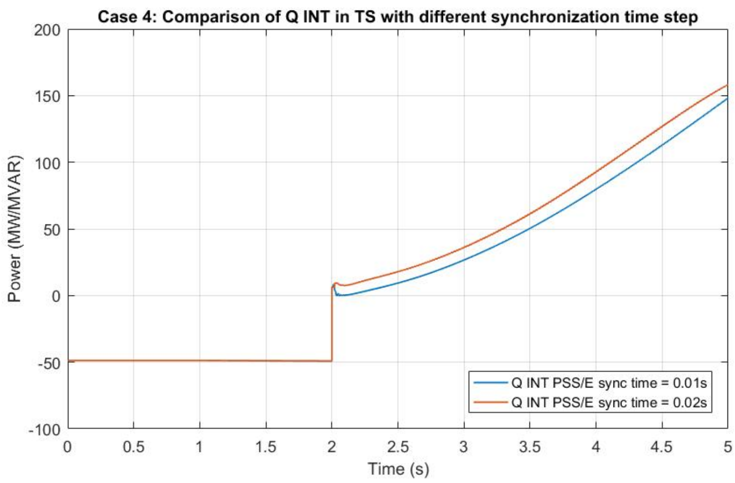

Figure 5.41: Result of Case 4: QINT in TS

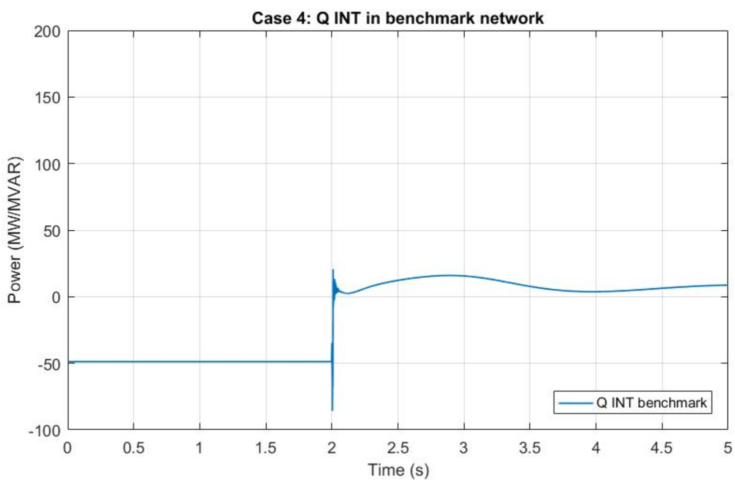

Figure 5.42: PINT in the benchmark Result

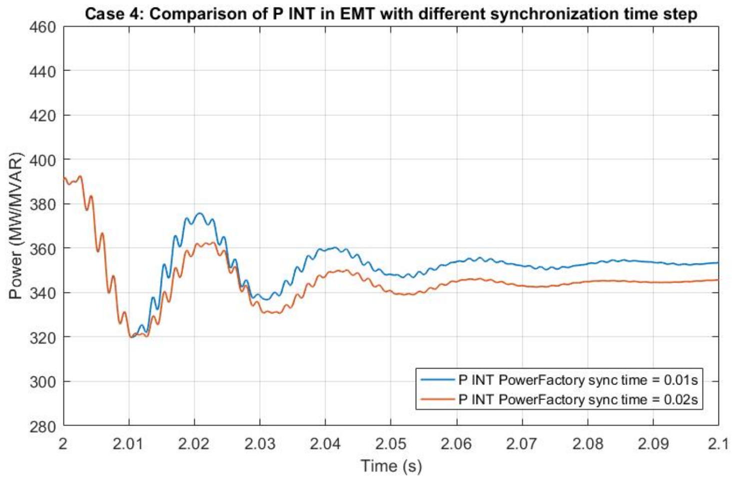

Figure 5.43: Result of Case 4: PINT in EMT a moment after the event is applied

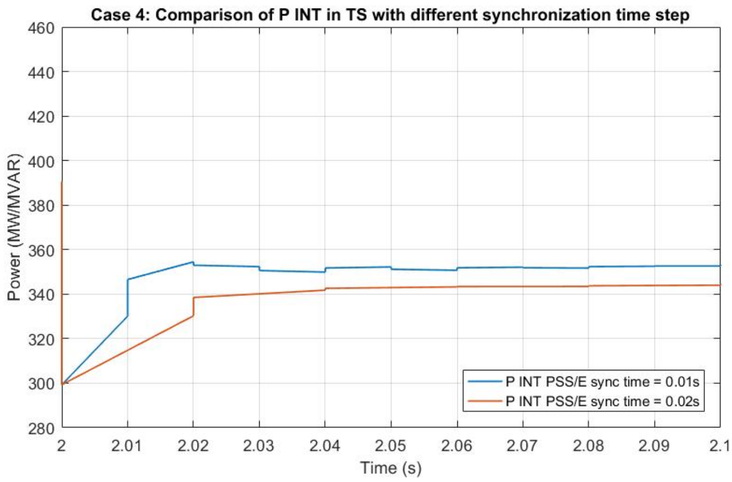

Figure 5.44: Result of Case 3: VINT in TS a moment after the event is applied

than the calculation in TS. Therefore, the addition of calculation in TS is not significant to the total simulation time.

5.6. Case 5: Effect of Different EMT Time Step in EMT-TS Co-simulation

In the fifth study case, a comparison between different EMT time step used in the co-simulation is presented. The objective of this study case is to examine how does the EMT time step parameter affects the result accuracy and the total simulation time of the developed co-simulation as corresponds to the fifth objective in this thesis.

5.6.1. Method

To perform the comparison, the EMT time step parameter in the master algorithm is modified. In addition, the number of data inside the *array buffer* block is also modified depending on the EMT time step being used. Then, the modified master algorithm is used to re-simulate a loss of transmission line event at TS side which has been performed in the second study case. The result from the modified time step simulation and the result from the second study case simulation are compared. And further, two variables which are active and reactive power, are evaluated.

Two EMT time steps are compared in this study case which is $50\mu s$ and $25\mu s$. The method to perform the loss of transmission line event is the same with the method defined in section 2. In this study case, the TS time step as well as the integration time step used for both EMT time step is 0.02s.

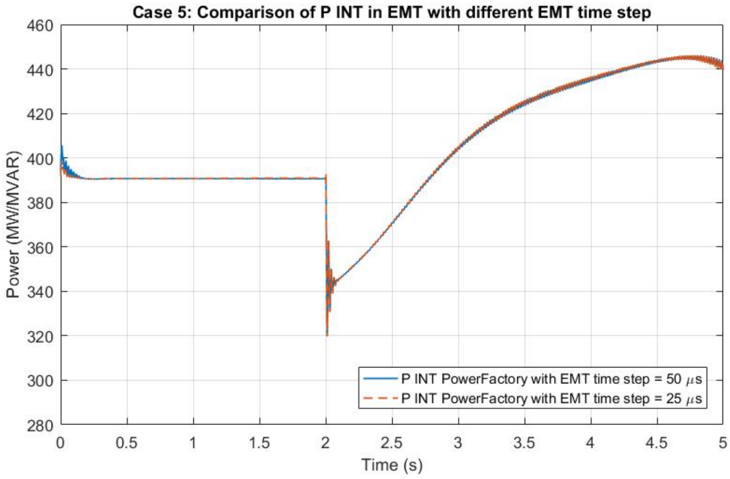

Figure 5.45: Result of Case 5: PINT in EMT

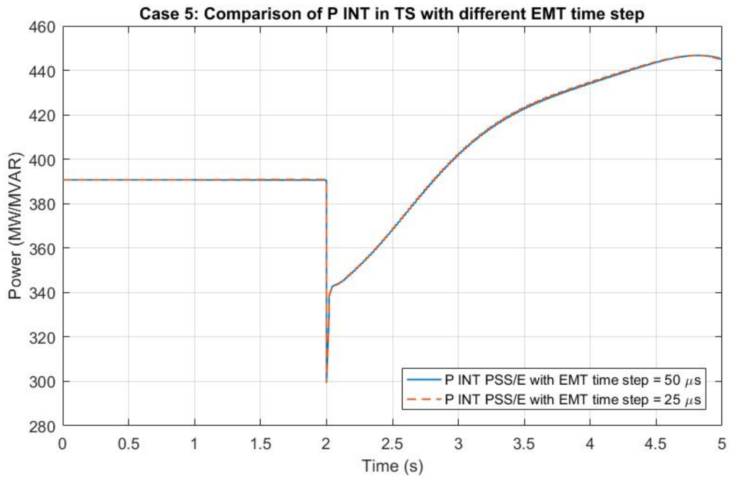

Figure 5.46: Result of Case 5: PINT in TS

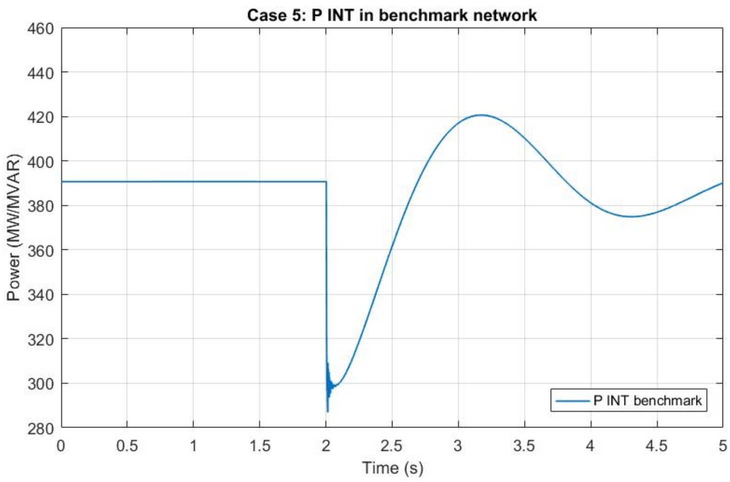

Figure 5.47: PINT in the benchmark Result

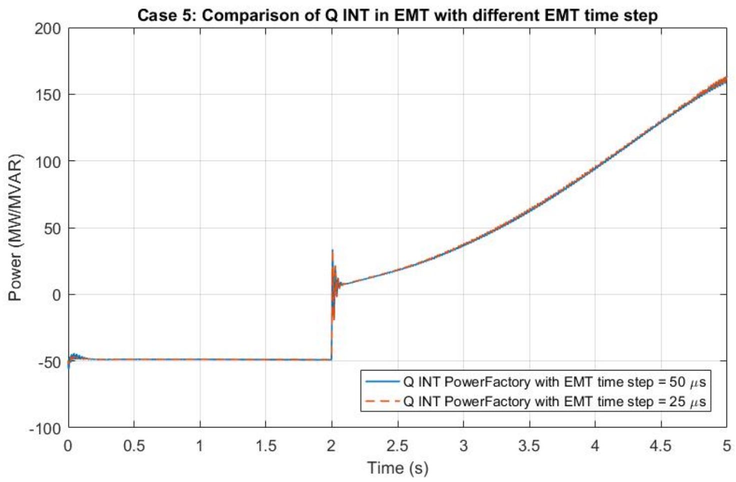

Figure 5.48: Result of Case 5: QINT in EMT

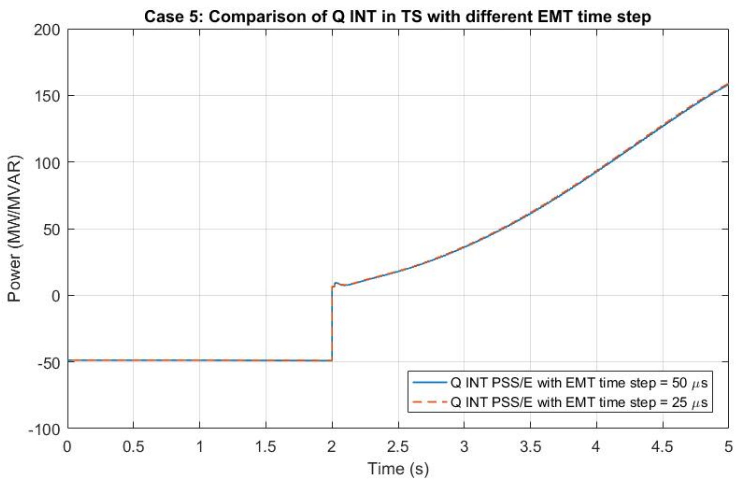

Figure 5.49: Result of Case 5: QINT in TS

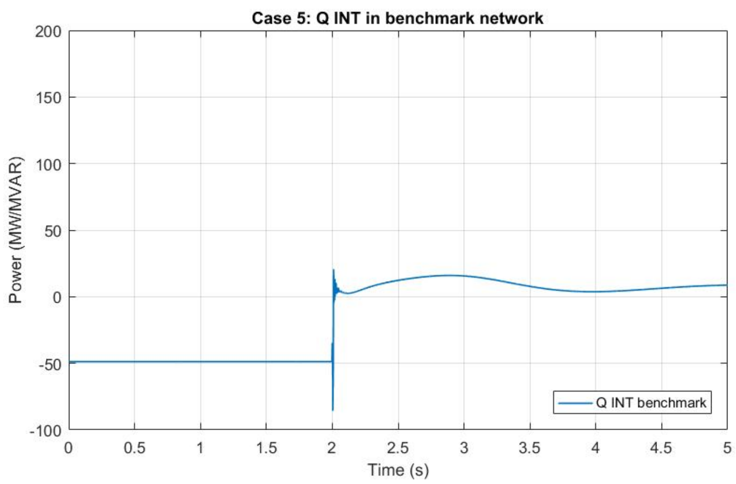

Figure 5.50: PINT in the benchmark Result

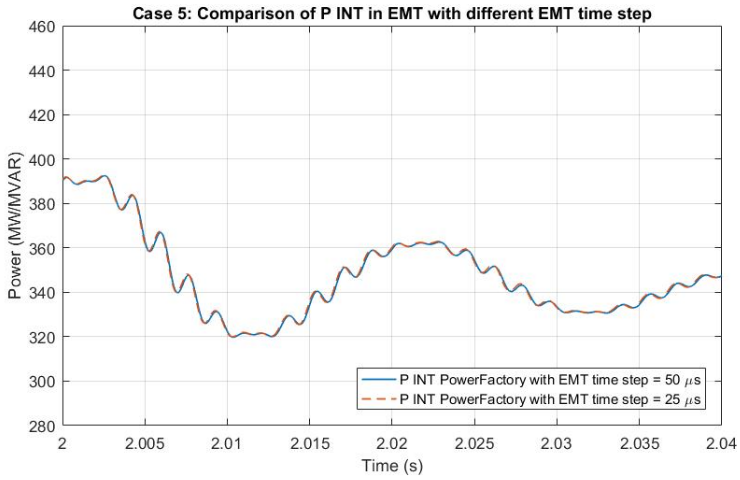

Figure 5.51: Result of Case 5: PINT in EMT between specific time window

5.6.2. Result and Discussions

The simulation result for case 5 are shown in Figure 5.45 - 5.50. In these figures, the comparison of the active power, reactive power in the INT BUS (Bus 8) obtained in PowerFactory, PSS/E, and benchmark result with different EMT time step are depicted respectively. The discussions regarding each of the results are as follows:

The Effect of EMT Time Step to the Accuracy of the Result

From Figure 5.45 - 5.50, it is observed that the result between different EMT time step are the same. Therefore, the analysis regarding the accuracy of the result is the same with the analysis done in the previous case 2. Furthermore, Figure 5.45 is observed in more detail in the time window between 2s and 2.04s with Figure 5.51 to compare the oscillation produced by both result. The similarity of the results show that the reduction of EMT time step smaller than $50\mu s$ does not give an advantage to the accuracy of the co-simulation result.

The Effect of EMT Time Step to the Total Simulation Time

The co-simulation with an EMT time step of $50\mu s$ finished in approximately 23 minutes whereas the co-simulation with an EMT time step of $25\mu s$ finished in approximately 42 minutes. From this comparison, it is shown that reducing the EMT time step significantly increases the total co-simulation time. The reason is due to the more calculation performed in EMT than in TS. The number of calculation in EMT simulation with a time step of $25\mu s$ is twice the number of calculation performed in EMT simulation with $50\mu s$ time step.

5.7. Chapter Summary

In this chapter, 5 study cases to asses the developed EMT-TS co-simulation have been presented. The summary of this chapter are as follows:

1. At the beginning of the chapter, the test co-simulation network based on Kundur 2 Areas 4 Generators as well as the method to create it has been described

2. In case 1, a loss of load event in TS area of the co-simulation network has been performed. From the results, it is shown that while the result of active power is identical with the benchmark result, the result of reactive power is in contrast to the benchmark. The difference between the result from co-simulation and the result from benchmark is caused by the delayed response between each simulator, the discrete information exchange, and the incorrect system solution caused by the separation of the network.

3. In case 2, a loss of transmission line event in TS area of the co-simulation network has been performed. From the results, it is shown that the active and reactive power have a similar behavior a moment after the event occurs. However, the result becomes more diverge when the co-simulation is run for longer time. The reason of the difference between co-simulation and benchmark result are the delayed response between each simulator and the slower dynamic characteristic of co-simulation network caused by a discrete information exchange.

4. In case 2, an additional discussion regarding the effect of equivalent impedance modification to the simulation result is presented. It is observed that the result obtained without updating the equivalent impedance is similar with the result obtained with updating the equivalent impedance. The active power and the voltage at BUS 9 result obtained with updating the equivalent impedance is slightly closer to the benchmark result. However, The reactive power obtained without updating the equivalent impedance shows better result compared with the result obtained with updating the equivalent impedance. Hence, no conclusion can be drawn from the discussion.

5. In case 3, a loss of transmission line event in EMT area of the co-simulation network has been performed. From the results, it is shown that the result of active and reactive power is identical with the benchmark result a moment after the event is performed. The results becomes more in contrast when the co-simulation is run for longer time. The reason is due to the slower transient nature of the co-simulation. It is observed that the reactive power result of case 3 is more accurate compared to case 1 and 2.

6. In the developed co-simulation, it is possible to apply an event either at TS or EMT side. However, the conclusion regarding which side is preferable to apply an event could not be made. Applying an event in TS can be more beneficial since the the equivalent impedance can be updated when the event occurs, although the difference between the obtained result from both case may not be significant. However, from the third study case, it is observed that the result by applying an event in EMT is more accurate than the result by applying an event in TS. Further investigation needs to be carried out to make a firm conclusion regarding which side is preferable to apply an event in the developed co-simulation.

7. From the result of case 1, 2, and 3, it is generally observed that the active power observed at the both PowerFactory and PSS/E interface shows a similar tendency with the benchmark network only for a certain moment after the dynamic event is applied. The difference between the co-simulation the benchmark result is evident. Moreover, the result between both diverges the longer the simulation is run.

8. From the result of case 1, 2, and 3, it is generally observed that in most cases, the reactive power shows a noticeable difference to the benchmark result and its value tends to keep increasing until the simulation ends. In the case of reactive power, the difference between the co-simulation and the benchmark result is more prominent compared with the active power result.

9. The total time needed for performing co-simulation in case 1, 2, and 3 is approximately between 23 to 24 minutes. This is in contrast with the total time required for full monolithic EMT simulation which only required 12s. Therefore, it is concluded that the developed co-simulation has not been beneficial in terms of execution time.

10. In case 4, a comparison of the different TS time step to the co-simulation result is presented. The results show that the shorter TS time step does not add significant effect on the accuracy of the co-simulation. In terms of the execution time, reducing the TS time step from 0.02s to 0.01s increases the total simulation time from approximately 23 minutes to 26 minutes. The difference between both case is considered small (3 minutes) because there is more calculation involved in EMT than the calculation in TS. However, it is possible that reducing the TS time step to be smaller than 0.01s could results a more noticeable improvement in the accuracy.

11. In case 5, a comparison of the different EMT time step to the co-simulation result is presented. It is observed that the result of 25μs EMT time step is the same with the result of 50μs. In terms of the execution time, reducing the EMT time step from 50μs to 25μs significantly increases the total simulation time from approximately 23 minutes to 42 minutes.

6

Conclusions and Recommendations

This chapter summarizes all the work done and gives conclusions regarding the the main research question and objectives in this thesis. In addition, this chapter also gives recommendation for the further development in this topic.

6.1. Conclusions

The main objective described at the beginning is to develop and study the benefits and limitations of the electromagnetic Transient - Transient Stability co-simulation based on PowerFactory and PSS/E. With regards to the main objective, the six specific objectives defined in the first chapter have been performed.

With regards to the first objective, the literature review on the existing implementations of EMT-TS co-simulation has been carried out. The documentation of the performed literature review is presented in the chapter 2. The review covers the basic explanation of co-simulation, the interfacing techniques, the interaction protocol, and data conversion between EMT and TS. The review proved to be an important stage as it gave a sufficient insight on how to design EMT-TS the co-simulation in which is crucial for obtaining the other objectives of this thesis.

The second objective, which is to develop an EMT-TS co-simulation using PowerFactory and PSS/E has been performed. The documentation of the development is presented in chapter 3. The chapter starts by describing the architecture of the co-simulation. Then, the four main components are presented. The first component is the master algorithm, the function of which are orchestrating the co-simulation, establishing a connection and exchange variables between simulators, and performing data processing. The second and the third components are the interfaces in PowerFactory and PSS/E, whose functions are to obtain and set the variables at the point of interconnection, and to act as an equivalent systemrepresentation of the other simulator. Lastly, the fourth component is the PSS/E wrapper whose functions are to control PSS/E, obtain and modify the data variables from PSS/E and enable data exchange between the master and PSS/E interface. Apart from the main components and its design consideration, the previous EMT-TS cosimulation design is also provided to give more informations regarding the design iteration that has been performed during this thesis.

For the third objective, the implementation of the developed EMT-TS co-simulation has been tested. The documentation of the performed test is presented in chapter 4. Three tests have been carried out which are the PowerFactory interface test, PSS/E Wrapper together with PSS/E interface test, and the co-simulation integration test using PowerFactory and PSS/E. It is concluded from the first and the second test that the PowerFactory interface, the PSS/E wrapper, and the PSS/E interface is able to function properly by setting the correct amount of power according to its power set point input. Then, it is concluded from the third test that all the mentioned components are able to work together to perform a co-simulation. Therefore, it is concluded that the developed EMT-TS in this thesis is correctly implemented.

The fourth objective, which is to compare the accuracy and execution time between the EMT-TS co-simulation result and the benchmark result has been carried out in the study case 1,2, and 3 in the chapter 5. It terms of accuracy, it is concluded that the active power observed at the both PowerFactory and PSS/E interface shows a similar tendency with the benchmark network only for a certain moment after the dynamic event is applied. The difference between the co-simulation the benchmark result is evident. Moreover, the result between both diverges the longer the simulation is run.

For the reactive power result, it is shown that in most cases, the curve is different with the benchmark result and its value tends to keep increasing until the simulation ends. In the case of reactive power, the difference between the co-simulation and the benchmark result is more prominent compared with the active power result.

In terms of execution time, the study cases performed in case 1, 2, and 3 has the execution time around 23-24 minutes. This is in contrast with the execution time of the benchmark which only required 12 s. Therefore, it is concluded that the developed co-simulation has not been beneficial in terms of execution time.

With regards to the fifth objective, the effect of different simulator time step on the accuracy and the execution time of the developed EMT-TS co-simulation has been investigated from the result obtained from study case 4 and 5 in chapter 5. In case 4, the effect of different TS time step is inspected. It is concluded that reducing the TS time step from 0.02s to 0.01s slightly increases the total simulation time from 23 to 26 minutes. The reduction of TS time step from 0.02s to 0.01s does not add significant improvement on the accuracy of the developed EMT-TS co-simulation. However, it is still possible that reducing the TS time step to be smaller than 0.01s could results a more noticeable improvement in the accuracy.

In the other hand, the effect of different EMT time step is examined in case 5. It is concluded that the result obtained by reducing EMT time step to $25\mu s$ is the same with the result obtained from $50\mu s$ EMT time step. However, reducing the EMT time step significantly increases the total simulation time from 23 to 42 minutes.

The last objective which is providing recommendation for the further development of EMT-TS co-simulation is presented at the next section of this chapter.

Based from the result achieved from each objectives, the main research question in this thesis is answered:

Can an Electromagnetic Transient - Transient Stability hybrid co-simulation platform based on PowerFactory and PSS/E be beneficial in terms of accuracy and execution time?

The Electromagnetic Transient - Transient Stability hybrid co-simulation platform based on PowerFactory and PSS/E has not been beneficial yet in terms of accuracy and execution time. From the performed study cases, it is shown that although the active power result shows a similar tendency with the monolithic EMT result, the difference between both are visible. The difference between both are more prominent in the reactive power result. Also, the total execution time of the co-simulation is significantly larger than the total execution time obtained from the monolithic EMT simulation. However, the developed co-simulation still has a lot of room for improvement and further developments in this topic might reverse this situation.

6.2. Recommendations

Based on the work done in this thesis, the recommendations for the future study are listed below:

1. Investigate what part in the co-simulation that causes the long execution time.

   It is evident from the conclusion that the total execution time of the developed co-simulation is significantly greater than the result from monolithic EMT simulation. Since the co-simulation is composed of many part, the reason of the longer execution time in co-simulation could be due to a long computational process in certain part that causes a 'bottle neck' in its execution. For example, the bottle neck could be in the waveform to phasor conversion process inside the master, or could be in the socket connection. By doing a research in this area, an improvement to the co-simulation execution speed can be made by specifically modifying a certain part in the co-simulation which causes the 'bottle neck'

2. Investigate the cause of inaccuracy after the dynamic event occurs.

   It is observed from the co-simulation result that the error in the co-simulation is keep accumulated, resulting an inaccurate simulation result when the simulation is run for a longer time. This phenomena needs to be further investigated to find out what is the cause of the error. By investigating the cause, the error accumulated at each time step could be suppressed, and the accuracy of the EMT-TS co-simulation could be improved

3. Modify the method of to process the power from EMT in TS

In the design of master algorithm in this thesis, the power sent to the PSS/E is the average of the power information inside the *array buffer*. However, it is found that averaging the power information also contributes to an incorrect data transfer between both simulators. Instead of averaging the power information, using the power information from the last time stamp probably could produce a more accurate result.

4. Implement frequency dependent equivalent circuit to PowerFactory interface.

   From the literature review, it is found that using a frequency dependent equivalent circuit in EMT co-simulation interface could give a more accurate representation of the external system over a wider frequency spectrum. This may be beneficial when the dynamic event is applied in the co-simulation network because the transient that occurs during the dynamic event consists of different signal frequency. In additon, the frequency dependent equivalent circuit could also be beneficial when a power electronic based component is included in the co-simulation due to its capability to interract with a high frequency signal caused by the power electronic's harmonic.

5. Include a phase compensator in the master algorithm design.

   The phase compensator works by giving a phase shift to the calculated voltage source phasor in the conversion process from TS to EMT. The phase compensation is necessary if the integration time step used in the co-simulation is less than 0.02 s, which is the period of a 50 Hz signal. By the The addition of a phase compensator, the TS time step could be further reduced to less than 0.02s. By reducing the TS time step, the data exchange between EMT and TS could be performed in a shorter interval. It could be the key to suppress the effect caused by the discrete information exchange to the co-simulation result. This could enable a further study regarding the effect of TS time step to a co-simulation accuracy

6. Investigate how to modify the equivalent impedance of PSS/E interface.

   The modification of equivalent impedance in PSS/E interface when an event occurs in EMT side could improve the accuracy of the system. Since the way to implement a modification to PSS/E impedance has not been figured out, this recommendation can be considered for the further improvement in this topic

7. Include power electronic component in the study.

   One of the background reason in the development of hybrid simulation is the need observe a fast transient that occurs in the EMT side. Therefore, including a power electronic component such as HVDC converter and Static Var Compensator could give more assessment to the performance of the developed co-simulation.

8. Develop an EMT-TS co-simulation that uses voltage or current as the exchange variable between both simulator and compare the result with the an EMT-TS co-simulation that uses power as the exchange variable.

   From the literature review, there are several publications that use voltage or current as the exchange variable in their hybrid simulation. The result comparison between the EMT-TS co-simulation that uses power and the one that uses voltage or current can be beneficial as it could give more insight on the advantage, disadvantage, and limitation of each exchange variable option. Then, a study can be performed to determine which variable is preferable for EMT-TS co-simulation

9. Study the relationship of the external system scale with the total execution time of co-simulation.

   In general, a TS simulation executes faster than an EMT simulation of the same power system. Increasing the scale of the external system simulated in TS simulation would increase the total simulation time. But, the increment may not be as much as the increasing of the total simulation time if the same system is simulated in EMT. If the size of the system simulated in TS is enlarged, It is possible that at a certain system size, the execution time between co-simulation and monolithic EMT simulation could become the same. This study could determine at which system size does the EMT-TS co-simulation may be beneficial to use.

10. Further investigation on the effect of equivalent impedance to the accuracy of the co-simulation.

    The similar investigation has been carried out in the additional discussion of the second study case. However, there is no firm conclusion that can be drawn. Additional discussion which involves more study cases is needed to further examine the effect of the equivalent impedance on the accuracy of the co-simulation. The method regarding this recommendation is described in chapter 5 in the second case study

11. Compare the co-simulation accuracy and execution time with different interaction protocol.

    Apart from the serial protocol that is used in thesis, there are other type of protocol that can also be implemented. Each of the interaction protocol type has its own advantage and limitation. The comparison between the result obtained by different interaction protocol could be beneficial to determine which one is more preferable for the EMT-TS co-simulation

A

Appendix A: Technical Implementation of the PowerFactory Interface

Inside the DSL model, a definition of the data that are sent/received as well as the script to initiate the socket connection need to be defined. The script inside the DSL model of this co-simulation are showed in Figure A.1.

There are several steps included in the DSL code. First, some variables need to defined. Then, as the signal received by DSL needs to be sent to master, a socket connection must be initialized. The initialization is realized by function *IPChannelStart*. After the socket connection is established, the voltages and currents that are sent need to be given initial condition.

Next, The data transfer to master is realized by function *IPChannelRead*. Using this function, the number and type of signal sent to master can be defined. The function has 3 arguments which are channelID, var, and value:

- *channelID*: an integer which is the identifier number used when establishing socket connection to master. This ChannelID must be the same with the ID defined in *PFIPConnection.xml*
- *var*: an integer which gives each of the sent variables a unique identifier at one data delivery. If there is 7 variables that are sent to master, then each of the sent variables must be given a unique var number
- *value*: a float number representing the value obtained from input signal

When master sends data to the interface, it must be able to receive the data and transfer the data to input signal of PowerFactory component. The function to receive the data from master is realized by command *IPChannelWrite*. The function has 2 arguments which are channelID, and value.

IPChannelRead and IPChannelWrite are not a built in function in PowerFactory. These functions are provided digexfun.dll which also provides function IPChannelStart to start the socket connection. To enable the socket connection to master, the following files must be put inside PowerFactory installation folder:

- PFIPConnection.xml
- DigExFunPFIP.dll
- DigExDynPFIP.dll
- PFIPConnection.dll
- Toolbox.dll

Apart from DSL configuration, the XML file need to be configured as well to enable proper TCP data transfer. As can be shown in figure, the important parameter that need to be updated is input, output, and blocking. These value have to be the same with the number of variables exchaned between emt and master. Figure A.2 shows the code inside *PFIPConnection.xml*:

```
! Define channelID
vardef(channelID) = ;
! Define internal dummy variable
vardef(dummy) = ;

! Init channelID
inc(channelID) = 1
! Init channel
inc(dummy) = IPChannelStart(channelID,60,0)
! Init voltages and currents
inc(Ua) = 0
inc(Ub) = 0
inc(Uc) = 0
inc(P) = 0
inc(Q) = 0
inc(Ea) = 77.185
inc(Eb) = -38.964
inc(Ec) = -38.221
inc(Req) = 14.00953
inc(Xeq) = 42.9524

! Send data to master, multiplied 1000 because the obtained value is in kV
dummy0 = IPChannelWrite(time(),channelID,0, time())
dummy1 = IPChannelWrite(time(),channelID,1, Ua*1000)
dummy2 = IPChannelWrite(time(),channelID,2, Ub*1000)
dummy3 = IPChannelWrite(time(),channelID,3, Uc*1000)
dummy4 = IPChannelWrite(time(),channelID,4, P*1000000)
dummy5 = IPChannelWrite(time(),channelID,5, Q*1000000)
dummy6 = IPChannelWrite(time(),channelID,6, 50)

! Receive data from master, divided 1000 because the input value must be in kV
Ea = IPChannelRead(time(),channelID,0)/1000
Eb = IPChannelRead(time(),channelID,1)/1000
Ec = IPChannelRead(time(),channelID,2)/1000
Req = IPChannelRead(time(),channelID,3)
Xeq = IPChannelRead(time(),channelID,4)
```

Figure A.1: The code inside com_interface DSL model in PowerFactory interface

```
<ipconnection logging="all" logfile="D:\PFIPConnection.log">
    <channel id="1">
        <host>127.0.0.1</host>
        <port>6000</port>
        <writeonchanged>yes</writeonchanged>
        <inputs>7</inputs>
        <blocking>yes</blocking>
        <outputs>5</outputs>
    </channel>
</ipconnection>
```

Figure A.2: The code inside com_interface DSL model in PowerFactory interface

B

Appendix B: Technical Implementation of the PSS/E Interface

To implement the interface in PSS/E, two files are needed which are DSUSRIEEEPWRDV33.dll and interface.dyr. The dll file is the file which modifies the static generator behavior during dynamic simulation. The dll file is similar with common model in PowerFactory; it contains a set of equations which determine the relationship between input, state, and output of the interface. The DSUSRIEEEPWRDV33.dll contains a set of equations which describes the behavior of PSS/E interface during dynamic simulation. The dll file is obtained by compiling a Fortran code which contains the above information. In this thesis, the DSUSRIEEEPWRDV33.dll has been developed by the author of [29]. Therefore, the dll and the source Fortran code is not described and documented in this thesis.

The .dyr file contains informations regarding the dynamic model used by each component in PSS/E. For example, the model of exciter or the model of synchronous generator in the system. The .dyr file needs to be properly configured before performing the dynamic simulation. An error when configuring the dyr file could result in a misbehavior of the power system components during dynamic simulation.

There are two .dyr files used in this co-simulation. The first .dyr file contains the dynamic model of the interface which refers to the DSUSRIEEEPWRDV33.dll model. The second .dyr file contains the dynamic model of power system components in PSS/E network other than the PSS/E interface, such as generator. Both .dyr files can be merged into a single .dyr file. However, in this co-simulation, the .dyr files are separated for the sake of easiness in reusing the .dyr file for different case study.

The .dyr file can be configured via PSS/E GUI or by manually writing .dyr script. However, the .dyr file for PSS/E interface can only be configured by writing dyr script. According to PSS/E manual, the format to configure the .dyr file is as follows:

BUSID 'USRMDL' IM 'model name' IC IT NI NC NS NV data list /

The information regarding each of this field are furtherly explained as follows:

Table B.1: The explanation of each field in the .dyr file

Field	Description
BUSID	The bus number which the interface is connected
'USRMDL'	A string indicating that the dynamic model is user defined. The default input for this co-simulation is 'USRMDL'
IM	The machine id of the interface
'model name'	The model name defined by dll file. The default input is 'INTPSSE'
IC	User model type code. The default input is 1 which indicates a generator model
IT	Type of the model. The default input is 1 which indicates a current injection model
NI	Number of ICONs used in the model. The default input is 1
NC	Number of CONs used in the model. The default input is 0
NS	Number of STATEs used in the model. The default input is 0
NV	Number of VARs used in the model. The default input is 10
Datalist	Contains the value of one ICON specifed in the model. The default value is the same with BUSID

C

Appendix C: PSS/E files of Kundur 2 Areas 4 Generators System

C.1. PSS/E RAW File

0, 100.00, 32, 0, 1, 50.00 / PSS(R)E 32 RAW created by rawd32 FRI, JUL 28 2017 13:28
FOUR MACHINE KUNDUR SYSTEM
POWER FLOW CONTROL
1,'BUS1 ', 20.0000,2, 1, 1, 1,1.03000, 27.0706
2,'BUS2 ', 20.0000,2, 1, 1, 1,1.01000, 17.3062
3,'BUS3 ', 20.0000,3, 2, 1, 1,1.03000, 0.0000
4,'BUS4 ', 20.0000,2, 2, 1, 1,1.01000, -10.1920
5,'BUS5 ', 230.0000,1, 1, 1, 1,1.00645, 20.6074
6,'BUS6 ', 230.0000,1, 1, 1, 1,0.97813, 10.5227
7,'BUS7 ', 230.0000,1, 1, 1, 1,0.96101, 2.1135
8,'BUS8 ', 230.0000,1, 3, 1, 1,0.94861, -11.7566
9,'BUS9 ', 230.0000,1, 2, 1, 1,0.97136, -25.3539
10,'BUS10 ', 230.0000,1, 2, 1, 1,0.98346, -16.9386
11,'BUS 11 ', 230.0000,1, 2, 1, 1,1.00825, -6.6284
0 /End of Bus data, Begin Load data
7,'1 ',1, 1, 1, 967.000, 100.000, 0.000, 0.000, 0.000, 0.000, 1,1
9,'1 ',1, 2, 1, 1767.000, 100.000, 0.000, 0.000, 0.000, 0.000, 1,1
0 /End of Load data, Begin Fixed shunt data
7,'1 ',1, 0.000, 200.000
9,'1 ',1, 0.000, 350.000
0 /End of Fixed shunt data, Begin Generator data
1,'1 ', 700.000, 185.029, 9999.000, -9999.000,1.03000, 0, 900.000, 2.50000E-3, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1, 100.0, 9999.000, -9999.000, 1,1.0000
2,'1 ', 700.000, 234.610, 900.000, -900.000,1.01000, 0, 900.000, 2.50000E-3, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1, 100.0, 9999.000, -9999.000, 1,1.0000
3,'1 ', 719.092, 176.024, 900.000, -900.000,1.03000, 0, 900.000, 2.50000E-3, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1, 100.0, 9999.000, -9999.000, 1,1.0000
4,'1 ', 700.000, 202.079, 900.000, -900.000,1.01000, 0, 900.000, 2.50000E-3, 2.50000E-1, 0.00000E+0, 0.00000E+0,1.00000,1, 100.0, 9999.000, -9999.000, 1,1.0000
0 /End of Generator data, Begin Branch data 5, 6,'1 ', 2.50000E-3, 2.50000E-2, 0.04375, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
6, 7,'1 ', 1.00000E-3, 1.00000E-2, 0.01750, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
7, 8,'1 ', 1.10000E-2, 1.10000E-1, 0.19250, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
7, 8,'2 ', 1.10000E-2, 1.10000E-1, 0.19250, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
8, 9,'1 ', 1.10000E-2, 1.10000E-1, 0.19250, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
8, 9,'2 ', 1.10000E-2, 1.10000E-1, 0.19250, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000

9, 10,'1 ', 1.00000E-3, 1.00000E-2, 0.01750, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
10, 11,'1 ', 2.50000E-3, 2.50000E-2, 0.04375, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
0 /End of Branch data, Begin Transformer data
1, 5, 0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,' ',1, 1,1.0000
0.00000E+0, 1.66700E-2, 100.00
1.00000, 0.000, 0.000, 900.00, 900.00, 900.00, 0, 0, 1.10000, 0.90000, 1.10000, 0.90000, 999, 0, 0.00000, 0.00000, 0.000
1.00000, 0.000
2, 6, 0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,' ',1, 1,1.0000
0.00000E+0, 1.66700E-2, 100.00
1.00000, 0.000, 0.000, 900.00, 900.00, 900.00, 0, 0, 1.10000, 0.90000, 1.10000, 0.90000, 999, 0, 0.00000, 0.00000, 0.000
1.00000, 0.000
11, 3, 0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,' ',1, 1,1.0000
0.00000E+0, 1.66700E-2, 100.00
1.00000, 0.000, 0.000, 900.00, 900.00, 900.00, 0, 0, 1.10000, 0.90000, 1.10000, 0.90000, 999, 0, 0.00000, 0.00000, 0.000
1.00000, 0.000
10, 4, 0,'1 ',1,1,1, 0.00000E+0, 0.00000E+0,2,' ',1, 1,1.0000
0.00000E+0, 1.66700E-2, 100.00
1.00000, 0.000, 0.000, 900.00, 900.00, 900.00, 0, 0, 1.10000, 0.90000, 1.10000, 0.90000, 999, 0, 0.00000, 0.00000, 0.000
1.00000, 0.000
0 /End of Transformer data, Begin Area interchange data
0 /End of Area interchange data, Begin Two-terminal dc line data
0 /End of Two-terminal dc line data, Begin VSC dc line data
0 /End of VSC dc line data, Begin Impedance correction table data
0 /End of Impedance correction table data, Begin Multi-terminal dc line data
0 /End of Multi-terminal dc line data, Begin Multi-section line data
0 /End of Multi-section line data, Begin Zone data
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
0 /End of FACTS device data, Begin Switched shunt data
0 /End of Switched shunt data, Begin GNE device data
0 /End of GNE device data
Q

C.2. PSS/E DYR File

1 'GENROU' 1 8.0000 0.30000E-01 0.40000 0.50000E-01
6.5000 0.00000E+00 1.8000 1.7000 0.30000
0.55000 0.25000 0.20000 0.00000E+00 0.00000E+00/
1 'EXAC4' 1 0.10000E-01 999.00 -999.00 0.0000
0.000 200.00 0.00000E+00 999.00 -999.00
0.00000E+00/
1 'STAB1' 1 20.00 10.00 2.50 0.020 0.5555 5.4000
999.00/
1 'IEEEG1' 1 0 0 15.000 0.0100 0.0000 0.0250 0.1140
-1.139 0.9500 0.0000 0.0000 0.0000 0.0000 0.2000
0.3000 0.0000 6.0000 0.3000 0.0000 0.4000 0.4000
0.0000/
2 'GENROU' 1 8.0000 0.30000E-01 0.40000 0.50000E-01
6.5000 0.00000E+00 1.8000 1.7000 0.30000
0.55000 0.25000 0.20000 0.00000E+00 0.00000E+00/
2 'EXAC4' 1 0.10000E-01 999.00 -999.00 0.0000

```
0.000 200.00 0.00000E+00 999.00 -999.00
0.00000E+00/
2 'STAB1' 1 20.00 10.00 2.50 0.020 0.5555 5.4000
999.00/
3 'GENROU' 1 8.0000 0.30000E-01 0.40000 0.50000E-01
6.1750 0.00000E+00 1.8000 1.7000 0.30000
0.55000 0.25000 0.20000 0.00000E+00 0.00000E+00/
3 'EXAC4' 1 0.10000E-01 999.00 -999.00 0.0000
0.000 200.00 0.00000E+00 999.00 -999.00
0.00000E+00/
3 'STAB1' 1 20.00 10.00 2.50 0.020 0.5555 5.4000
999.00/
3 'IEEEG1' 1 0 0 15.000 0.0100 0.0000 0.0250 0.1140
-1.139 0.9500 0.0000 0.0000 0.0000 0.0000 0.2000
0.3000 0.0000 6.0000 0.3000 0.0000 0.4000 0.4000
0.0000/
4 'GENROU' 1 8.0000 0.30000E-01 0.40000 0.50000E-01
6.1750 0.00000E+00 1.8000 1.7000 0.30000
0.55000 0.25000 0.20000 0.00000E+00 0.00000E+00/
4 'EXAC4' 1 0.10000E-01 999.00 -999.00 0.0000
0.000 200.00 0.00000E+00 999.00 -999.00
0.00000E+00/
4 'STAB1' 1 20.00 10.00 2.50 0.020 0.5555 5.4000
999.00/
```

D

Appendix D: PSS/E Files of the Simple Test Case System

D.1. PSS/E RAW File

0, 10.00, 33, 0, 1, 50.00 / PSS(R)E-33.5 FRI, AUG 25 2017 9:05
1,"GEN_BUS' ', 11.0000,3, 1, 1, 1,1.00000, 0.0000,1.10000,0.90000,1.10000,0.90000
2,"INT_BUS' ', 11.0000,1, 1, 1, 1,0.99568, -0.6553,1.10000,0.90000,1.10000,0.90000
3,"LOAD_BUS' ', 11.0000,1, 1, 1, 1,0.99149, -1.3162,1.10000,0.90000,1.10000,0.90000
0 / END OF BUS DATA, BEGIN LOAD DATA
3,'1 ',1, 1, 1, 4.000, 1.000, 0.000, 0.000, 0.000, 0.000, 1,1,1
3,'2 ',1, 1, 1, 4.000, 1.000, 0.000, 0.000, 0.000, 0.000, 1,1,1
0 / END OF LOAD DATA, BEGIN FIXED SHUNT DATA
0 / END OF FIXED SHUNT DATA, BEGIN GENERATOR DATA
1,'1 ', 8.020, 2.200, 5.000, -5.000,1.00000, 0, 10.000, 0.00000E+0, 2.00000E-1, 0.00000E+0, 0.00000E+0,1.00000,1, 100.0, 10.000, 0.000, 1,1.0000
0 / END OF GENERATOR DATA, BEGIN BRANCH DATA
1, 2,'1 ', 1.46000E-3, 1.46000E-2, 0.00012, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
2, 3,'1 ', 1.46000E-3, 1.46000E-2, 0.00012, 0.00, 0.00, 0.00, 0.00000, 0.00000, 0.00000, 0.00000,1,1, 0.00, 1,1.0000
0 / END OF BRANCH DATA, BEGIN TRANSFORMER DATA
0 / END OF TRANSFORMER DATA, BEGIN AREA DATA
0 / END OF AREA DATA, BEGIN TWO-TERMINAL DC DATA
0 / END OF TWO-TERMINAL DC DATA, BEGIN VSC DC LINE DATA
0 / END OF VSC DC LINE 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
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
0 / END OF FACTS DEVICE DATA, BEGIN SWITCHED SHUNT DATA
0 / END OF SWITCHED SHUNT DATA, BEGIN GNE DATA
0 / END OF GNE DATA, BEGIN INDUCTION MACHINE DATA
0 / END OF INDUCTION MACHINE DATA
Q

D.2. PSS/E DYR File

1 'GENROU' 1 5.0000 0.60000E-01 0.20000 0.60000E-01

3.0000 0.0000 1.6000 1.5500 0.70000
0.85000 0.35000 0.20000 0.90000E-01 0.38000 /
1 'SEXS' 1 0.10000 10.000 100.00 0.10000
0.0000 4.0000 /
1 'TGOV1' 1 0.50000E-01 0.50000E-01 1.0500 0.30000
1.0000 1.0000 0.0000 /

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